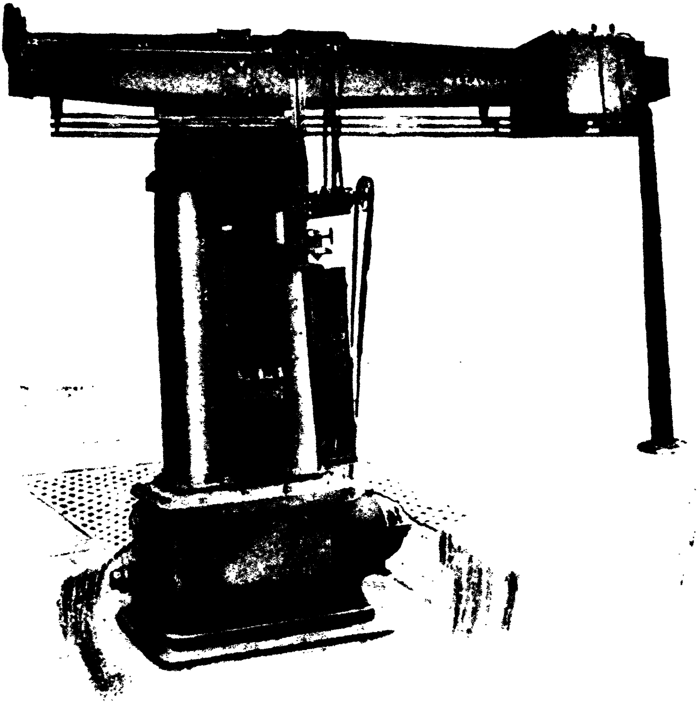
MATERIALS AND THEIR APPLICATION TO ENGINEERING DESIGN

ENGINEERING AND TECHNICAL BOOKS

DESIGN OF STRUCTURES	S. Anglin.	16 –
BRIDGE CONSTRUCTION	T. Claxton Fidler.	30 –
PLATE GIRDER BRIDGES	H. H. Bird.	15 –
FOUNDATIONS FOR GAS AND OIL ENGINES	E. L. Parry.	7/6
DOCK ENGINEERING	Brysson Cunningham.	42 –
HARBOUR ENGINEERING	Brysson Cunningham.	30 –
DOCK AND HARBOUR ENGINEERS' REFERENCE BOOK	Brysson Cunningham.	9 –
CENTRIFUGAL PUMPING MACHINERY	E. W. Sargeant.	—
MODERN PUMPING AND HYDRAULIC MACHINERY	E. Butler.	25 –
MANUAL OF CIVIL ENGINEERING PRACTICE	F. N. Taylor.	34 –
MANUAL OF MARINE ENGINEERING	A. E. Seaton.	40 –
MARINE ENG. RULES AND TABLES	Seaton & Rounthwaite.	15 –
LUBRICATION AND LUBRICANTS	Archbutt & Deeley.	36 –
THE RUNNING AND MAINTENANCE OF THE MARINE DIESEL ENGINE	J. Lamb.	18 –
QUESTIONS AND ANSWERS ON CONSTRUCTION AND OPERATION OF DIESELS, ETC.	J. Lamb.	10 –
LAND AND MARINE DIESEL ENGINES	G. Supino.	15 –
INTERNAL COMBUSTION ENGINE (Design and Practice)	E. Butler.	21 –
THE BALANCING OF OIL ENGINES	W. K. Wilson.	25 –
MODERN ENGINEERING WORKSHOP PRACTICE	H. Thompson.	7 6
AUTOGENOUS WELDING	Granjon & Rosemberg.	7 6
THE PROBLEM OF FLUCTUATING LOADS ON BOILERS	G. E. Hider.	7 6
STEAM TURBINES	G. Belluzzo.	21 –
BOILER FEED WATER	P. G. Jackson.	5 –
TRANSMISSION GEARS (Mech., Elect., Hydraulic)	E. Butler.	8 6
OVERHEAD ELECTRIC POWER TRANSMISSION ENGINEERING	W. T. Taylor.	35 –
DISTRIBUTION OF ELECTRICITY BY OVERHEAD LINES	W. T. Taylor.	25 –
ELECTRICITY SUPPLY TRANSFORMER SYSTEMS AND OPERATION	W. T. Taylor.	20 –
ELECTRIC CRANE CONSTRUCTION	C. W. Hill.	30 –
PRACTICAL HINTS ON COLLIERY POWER PLANT	R. Rogerson.	16 –
STEEL SHIPS (Construction and Maintenance)	T. Walton.	30 –
PRESENT-DAY SHIPBUILDING	T. Walton.	25 –
MATERIALS AND THEIR APPLICATION TO ENGINEERING DESIGN	E. A. Allcut & E. Miller.	18 –
ALIGNMENT CHARTS (For Engineers and Students)	W. J. Kearton & G. Wood.	10 6
THE NON-FERROUS METALS	W. Gowland.	30 –
METALLURGY OF STEEL—In Two Volumes	Harbord and Hall.	Each 32 –
CAST-IRON IN THE LIGHT OF RECENT RESEARCH	W. H. Hatfield.	18 –
PHYSICO-CHEMICAL PROPERTIES OF STEEL	C. A. Edwards.	21 –
METALLIC ALLOYS (Structure and Constitution)	G. H. Gulliver.	15 –
VALUE OF SCIENCE IN SMITHY AND FORGE	W. H. Cathcart.	6 –
METHODS OF MEASURING TEMPERATURE	E. Griffiths.	10/6

PUBLISHED BY

CHARLES GRIFFIN & COMPANY, LTD.



Electrically-driven Testing Machine. Capacity: 100 Tons.
Tests: Tension, Compression, and Bending.

[*Frontispiece.*

MATERIALS

AND THEIR APPLICATION TO

ENGINEERING DESIGN

BEING A PRACTICAL TREATISE FOR ENGINEERS,
DESIGNERS, AND OTHERS, PREPARED FROM THE
STANDPOINT OF WORKS PRACTICE

BY

E. A. ALLCUT
M.Sc.(Eng.)
Mem. A.S.M.E., A.M.I.Mech.E.,
A.M.Inst.C.E., A.F.R.Ae.S.,
Associate Professor of Thermodynamics,
University of Toronto

AND

E. MILLER
Hons. Medallist Electro-Metallurgy
City & Guilds London Inst.,
M.I.Met., M.I.Brit. Foundrymen,
Met. Eng., Incandescent Heat Co., Ltd.,
Birmingham

WITH FRONTISPIECE AND 221 ILLUSTRATIONS

SECOND EDITION

LONDON
CHARLES GRIFFIN AND COMPANY, LIMITED
42 DRURY LANE, W.C.2
1932

PRINTED IN GREAT BRITAIN

PREFACE

The subject of "Materials and their Application to Engineering Design" is one of great interest and importance to every mechanical engineer or designer, yet it is often the case that knowledge is limited to theoretical consideration and general principles. Such excellent manuals on Applied Mechanics as those of Professor Rankine and Professor Jamieson are invaluable to the student and provide sound instruction, but in the sphere of commercial application problems present themselves that are not dealt with in the text-books. Few engineers have a thorough understanding of the various metallurgical and mechanical operations that are employed in producing the metals and alloys that form the raw materials for the engineering industry, and consequently many are faced with difficulty in the selection of suitable materials for engineering design. The data contained in many handbooks are too often quite inadequate and misleading.

The present work, whilst it does not profess to deal exhaustively with such subjects as material testing and heat treatment, yet indicates the important part these play in the selection of materials. The subject of materials is treated on economic and practical lines, and to the engineer in practice, who cannot spare time to refer to the many metallurgical books, articles, and papers read before scientific societies, this treatise should be of service.

Certain materials are used in small quantities and others for very specialised work, while some may be regarded at present as of academic interest only, and all of these naturally find but small space in a book dealing with commercial uses. Other classes of material are of interest more to the civil than the mechanical engineer, and are not dealt with herein.

Works practice governs most considerations in this treatise. The figures, curves, and micrographs given relate to commercial supplies and not to samples prepared from comparatively pure metals under laboratory conditions (such as are often given for alloys) which are ideal rather than practical. Impurities on a commercial scale often have an important influence on results, and therefore average conditions as met with in practice are given herein. This method of treatment is maintained throughout, and detailed information on special branches of the subject is not included, as the limits of space do not allow of this.

In a work such as this, which is intended for engineers and deals with a subject that is mainly metallurgical, it is difficult to avoid the use of certain metallurgical terms. In fact, it is well to include such expressions in view of the fact that the successful engineer and designer must eventually acquire some knowledge of the metallurgical principles underlying the manufacture and heat treatment of materials. An endeavour has been made, however, to treat the subject on engineering rather than on metallurgical lines.

The publishers have spared no expense in providing illustrations from micrographs and specially prepared diagrams, and the authors are also indebted to Sir Herbert Austin, K.B.E., and the Austin Motor Co., Ltd., for permission to use test figures, examples of current practice, and other practical applications. The authors desire to thank Prof. O. W. Ellis, Messrs. F. Johnson, D.Sc., and J. Fallon, and Prof. J. H. Parkin for their valuable advice and assistance in correcting the proofs. Thanks are due to the following firms for illustrations and descriptions of their standard machines, viz. W. and T. Avery, Ltd., Joshua Buckton & Co., Ltd., Samuel Denison & Co., Ltd., The Foster Instrument Co., Ltd., and The Cambridge & Paul Instrument Co., Ltd.

E. A. A. and E. M.

June, 1923.

PUBLISHER'S NOTE TO SECOND EDITION.

To meet the continued demand for this book, and at the same time to render it available to many as a less expensive volume, this Second Edition is issued at a reduced price.

CHARLES GRIFFIN & CO., LTD.

April, 1932.

CONTENTS

CHAPTER I

THE INFLUENCE OF MATERIALS ON ENGINEERING DESIGN

CHAPTER II

DIFFERENT KINDS OF STRESSES AND THEIR USES IN DESIGN

CHAPTER III

TESTING AND MEASUREMENT OF STRESSES

CHAPTER IV

STRAIN MEASURING APPARATUS

CHAPTER V

IMPACT TESTING

CHAPTER VI

THE MEASUREMENT OF HARDNESS

CHAPTER VII

CHEMICAL COMPOSITION AND MICRO-STRUCTURE OF MATERIALS

CHAPTER VIII

MICRO-STRUCTURE AND COMPOSITION OF STEEL

CHAPTER IX

CHEMICAL COMPOSITION AND MICRO-STRUCTURE OF CAST-IRON, MALLEABLE IRON CASTINGS, STEEL CASTINGS, NON-FERROUS METALS, AND ALLOYS

CHAPTER X

THE HEAT TREATMENT OF STEEL AND OTHER MATERIALS

CHAPTER XI

CARBON STEELS

CHAPTER XII

ALLOY STEELS

CHAPTER XIII

CASE-HARDENING STEELS

CHAPTER XIV

IRON AND STEEL CASTINGS, INCLUDING MALLEABLE IRON AND SEMI-STEEL CASTINGS

CHAPTER XV

NON-FERROUS METALS AND ALLOYS

CHAPTER XVI

BEARING METALS

CHAPTER XVII

THE INSPECTION OF MATERIALS

CHAPTER XVIII

NON-METALLIC MATERIALS

CHAPTER XIX

EXAMPLES OF PRACTICAL APPLICATION

CHAPTER XX

TABLES

MATERIALS AND THEIR APPLICATION TO ENGINEERING DESIGN

CHAPTER I

THE INFLUENCE OF MATERIALS ON ENGINEERING DESIGN

Design and its Objects.—With a few great exceptions, in the early stages of Engineering development, design was limited to the improvement of existing mechanisms or types of construction.

In those days, machining and constructional facilities were crude and scarce, causing slowness in production, and consequent delay in observing the effects of alterations in design. It follows, therefore, that improvement was slow and limited in extent.

The giant strides of latter day engineering have been made possible largely by the use of mathematical processes in Engineering design. This obtains to such an extent that design may be defined as the result of a logical train of thought directed towards a given end. It is a synthesis, of which draughtsmanship is the subsequent analysis.

An engineer has been described as " A man who can do for one dollar what anybody can do for two," and this definition also sums up the main object of design.

Work of a definite and known character and amount has to be done, and the object of the designer is to find the best and cheapest way of performing that work.

If a river has to be spanned, the bridge must be constructed with the least expenditure of material and time consistent with safety.

If it is desired to traverse a given distance, the mechanism used must not only be constructed as cheaply as possible, but must run with the least expenditure of fuel and lubricant, and with as little cost as possible in repairs and renewals.

These two objects are often mutually incompatible, and therefore an engineering design is almost invariably a compromise between mechanical perfection and cost of production.

Influence of Mathematics.—It has already been stated that the development of the science of design has been greatly facilitated by the use of mathematical processes. This is true, but students and young draughtsmen must be careful not to carry the operation too far.

The tendency on the part of a young scientifically trained engineer, who generally has not the " ballast " of practical experience, is to apply mathematical processes and reasoning to all cases of design, without inquiring whether the conclusions arrived at are borne out by existing practice.

It should always be kept in mind that the whole of the conditions governing the design of parts of a machine or structure are very seldom known with great accuracy, and that the correctness of any conclusions based upon those premises will be entirely governed by such conditions. This is a point that is too often forgotten by young designers, and one which leads to many absurd results.

These results are due to wrong starting points which make the subsequent deductions quite useless for practical purposes.

Factors of Safety.—For this reason, it is necessary in all engineering designs to allow an ample margin of strength over that calculated as necessary for the work to be done.

This margin is called the " factor of safety," and varies with the kind of work to be done, the accuracy with which the prevailing conditions can be assessed and calculated, and the homogeneity or reliability of the material used.

The cooling of a complicated casting, for instance, introduces forces of unknown magnitude into the material of which that casting is made, and these, when increased by the application of external forces, may cause the casting to crack or break.

The presence of internal flaws or blowholes in the material composing a forging or casting, is a source of weakness that has to be compensated for by an increase in the factor of safety, and by careful tests of the material that is to be used.

In aeronautical work, lightness in every detail is absolutely necessary, and therefore the factor of safety has to be cut down to the lowest possible limit. This can only be done by a very careful selection of the material used for every part, to ensure that the element of uncertainty in the quality of the material is reduced to the lowest possible limit.

In heavier classes of work, the dead weight of the machine or structure itself often imposes considerable stresses on some of the component parts, and in these cases lightness is a useful asset.

The reduction of the factor of safety up to a certain point is economical, because it effects a saving of material without necessitating a corresponding increase in the cost of workmanship. Beyond this point, reduction of weight can only be accomplished by expensive machining processes, so that the saving in material is more than counteracted by the cost of removing the excess from the detail in question.

Aero engine parts are extreme instances of the latter condition, and the rigid selection of the materials used, combined with the expensive machining operations employed in removing all excess material, make these engines very costly to manufacture.

Stresses and Strains.—Every detail of a machine or structure must be designed to resist the external forces that are applied to it, and this entails an *intensity* of loading which depends upon the amount of material available for resisting those forces.

This intensity of loading is called "Stress," and is usually expressed in pounds or tons per square inch of section, or in kilogrammes per square millimetre.

As the area of material available for this purpose is very seldom uniform, the term "stress" usually means the *greatest* stress present in any part of the detail under consideration.

When any object or material is loaded, or "stressed," it becomes deformed or altered in shape. This deformation is called "Strain," but, for the purpose of comparison, it is usual to express this as a ratio or percentage of the original dimensions of the object. Thus if an object 2 inches long is pulled until it becomes 2½ inches long, the strain is said to be 0·25 or 25 per cent. of the original length.

Strains are of two kinds, "Elastic" and "Plastic." If a piece of material is subjected to a load of continually increasing magnitude, it will distort, and, provided the load does not exceed a certain intensity, the distortion will disappear when the load is removed. This distortion is said to be "Elastic." The stress at which elastic distortion ceases, is called the "Elastic limit," and, if the loading is taken beyond this point, permanent distortion is obtained. This is "Plastic distortion" or "Permanent set," and the point at which it commences, marks the limit of the useful life of any material for engineering purposes. The correct measurement of this elastic limit is therefore a very important point when testing material to ascertain its suitability for a structure or machine part.

Stresses are named according to the kind of distortion produced by them, as follows :—

1. *Tensile* stress *lengthens* or elongates the loaded parts.
2. *Compression* stress *shortens* the loaded part.
3. *Shearing* stress tends to *cut* through or across the material.
4. *Bending* stress is a combination of tension in one part of the article, and compression in another part.
5. *Torsion* stress has a *twisting* effect.

Various materials are specially suitable for resisting any one or more of these stresses. For instance, cast iron is much stronger in compression than in tension, while some alloys are strong in tension and compression, but very weak in shear.

Selection of Material.—The final form of any design will depend upon the kind of materials chosen for the construction of its component parts.

Each kind of material has its own range of usefulness, but in many cases a choice of several materials is possible for the same detail, and then other considerations than those of strength must rule.

In large and costly structures, *time* is an important factor, as, particularly in cases of public convenience, it is difficult to renew the structure at short intervals.

The cost of periodic examination is also important in such cases. It is therefore necessary that the material chosen shall be *durable* and *reliable*.

In machines or structures that are exposed to weather conditions, the effects of *corrosion* (*e.g.* rusting) have an important influence on the choice of material, and the cost of protecting large structures from corroding influences is very great. When machines are being made for use in tropical or cold countries, the effects of *temperature* are sometimes influential, particularly when the results of expansion or contraction have to be guarded against. The effects of higher temperatures, as met with in locomotive fireboxes and stays, are generally very considerable, in many instances ruling out materials that are otherwise suitable.

Erosion troubles, due to the action of steam or other gases at high temperatures and moving at high velocities, are liable to be serious, as in the case of turbine blades. With water it is often necessary to take this into account, *e.g.* with hydraulic valves and propellers.

Generally, in Mechanical Engineering, the primary factors (after *strength*) in the selection of materials for a design, are *cheapness*, and *ease* of *machining*. As the object of design is to make a machine as cheaply as possible, it follows that, other things being equal, the material that can most readily be adapted to the required form, will be the best for the purpose.

Mechanisms.—In the foregoing paragraphs the problems of design have only been considered from a static point of view, but in the design of mechanisms, the relative motion of the constituent parts is a crucial factor, and considerably influences the selection of material to be used in the moving parts, or the parts with which they are connected. The effect of *inertia* in fast-running mechanisms (such as petrol engines) limits the weight of material in such parts to the absolute minimum.

This necessitates the use of the best material available, in its best possible state, and, in the case of steel, this is achieved by suitable heat treatment and rigid inspection. The influence of *velocity* is also very great, particularly when combined with *pressure*, as in the case of crank pins or other highly stressed journals.

This must be met partly by efficient lubrication, and partly by the use of a suitable bearing metal that is capable of resisting *wear* with a minimum expenditure of energy in friction.

Stiffness and Rigidity.—These are generally highly desirable assets in working details, and are obtained by the use of the right kind of material disposed in a suitable manner with respect to the direction of the load. Thus, a bicycle frame made of steel wire would collapse immediately, but if the same kind and weight of steel is made in the form of tubes, it will support its load easily. This principle applies to all forgings, castings, etc., and is too often disregarded in the design of details.

It may generally be stated that in the design of moving parts, it is desirable to avoid acute angles (with their consequent lost motion), many joints, large relative motions, and heavy reciprocating weights. Simplicity is the "hall mark" of design.

A simple machine has the advantage of being easy and cheap to make, with consequent high production and rapid delivery, few working parts, reliability, little expenditure in repairs and a minimum of supervision. It also generally produces a better article than does a machine of greater complication.

While the materials used only influence this factor to a slight extent, improvements in this direction are often made feasible by the adoption of a better class of material than that already in use, allowing the design to be made lighter and more compact, and often saving many complications in the design and running of the machine.

CHAPTER II

DIFFERENT KINDS OF STRESSES AND THEIR USES IN DESIGN

Tension.—This has already been described as a stress that tends to lengthen or elongate the body to which the stress is applied. Typical cases of tension in design, are the stresses in the piston rod of a steam engine during the backward stroke of the piston, and in the studs which hold the cover in position on any engine cylinder. Where a pure tension stress is present, as in the above instances, it is an easy matter, knowing the strength of the material, to calculate the size of rod, stud, or other part necessary to give the required resistance to that part. Having decided the factor of safety, f, for the particular detail under consideration, a test of the material is taken, which shows its tensile strength to be T tons per square inch. The maximum load calculated to be applied to the part is L tons.

Therefore, the area of the smallest section which has to carry that load must be $\frac{\mathrm{L}f}{\mathrm{T}}$ square inches.

It is necessary to emphasise the words "smallest section." As the strength of a chain is only that of its weakest link, so the strength of any casting or forging is only that of its weakest section, and any material added elsewhere is useless from this point of view, as the detail is only likely to break at its weakest part. Occasionally advantage is taken of this fact to put in a "breaking piece" which is cheap, simple, and easy to replace, so that in case the machine is unduly stressed, this unimportant part will give way before any other damage is done.

The strength of a bolt or stud, is not that of the shank, but of the section at the bottom of the thread. It is advisable in case of tension pieces, to make the ratio of length to cross section as great as possible, in order to give the part increased resilience. This is taken advantage of in marine connecting-rod bolts and other important parts, where the plain parts of the bolts are often turned down to the same diameter as that at the bottom of the thread, thus preventing all the stretch imposed by the load from being concentrated within the comparatively short threaded length.

The best material for resisting tension is steel, especially alloy steels, which can be heat treated to give tensile strengths up to, and exceeding 100 tons per square inch, without becoming unduly brittle. In some cases, however, owing to corrosion and other troubles, steel or iron cannot be used, and in such instances the various copper alloys are generally employed. The great disadvantage of these, however, is high cost, so that if it is possible to protect the steel, or in other ways to render it immune from the anticipated troubles, it is advisable to use the cheaper material.

Composite materials such as masonry, concrete, etc., should never be subjected to tensile stresses, as their resistance to this kind of stress is very small.

Fabrics, ropes, and belts are not simple materials in themselves, but are structures disposed in such a way that they will readily resist tensile stresses, while offering little opposition to distortion in some other directions.

Compression.—This stress tends to diminish the size of the specimen or part to which it is applied, and therefore increases its coherence by forcing the particles into closer contact with one another. The cheapest metal for use where compressive strength is required is cast iron. This can readily be made in any convenient form, and when used in the form of columns or box sections, forms a very strong and rigid resistant.

Where large, heavy, and solid masses of material are necessary, brickwork or concrete is usually employed, as these can be transported in comparatively small quantities, and built up cheaply on the job. They have the additional advantage of not needing bolt or rivet fastenings to hold the various sections together, but are subject to the influence of the weather while construction is in progress.

Timber is also used to a certain extent for resisting compressive stresses. This material must be "seasoned" before being used, as otherwise it is apt to change its shape when in use. It is also subject to weather conditions when used outside, and in hot countries is liable to be attacked by insects. Timber is not so reliable as the materials mentioned above, but is often used in constructional work because it is plentiful. In aviation work it is employed on account of its comparative lightness, but in this respect it is being superseded to some extent by the use of aluminium alloys and thin steel tubing.

Alternating Stresses.—In the case of piston rods, connecting rods, and other reciprocating parts, the stress often varies from tension to compression in each cycle of operations. Wohler states that the effect of a positive and negative load, acting alternately, is the same in its destructive effect as a positive load equal to the sum of the two. That is, if a piston rod is subjected to a tensile stress of 2 tons per square inch and a compressive stress of 2½ tons per square inch, the effect on the material is the same as if an intermittent tensile stress of 4½ tons per square inch were employed. It is doubtful whether this extreme view need be taken for all cases of alternating stresses, but the "range of stress" must always be carefully considered in such instances.

Shear.—May be described as the force which tends to make the particles of a body slide *across* one another.

When a metal plate is being punched, the area of plate under the punch is forced to accompany the downward movement of the tool, while the parts immediately adjacent to, and surrounding it, are kept stationary by the table of the machine.

Thus the punched area is removed by a sliding motion that is confined to a very narrow belt of material.

If the distance between the point of application of the force and the resisting medium is increased, the conditions become more and more those of "bending" as the distance becomes greater.

This form of shear is therefore local in its action, but severely distorts the metal adjacent to the sheared surface. In punched boiler plates, the damage is so great that it is customary to punch out the holes smaller than the size required, and ream out the material immediately surrounding the holes.

A typical case of shearing stress is that of the rivets which hold together the plates of a boiler. When the boiler pressure rises, the plates tend to slide apart, and are only prevented from doing so by the shearing strength of the rivets.

Some metals, while strong in tension and compression, are very weak in shear. This is particularly the case with many alloys, such as the tin-zinc-copper alloys. Naval brass is only about half as strong in shear as it is in tension, while in wrought iron and steel, the shearing strength is about four-fifths of the tensile strength.

Cast-iron and phosphor bronze are stronger in shear than in tension, and as shearing stresses are often set up as a secondary effect when other stresses are applied, this point must be carefully watched. In fact, many brittle materials when tested in tension or compression actually fail by shearing.

Bending.—The fact that the parts of mechanisms are seldom supported along their entire length, makes bending one of the most common phenomena met with in engineering practice.

In some instances, such as bridges and other heavy bodies, where the distance between the points of support is great, the dead weight of the detail itself produces serious stresses, but in mechanical engineering this is not usually so. On the other hand, the forces applied to mechanical engineering details are usually from a source external to the objects themselves, and, being generally of a "live" nature, are more difficult to deal with than in the case of dead weight.

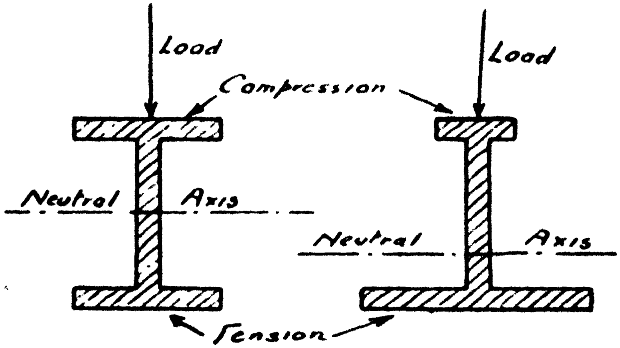


FIG. 1.—Position of Neutral Axis in Beams.

When a force is applied to a detail, in a direction perpendicular to its main axis, and between two points of support, it produces a compression stress on the side where the force is applied, and a tension stress on the other side. Between these two sides, the stress becomes less and less until, at some plane in the detail, the material carries no stress at all. This plane is called the neutral axis of the section. In a symmetrical section, the neutral axis lies midway between the tension and compression surfaces, but in an unsymmetrical section, it will be nearer to the larger side. (See Fig. 1.)

In bending problems, it is therefore necessary to study both the tensile and compressive strengths of the material to be used, and if the material is weaker in tension than in compression, the section must be designed to allow for this fact.

Formulæ and calculations for different kinds of loadings and stresses do not come within the scope of this work, but it is necessary for the student of materials to have some knowledge of these, so that he may apply his knowledge intelligently to specific cases of design.

For such information readers are referred, therefore, to standard pocketbooks and works on Mechanical Design.

Torsion.—All shafts, and most other rotating bodies, are subject to twisting or torsional stresses, and these stresses produce shearing stresses on planes at right angles to the centre lines of the shafts or rotating bodies. Torsion, therefore, may be considered to be a special case of shear, as the latter is the principal stress involved. Many shafts, such as crankshafts, have in addition to the twisting moment, bending stresses, so that any ultimate failure is usually the result of these combined stresses.

In the case of a crankshaft, the torsion or "torque" is not a constant quantity, but varies considerably at different points of the cycle. An increase in the number of cylinders in the engine, makes the twisting moment or "torque" much more uniform, but in any case, the proportion of the load carried by the outside layers of the shaft is much greater than that carried by an equal area near the centre of the shaft. Therefore, in aero engine and marine crankshafts, where weight is an important item, only the outside and more efficient layers are used, the shaft being bored hollow.

In complex cases such as crankshafts, however, it is impossible to estimate the stresses carried by the different portions of the shaft, as it is certain that in very few cases is the stress uniformly distributed over the sectional area involved.

For the purpose of calculation, it is usual to express the effect of combined twisting and bending in the form of an "equivalent twisting moment," and to complete the calculation as if the shaft were in pure torsion.

For this purpose, the modulus of transverse elasticity is required, and the average values of this quantity are given in Table 8, see Appendix.

Working Stresses.—In this work, it is not intended to give any list of stresses suitable for use in different designs, as, to do so, it would be necessary to give special figures, not only for each kind of detail, but for many different kinds of design and material within those limits.

Even then, the figures would be of little value to designers, as each new case has to be considered on its merits, and the increased use of the Impact Test has considerably modified factors of safety that were previously accepted as standards.

A very common practice is to base the factor of safety upon the breaking strength of the material in tension, but the authors hold that this is illogical, as the elastic limit marks the end of the useful range of stress in the material,

If the stress in any detail exceeds the elastic limit, there will be a certain amount of permanent stretching with each application of the load. This will ultimately result in the failure of the detail, and therefore the most logical estimate of the factor of safety is based upon the elastic limit. This is particularly important, as the ratio of the elastic limit to the breaking strength varies considerably in different materials or in varieties of the same material. In soft steel, the elastic limit is usually from one-half to two-thirds of the ultimate tensile strength, while in very hard steel the two are often nearly identical.

The most rational arrangement for ordinary live loads (apart from shocks), would appear to be the use of a working stress of about half the stress at elastic limit. This would result in higher working stresses than are at present employed being used for many parts, but in view of the experience gained with highly stressed details in aviation work, it is evident that the working stresses in use up to comparatively recent times, can be considerably increased with perfect safety.

These remarks, however, are subject to the efficient inspection and testing of the raw materials supplied.

It is obvious that if the material does not meet the specification laid down by the designers, no factor of safety is of any value. A blowhole, flaw, or seam in the casting, forging, or bar comprising a machine detail, may upset the best calculation and lead to infinite trouble and much expense.

Superficial examination and careful scrutiny of the material supplied by contractors pays for itself many times over, in protecting the reputation of the manufacturing firm, and reducing the possibility of breakages and subsequent replacements.

The moral effect, on the supplier, of such inspection is a factor of great value as it frequently prevents the delivery of poor-grade material, and this, in turn, reduces the cost of production by avoiding delay and rejections.

CHAPTER III

TESTING AND MEASUREMENT OF STRESSES

Principles to be Observed.—The correct measurement of stresses in a machine part or structure is generally impracticable, owing to the size, form, and position of the stressed part. It is therefore advisable either to test a model of the part or structure, or to measure the stress necessary to break a piece of similar material, so that a fairly correct estimate may be made of the factor of safety.

The former method is somewhat costly, and can only be adopted when very large structures have to be erected, or when many similar structures have to be made.

The method usually adopted in mechanical work is to select a piece of the material that is to be used, and test it to destruction. This is done in a testing machine, which therefore may be resolved into two portions :—

1. The apparatus for *applying* the stress.
2. The apparatus for *measuring* the stress.

These two parts will be dealt with separately, as any of the methods enumerated below, for applying the stress, may be used in conjunction with any of the known methods of measuring the stress, though for some purposes particular combinations are preferable to others.

Straining Gears

The appliances used for loading a test piece are known in the shops as "straining" gears. The capacities of various machines range from 1 lb. to 5,000 tons, and it is therefore obvious that many different types of straining gear must be used.

They may be divided into five classes, according to the method of applying the driving force :—Gravity, Hand drive, Belt drive, Electric drive, Hydraulic pressure.

Gravity Straining Gears.—In this form of straining gear the load is applied to the specimen by means of a falling weight. As the load must be applied gradually, a dashpot attachment is usually incorporated with the loading device, to prevent too rapid stressing of the specimen, and to avoid premature fracture. It is evident that this method can only be used for small capacities, as otherwise the weights used would be very unwieldy.

Fig. 2 shows a small machine made for testing fine filaments in tension. The stress is applied by means of a brass plunger which is allowed to fall in its cylinder by running out the oil from the bottom. The flow of oil is regulated by a needle valve through which it passes on its way to the reservoir formed by the enlarged top of the cylinder. The ram is allowed to return at a rapid rate by opening a large valve, which itself forms the seating for the needle valve.

The lever shown pivoted to the top of the cylinder is used for returning the ram after each test, and at the top of the stroke is trapped automatically by a trip gear, while the broken specimen is taken out and a new one inserted. The large valve is then closed, leaving the needle valve open to the same extent as in the previous tests.

All tests can thus be made at the same rate of loading.

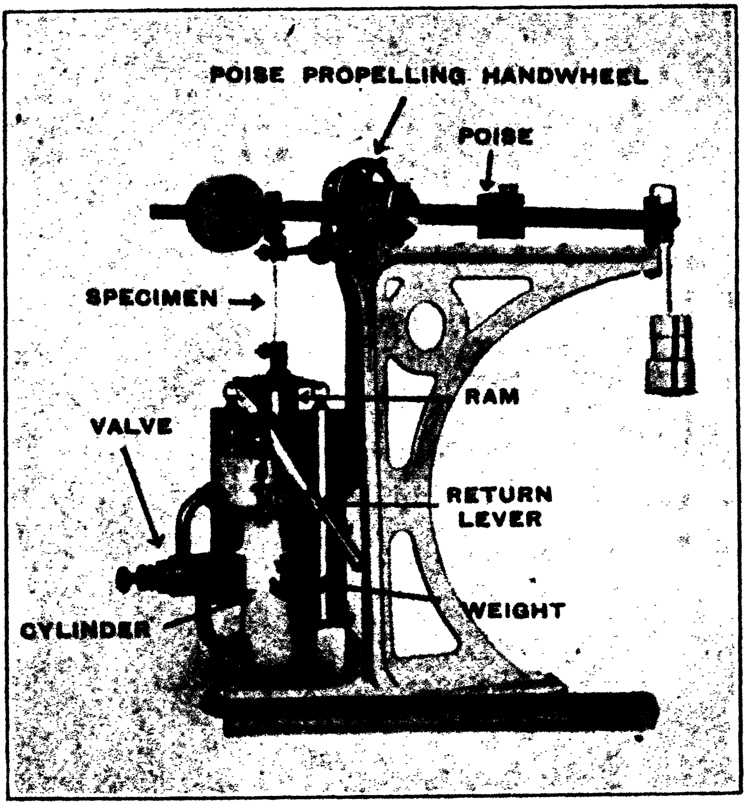


FIG. 2.—Testing Machine for Filaments (Gravity-driven).

Hand-propelled Straining Gears.—In this type of gear, the bottom of the specimen is inserted in a holder mounted on a screw called the "straining screw."

This is prevented from rotating by means of a key, but is free to move in the direction of its length. A worm wheel, with a threaded bush, rotates about the screw and causes the latter to move up or down, according to the direction of rotation.

In machines of small capacity, the worm which rotates the worm wheel may be driven directly by a handwheel, but in larger machines, a pair or a train of gears is interposed between the handwheel and the worm gear.

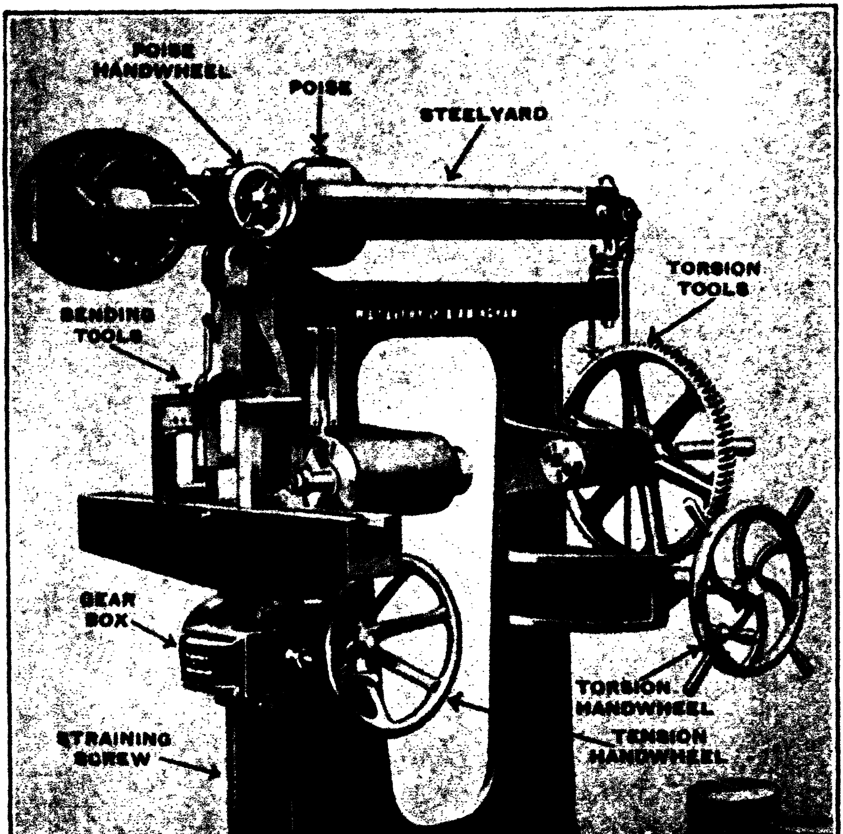


Fig. 3.—Universal Testing Machine (Hand-driven). Capacity 10,000 lbs. and 10,000 inch-lbs. Tension, Compression, Bending, Shearing, Torsion, and Cement Tests.

In the machine shown in Fig. 3, three gear speeds are provided to allow specimens of small and heavy section to be handled conveniently, and to allow a quick return of the screw between the end of one test and the beginning of the next.

A hand drive may be adopted for machines with capacities up to 20 tons, but for anything exceeding 5 tons the test is so slow and laborious, that it generally pays to have a power-driven machine. The advantages of the hand

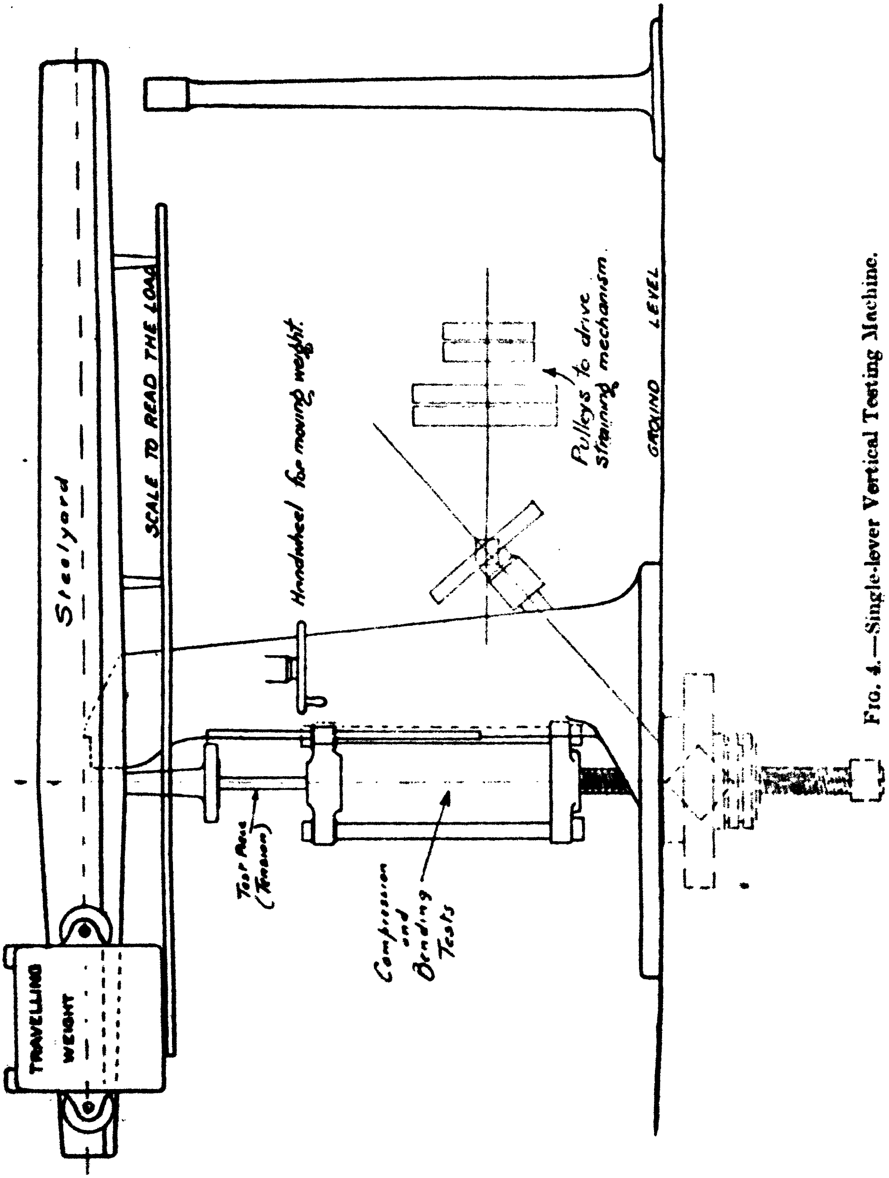


Fig. 4.—Single-lever Vertical Testing Machine.

drive are cheapness, compactness and suitability for positions where no power is available.

Generally, however, it is preferable to have a power-driven machine, on account of its greater speed and ease of working.

Belt Drive.—This is similar to the hand drive in having a worm driven screw for applying the load, but is driven by pulleys instead of a hand wheel. Usually fast and loose pulleys together with a belt striking gear are incorporated with the machine, so that the straining gear control is within easy reach of the operator who has also to observe the weighing gear.

A typical belt-driven machine is shown in Fig. 4. In this machine, an extra pair of small pulleys is provided to give a greater speed for returning the straining screw than can be used in the actual testing operations. It should be remembered that the distortion of the specimen, which is bound to occur in every test, is taken up by a downward movement of the straining screw, and that this distance has again to be traversed by the screw before the specimen holder is in the right position for the next test. With belt or electrically driven machines a considerable amount of time is wasted between consecutive tests, unless some convenient means are provided for returning the screw rapidly to its initial position after each test.

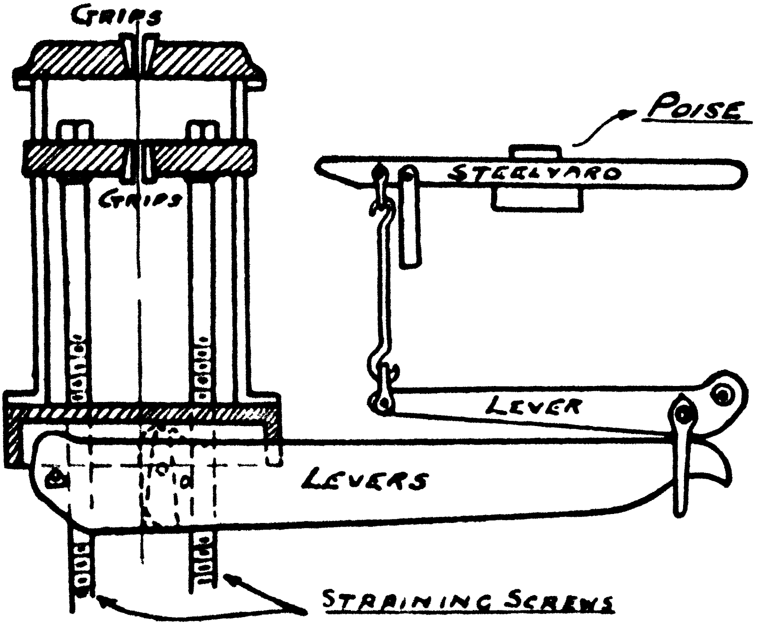


Fig. 5.—Multiple-lever Testing Machine.

When machines of large capacity (*e.g.* above 20 tons) are designed, the straining screw becomes very large, and to avoid this, and also to provide more facilities for inserting test pieces, multiple screws are sometimes used.

These are very convenient in manipulating the machine, and for this reason multiple screws are occasionally adopted in smaller machines. The number of screws used is two, three, or four, depending on the size of the machine. These must rotate simultaneously, and so they are generally driven by a single spur wheel which regulates the rotation of all the others. This arrangement is shown in Fig. 5.

The threads and nuts on the straining screws must be very carefully made, as otherwise all or most of the load may come on one corner of the test holder and break it off. Multiple screws are very convenient for applying bending and compression tests, as will be described later.

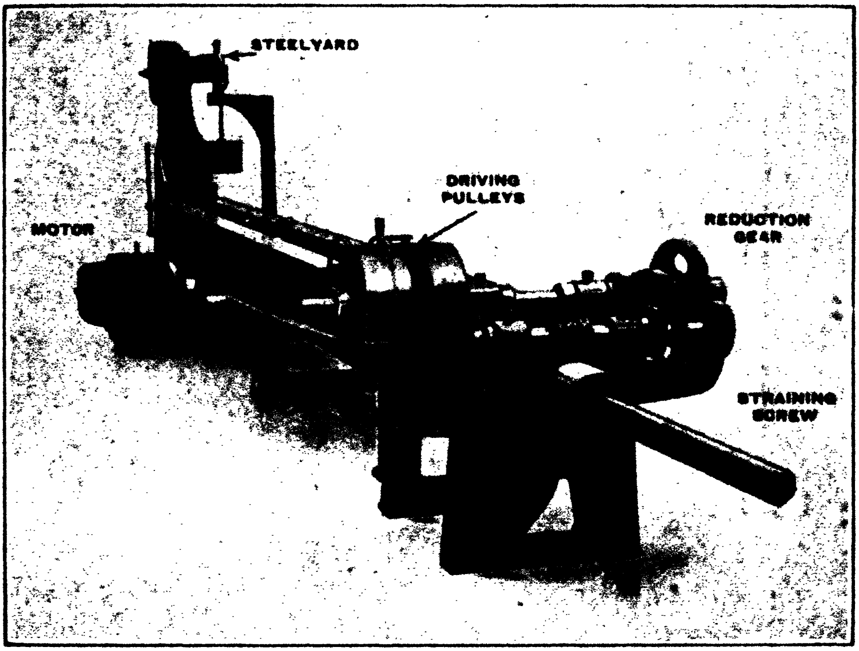


Fig. 6.—Belt-driven Chain Testing Machine. Capacity 20 tons.

The advantages of a belt drive over a hand drive are superior speed and ease of working.

Its advantages over other forms of power drive are cheapness and ease of application, as all works have some arrangement of shafting to which a belt drive can be applied.

The great disadvantage of a belt drive is its inflexibility. The machine cannot be controlled easily, and the readings are liable to be inaccurate for this reason. Whenever possible it is preferable to use electric or hydraulic control, as greater flexibility and accuracy can be obtained in that way.

A belt-driven chain testing machine is shown in Fig. 6.

Electric Drive.—The arrangement of straining gear is similar to that used in the case of belt drives, but the gearing is driven by an electric motor, preferably by a variable speed motor.

The latter is a great convenience, as it enables the straining speed to be adjusted easily and quickly to suit the kind and size of material under test.

Brittle materials are best tested with a fairly slow loading, while very ductile materials can be pulled much more rapidly, owing to the large amount of stretching that takes place just before fracture. This causes much waste of time in a constant-speed machine, as the stretching period is lengthy, and during this time no useful object is served by keeping the speed down to the limits desirable when running the stress up to the elastic limit of the material. A motor working on direct current can be made with a speed variation of 300 to 1200 revolutions per minute, and with suitable reduction gearing, this speed ratio is a convenient one for testing purposes. Higher ratios than 1 to 4 cannot conveniently be obtained, but if a mechanical change speed gear is also incorporated in the machine, any desired speed ratio can be used.

The size of motor required for a 25-ton machine is about 2½ H.P. and it is preferably fitted with a paper or raw hide pinion to avoid noise. If the worm gear is totally enclosed and immersed in an oil bath, as in the machine shown in Fig. 7, the running is practically noiseless and very smooth.

The speed control gear is best mounted on a switchboard near to, or attached to the machine, so that the operator may traverse the travelling poise with the left hand, and control the speed with the right. It is also very useful to incorporate with the switch gear a reversing switch, so that the straining screw can be run back by power instead of by hand.

A difficulty occurs in the case of alternating-current motors, due to the fact that, when the load increases, the speed of the motor decreases. As the low speed is generally required at light loads, and the high speed at heavier loads (except when returning the screw for another test), it is advisable to use direct current whenever possible.

The advantages of the electric drive are accuracy, flexibility, cleanliness, silence, and ease of manipulation.

It is much costlier than the belt drive, and in some cases is not so easy to apply, but is preferable to the latter in every other respect.

As compared with the hydraulic machine, it is cheaper if the cost of an accumulator is included with the latter, but if a steady hydraulic pressure is already available, the electric machine is the more expensive of the two.

It is also slower than the hydraulic machine, but is more cleanly and is not subject to the disadvantage of joints and packings that are liable to give way or leak.

Hydraulic Straining Gears.—These consists of a hydraulic cylinder in which the ram is moved outwards by hydraulic pressure ranging from 1,000 to 4,000 lbs. per square inch. It is better, whenever possible, to adopt a fairly low pressure, say 1,000 to 1,500 lbs. per square inch (although this entails a larger cylinder than would otherwise be required), as more trouble is experienced with joints and packings when high pressures are used.

Also, high-pressure pumps give more trouble and cost of upkeep than do low-pressure pumps. It is advisable to instal an accumulator in all cases where hydraulic pressure is used, as otherwise, the size of pump required for moving the straining ram at its maximum speed is excessive. An accumulator serves as a reservoir of energy that can be drawn upon when needed, and also steadies the pressure, preventing the pulsations of the pump from reaching the machine.

The jerky movement of the ram when no accumulator is used makes it difficult to control the testing machine and facilitates premature breakage of the specimen.

With large machines it is necessary to economise "pressure water," as

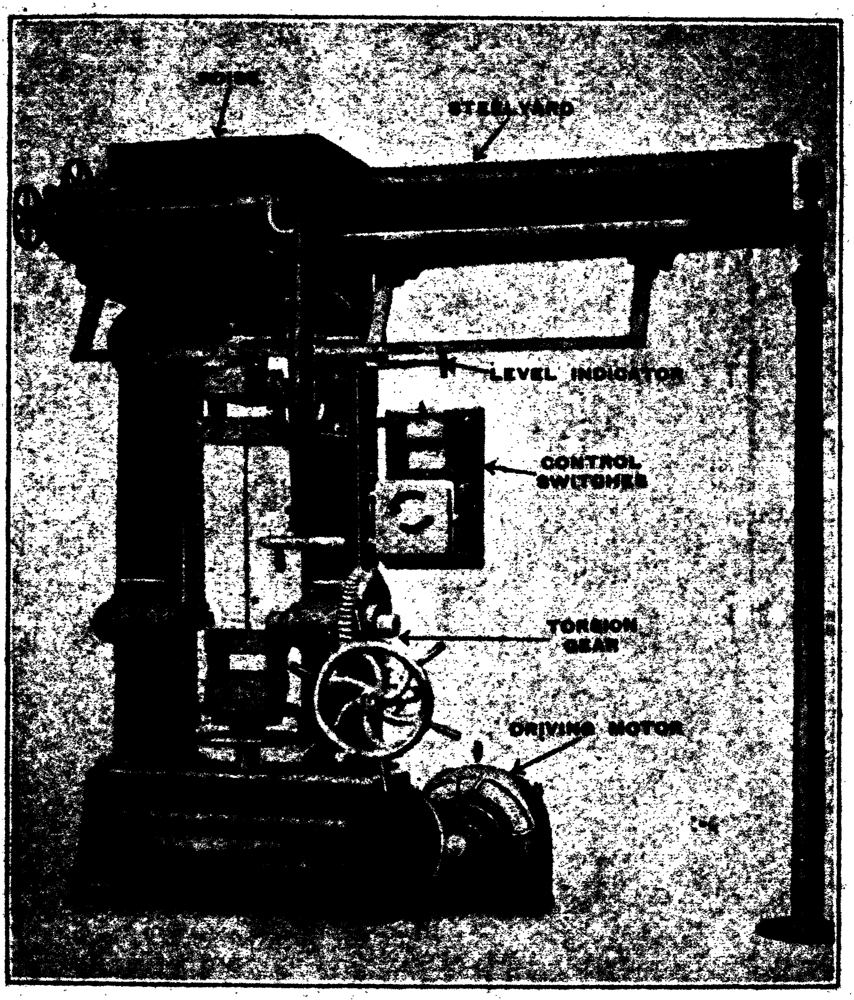


FIG. 7.—Electrically-driven Testing Machine Capacity 25 tons and 10,000 inch-lbs. Tension, Compression, Bending, Shearing and Torsion Tests.

otherwise the cost of making a test would be very great, and also the size of accumulator required would be prohibitive.

For this reason, and also to increase the speed of the ram on its return stroke, two different pressures are sometimes supplied to the machine.

This is done in the 300-ton machine installed at Birmingham University, and diagrammatically shown in Fig. 8.

In this machine, the hollow ram slides on a guide, to the centre of which is introduced town water under a pressure of about 85 lbs. per square inch, for returning the ram after each test.

Quick adjustments of the ram before, and during a test, are made by supplying low-pressure water through the pipe shown in the bottom of the cylinder, while the high-pressure water at 1,000 lbs. per square inch is only applied for actually stretching and breaking the specimen, thus effecting a considerable economy.

In the case of small machines, the ram is generally returned by a counterweight. This must be sufficiently heavy to balance the weight of the ram itself (when this works vertically), to expel the water from the cylinder and through the exhaust pipes, and to overcome the resistance of the hydraulic leathers which form the packings. The friction of the packings is particularly great when the machine has been standing for some time, and for this reason the balance weight should be considerably heavier than the ram.

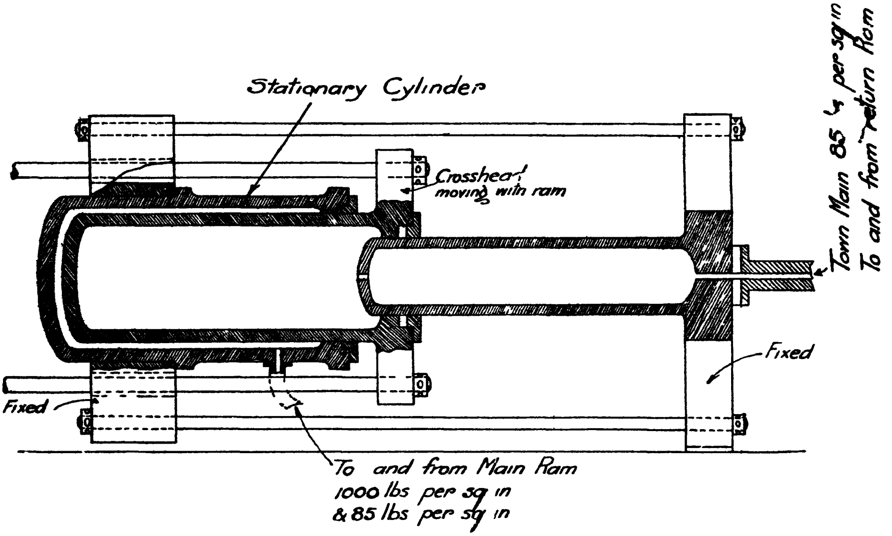


FIG 8 —Straining Gear for 300-ton Testing Machine.

The chain supporting the balance weights must also be parallel with the centre line of the ram, as otherwise the side pull of the chain considerably increases the friction and may cause the ram to stick in the cylinder.

This actually happened in the machine shown diagrammatically in Fig. 9, and the town water connection (shown dotted) was added to overcome the extra friction resulting from the obliquity of the chain.

Another form of hydraulic straining gear is shown in Fig. 10. This is operated by means of a rotary pump of the "Hele Shaw" type. The action of this pump has been frequently described in the technical press, to which those who are interested can refer.* The even delivery of oil from a rotary pump of this kind, makes it possible to dispense with an accumulator, and to run the machine by means of a motor or belt. The speed of the ram is controlled by means of a lever or handwheel which alters the stroke of the pump plungers, and gives any delivery of oil from nothing to the full capacity of the pump. The only objection to this form of straining gear is the fact that if the pump is not very accurately made, oil is liable to leak past the plungers at high pressures, and so limit the capacity of the testing machine.

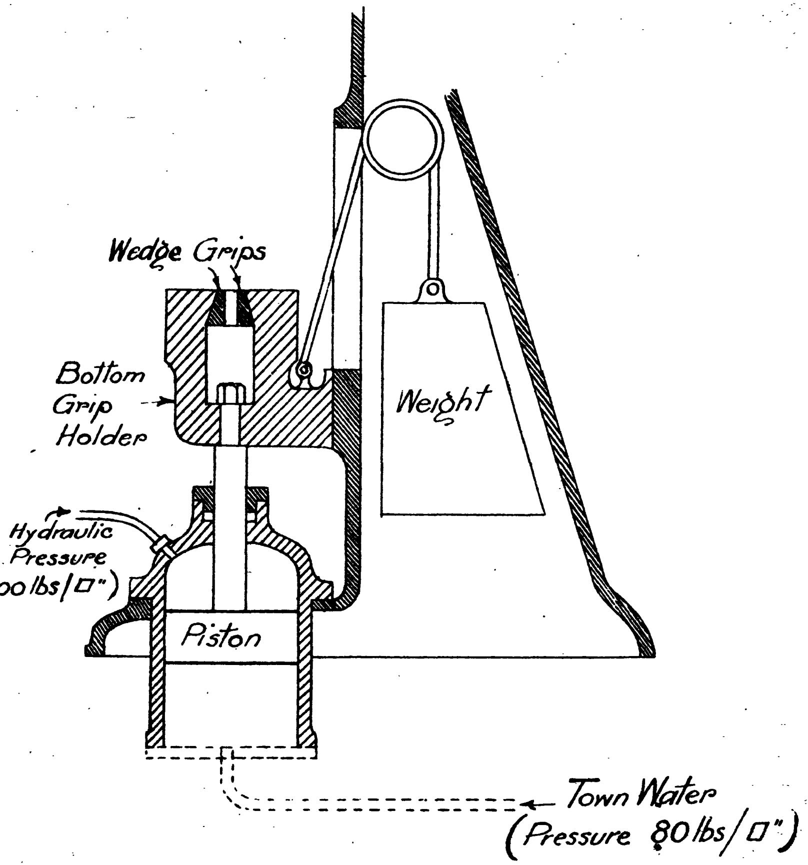


FIG. 9.—Straining Gear of Hydraulic Testing Machine. Capacity 20 tons.

The great advantage of hydraulic working is speed. Whereas the maximum speed of the screw in a belt or motor-driven machine is generally about six inches a minute, that of a hydraulic ram may be anything from two to four feet a minute.

This is a great convenience in such cases as chain or spring testing, where the distance moved by the screw or ram is comparatively great.

---

* Made by S. Denison and Sons, Leeds.

It is also very flexible and easy to control.

Its disadvantages are, cost and large floor space occupied (where special pumps and accumulator have to be provided), and leakage from ram packings and joints, causing the machine to be somewhat messy in operation.

As a general rule, machines with capacities ranging from 25 to 50 tons are best driven electrically, unless a long working stroke or rapid movement is called for. Between 50 and 100 tons, the choice of electric or hydraulic drive will depend upon the conditions at the buyer's works. Above 100 tons, hydraulic machines are generally preferable.

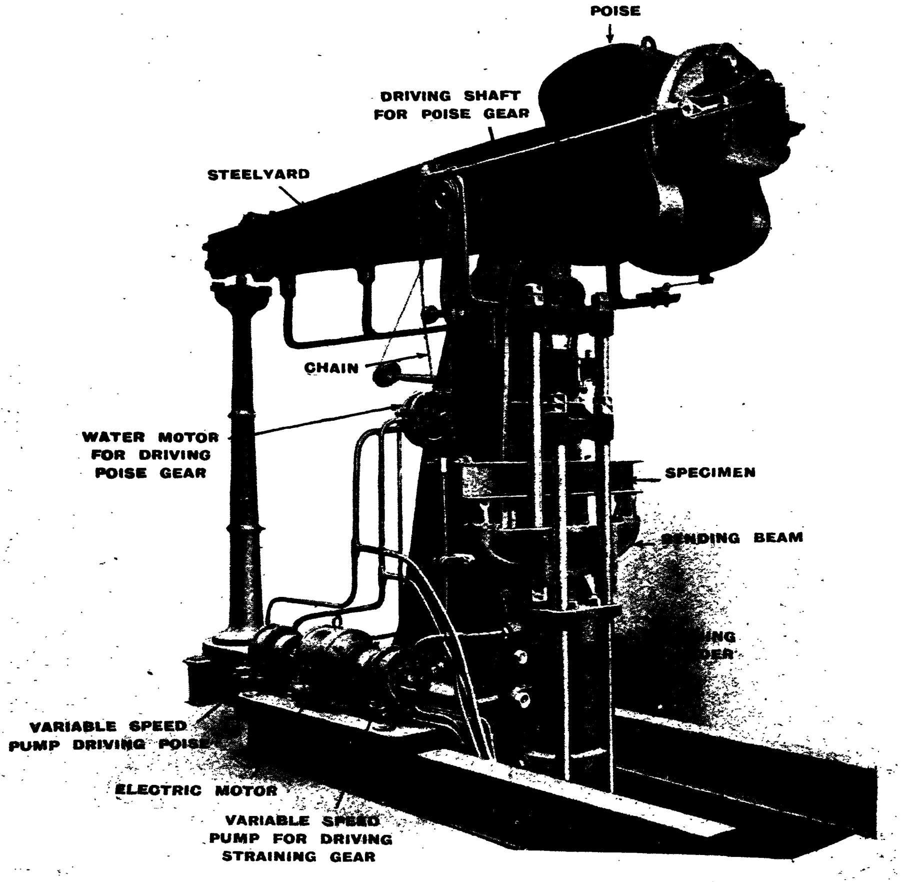


FIG. 10.—Testing Machine with Straining Gear and Poise driven by Rotary Pumps.

Weighing Gears.—The measurement of stresses or loads when testing is a weighing operation, but as the load to be measured is variable, the problems involved are very different from ordinary weighing problems, where the load is comparatively a constant quantity. The operation of weighing must be "instantaneous," and the indications of the measuring apparatus must follow the load applied by the straining screw without appreciable "lag." The indicators generally used for this purpose may be divided roughly into three classes :—

1. Mechanical.
2. Electric.
3. Hydraulic.

Mechanical weighing of all kinds is usually based upon the principle of the "lever," though departures from this principle are occasionally made.

These will be described later, but for the moment the lever machines only will be considered.

Lever Machines.—These, again, may be divided into two classes, viz. Single and Multiple Lever Machines.

The difference between the two is primarily that of size. When a heavy load has to be measured, it is impossible to balance it directly by a known equal weight, as in the case of shop scales. A steelyard is therefore used, where the load is suspended from a short arm, and a smaller weight is moved along a longer arm until the two sides are in balance.

The balancing effect of the small weight or "poise" is thus increased in the ratio of the leverage. Thus, if the load to be measured is 10 tons, and the travelling poise is 5 cwt. ($\frac{1}{4}$ ton), the distance from the poise to the "fulcrum" (point of suspension) of the lever must be forty times the distance from the load to the fulcrum, to enable the small weight to balance the large force.

If the load is very large (say 50 to 400 tons), the lever required to balance it becomes very large, unwieldy and costly. In such instances a pair or series of levers is often employed, the last of the series being used as a measuring lever or "steelyard." This enables short levers, and a small poise weight to be used, as the total leverage is considerably increased. These machines are termed "Multiple-lever Machines," as distinct from the "Single-lever Machines" in which only one measuring lever is used.

Single-lever Machines.—In these machines, the load applied to the test piece is taken by a hinged shackle, which transmits it to a hard steel knife-edge, which is fixed in the steelyard. The steelyard itself is supported on the frame of the machine by means of a second knife-edge, which rests on a hardened steel bearing.

This arrangement is shown diagrammatically in Fig. 11. The steelyard has one or more machined tracks along which the poise slides. In large machines, the poise runs on rollers.

The propulsion of the poise is a difficult matter, as it must move smoothly along the steelyard during the testing operation, and the propelling mechanism must not interfere with the weighing operations.

This is done in the small machine shown in Fig. 3 by attaching the hand-wheel that propels the poise to a small toothed wheel. The latter gears with another toothed wheel of the same size in such a way that the point of contact of the teeth, is directly opposite the supporting knife-edge of the steelyard. Thus, the force exerted through the teeth of the gear wheels does not affect the free oscillation of the steelyard. The motion is then transmitted through small bevel gears to a quick-pitched screw, and the poise is moved along the steelyard by means of a half nut which engages this screw. To save the time and trouble of winding the poise back again to zero when starting a new test, this nut is fixed in a plunger which can be lifted clear of the screw, when the poise can rapidly be pushed back by hand. The weight of the poise on a machine of 5 tons capacity is about 80 to 90 lbs., and this can easily be moved in the manner described, but poises on larger machines are situated at a greater height from the ground, and, being much heavier, are more difficult to move, so that the poise propelling gear is more complicated. This consists of a handwheel rotating a vertical shaft, which drives a horizontal shaft, through bevel gearing. This shaft has a universal joint directly opposite to the steelyard knife-edge, so that one part is fixed to the frame, and the other oscillates freely with the steelyard. The steelyard end of this shaft is connected by gearing to the propelling screw which drives the poise by means of a half nut. This arrangement is shown in Fig. 7.

If this method of driving the poise is adopted, it is advisable to avoid the use of chains, belts, or ropes as far as possible, as the backlash creates difficulties when reversing the direction of movement during a test.

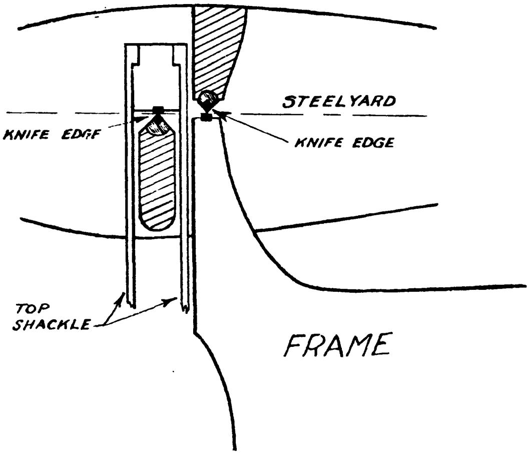


Fig. 11.—Arrangement of Knife-edges and Bearings in Single-lever Testing Machines.

The machine shown in Fig. 10 has two rotary pumps driven by an electric motor. The pump shown on the right-hand side operates the straining ram in the manner already described, and that on the left works a water motor of similar design to the pump. This water motor operates the poise propelling gear, so that the speed of the poise can be varied to keep the steelyard in balance on its knife-edges, by operating the control lever or screw.

A belt drive is also used in some instances, but as this can only be used at a constant speed, it is of little use for accurate testing. It is convenient, however, for returning the poise to its zero position at the end of each test. In these machines it is advisable to have an alternative hand drive for the poise so that it may be traversed slowly when required. It is probable that this difficulty may be surmounted by the insertion of a slipping clutch between the belt drive and the poise screw, so that the speed can be varied over the entire range by a simple lever movement.

The control of poise movement on small machines is much simpler, and is capable of greater refinement than it is on large machines, as in the latter case, the inertia of the poise is so great that starting and stopping the poise is a matter of some difficulty, and this makes the use of automatic appliances very difficult.

Methods of traversing small poises will be dealt with under "Multiple-lever Machines," as single-lever machines with small poises are usually controlled by a simple hand gear in the manner already described.

In some machines, the weight of the poise only enables the test to be taken up to a small portion of its total capacity. For instance, the 10,000-lb. testing machine shown on Fig. 3 is only graduated up to 1000 lbs. on the steelyard, the other 9,000 lbs. being obtained by hanging loose weights on the end of the steelyard. Intermediate readings are obtained by running back the poise to the starting point before adding another weight, or by supporting the steelyard while the weight is added, and then returning the poise.

The advantage of the loose-weight system is that it enables a more open scale to be used, with consequent convenience and accuracy.

Thus small specimens may be tested with the same accuracy as large ones, so that the range of usefulness is increased.

This is very convenient for Technical Colleges or research work, and also for small factories, where the work is of a varied character and where the cost of a large machine is prohibitive, but for ordinary commercial work, the time taken in running the poise backwards and forwards over the full length of scale during a test is a serious drawback. In fact, the use of loose weights is equivalent to increasing the length of the steelyard in proportion to the number of weights added.

Another, and better method of increasing the range of the machine is to divide the poise into several parts.

The 100-ton machine shown in the Frontispiece has a poise weighing 2 tons, but the various parts weigh 1 ton, 10 cwt., and 10 cwt. respectively. There are three scales, reading to 100 tons, 50 tons, and 25 tons, which can be used respectively when the entire, half, or quarter poise is moved along the steelyard.

A vernier should be fitted to the poise to enable subdivisions of the markings on the scale to be read accurately.

In some machines alternative pairs of knife-edges can be put into use, altering the leverage of the machine and so making it suitable for small or large specimens as may be required. This method is not so good as the split poise.

Knife-edges.—The accuracy and usefulness of any lever machine, depends entirely upon the correctness and reliability of the knife-edges. In small machines these are usually made from a bar, the ends of which are machined to the required form, and the centre driven into the steelyard acts as support. Large machines, however, have a backing of softer steel into which the hard knife-edge is fitted. The support consists of a round bar into which a groove is machined to hold the knife-edge. The latter is a piece of ½-inch or ¾-inch square steel let into the soft steel backing, and one edge of the square is used as the knife-edge. When this wears or chips, the other edges can be used. The steel used should have a high ultimate strength, together with a high resistance to penetration and abrasion, and a marked degree of ductility and toughness. If the knife-edge is glass hard, the ductility is sacrificed, and the edge is apt to chip off.

The steel generally used for this purpose, contains about 1·2 per cent. carbon, and has the following physical properties after heat treatment :—

Ultimate strength	54 tons per square inch.
Elastic limit	45 ,, ,,
Elongation	2 per cent.

Alloy steels such as Chromium, Chrome Vanadium, and Tungsten (high speed) steels are also used, and in the case of Chrome Vanadium steel, the absence of excessive warping when the knife-edge is hardened, gives it an important advantage over other steels used for this purpose.

The analysis of a suitable steel for knife-edges is, Carbon 1 per cent., Chromium 1 per cent., Vanadium (when present) 2 per cent., and when heat treated, this steel gives the following test results :—

Ultimate strength	90 tons per square inch.
Elastic limit	72 ,, ,,
Elongation	5 per cent.
Scleroscope hardness ..	90

The great difficulty experienced with large testing machines is the length of the knife-edges. The usual loading allowed is 5 tons per inch length, but this figure has frequently been exceeded. As much as 25 tons per inch length has been used, but this is very exceptional. With the standard loading, the knife-edges of a 100-ton machine are 20 inches long, and it is a matter of some difficulty to get these straight after hardening. They must be dipped vertically into thin oil.

The distance apart of the knife-edges is a most important factor in the design of the machine. This depends very largely on the design of the link to which the top grip holder is attached, but for large machines the proportion is 3 inches for every 100 tons capacity. For smaller machines the distance apart is usually 2 to 3 inches, owing to difficulties of design which occur when the knife-edges are very close together.

The ratio of leverage in a 30-ton single-lever machine is usually about 60 to 1, but machines have been made with a ratio of 500 to 1. It is not good practice to exceed a ratio of 100 to 1 in single-lever machines.

Horizontal Machines.—The machines described hitherto, have all been of the vertical type, *i.e.* the tensile specimen is pulled in the vertical position.

These are subject to the disadvantage that long specimens cannot be tested without having a very tall, and consequently awkward, machine. For such purposes, the horizontal machine is much more convenient, but it has the disadvantage of requiring a lever of the " knee " or " bell-crank " type. Most horizontal machines have multiple-lever weighing mechanisms, but the " Werder " machine, which is diagrammatically illustrated in Fig. 12, is a single-lever machine, and is used to a considerable extent on the Continent. It will be noted that the straining and weighing gears are both at the same end of the test piece, so that extensions of any length can be put in the machine, to enable very long specimens, such as " struts," to be tested. The authors prefer (whenever possible) to use a vertical machine for testing, as the specimens are much more convenient to handle in this way, and the weight of the specimens when tested in compression does not influence the results.

Sir Alexander Kennedy, however, makes the following observation in his paper on "Engineering Laboratories," read before the Institution of Civil Engineers in 1887 :—"The notion that a strut tested in a horizontal machine would naturally tend to buckle downwards because of its own weight seems a mistake. The author has found just as many to buckle upwards or sideways as downwards. For the proper testing of a strut, stiffness and accuracy of end bearings are practically the vital matters, and in this respect one type does not seem to have any advantage over the other." Other authorities, however, contradict this statement, and it is quite likely that under many circumstances, the horizontal machine is distinctly inferior in this respect.

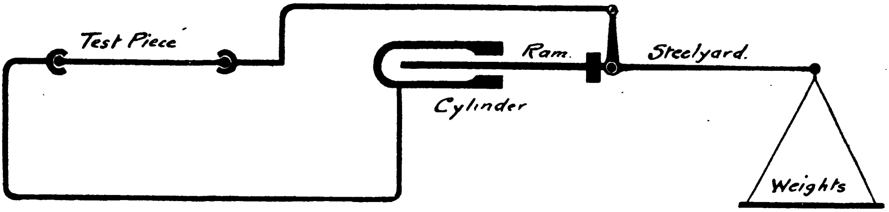


Fig. 12.—Werder Testing Machine, Lever System.

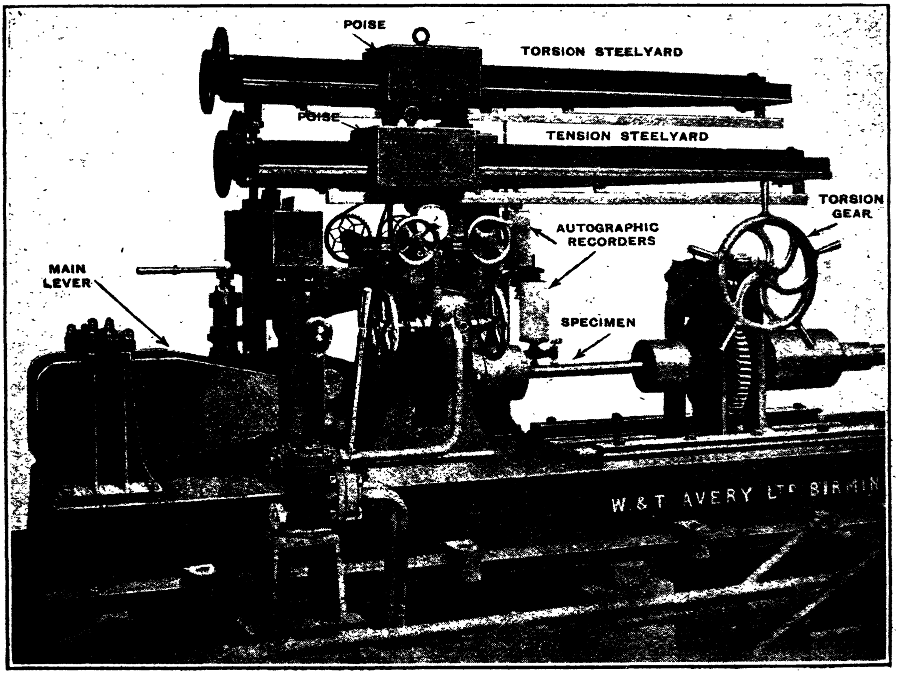


Fig. 13.—Combined Tension and Torsion Testing Machine. Horizontal Type with Multiple Levers.

Multiple-Lever Machines.—In these machines the leverage is considerably greater than that of single-lever machines, and this increase is

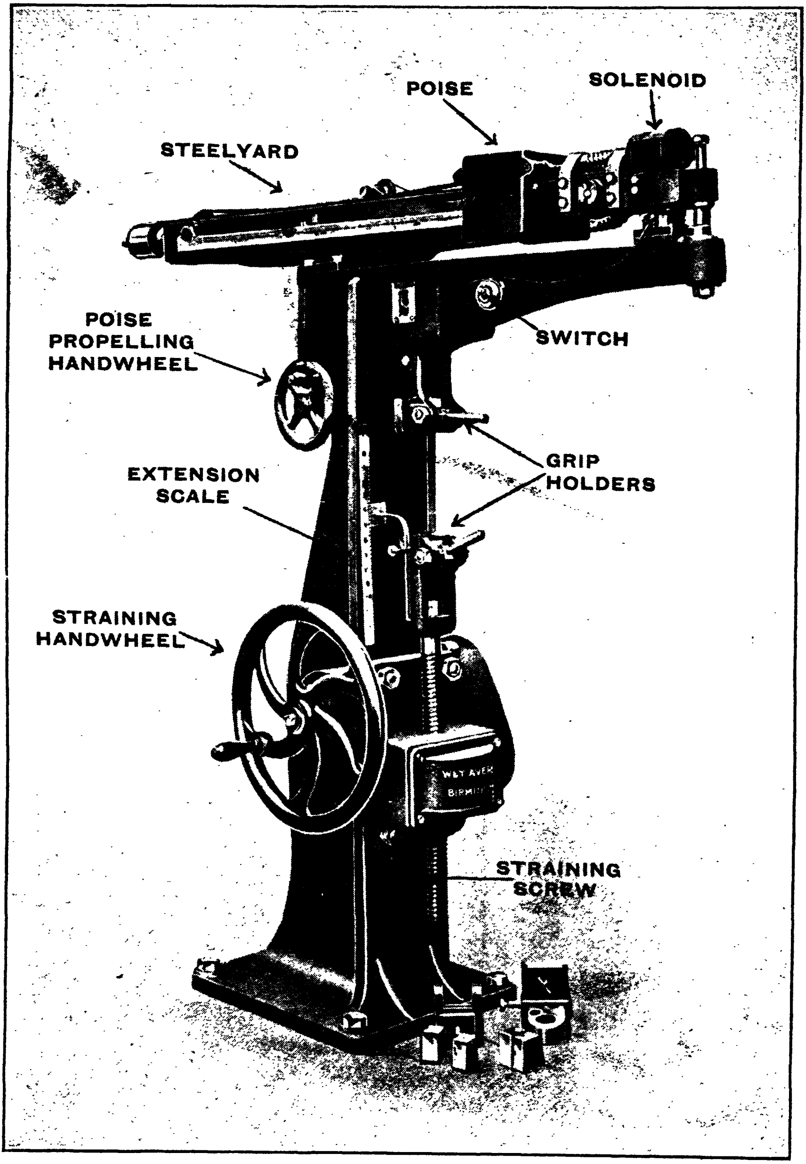


Fig. 14.—Wire Testing Machine. Capacity 6000 lbs. Poise Gravity-driven and Electrically controlled.

obtained by using a series of levers, so that the steelyard, or final lever can be comparatively small, and the poise very light.

This makes the machine light and compact, but entails the disadvantages of a short and close scale and numerous knife-edges, each of which is a potential source of trouble and inaccuracy.

Some machines have as many as eleven to fourteen sets of knife-edges, and are decidedly inferior to single-lever machines in this respect.

A typical multiple-lever machine is shown in Fig. 5, where the frame is mounted on two forked levers, and the load is transmitted by them to an intermediate lever, which is connected by a link to the steelyard.

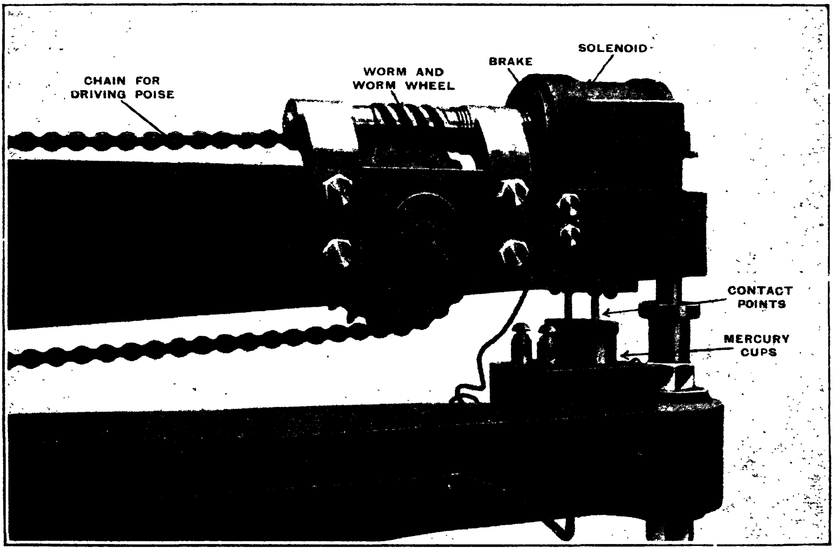


FIG. 15.—End of Steelyard of 6,000-lb. Wire Tester, showing Method of controlling Poise Movements.

Most horizontal machines are of the multiple-lever type, and a machine of this kind is shown in Fig. 13.

The load is transmitted to the bell-crank levers by a shackle suspended from the frame, and is then taken by links in the usual way to the steelyard. The small poise used in multiple-lever machines makes it possible to adopt automatic traversing devices.

The machine shown in Fig. 14 has a poise worked by gravity. A weight, falling steadily in a tube filled with oil, works the poise by means of an endless chain. The latter also drives a small worm wheel that is fixed on the end of the steelyard, and is geared with a worm which it thus rotates at a high speed (see Fig. 15). A solenoid is fixed on the end of the steelyard, and its winding is connected to two contact pins. When the steelyard falls, the contacts dip into two mercury cups connected up to an electric circuit. This causes current to flow through the solenoid, and applies a magnetic brake to the worm spindle.

The latter is stopped by the brake, and arrests the movement of the poise immediately. The poise remains stationary until the steelyard is restored to equilibrium, when the contacts rise clear of the mercury, breaking the circuit and releasing the magnetic brake, which is pressed out of action by a spring. Thus the machine is automatically controlled.

In some machines, the poise is made to move both backwards and forwards by means of electric contacts above and below the steelyard or by a rotating disc, upon the face of which a roller rotates. In the latter case the speed is varied by moving the roller from the centre towards the circumference of the disc. Reverse motions are obtained by moving the roller across the centre of the disc to the other side.

Automatically controlled poises are not so accurate as those driven by hand, as the inertia of the moving parts prevents nicety of control, but they are very convenient for rapid work, such as wire testing, and other routine tests.

Calibration and Accuracy.—The best method of calibrating lever and other testing machines is by the use of a known weight, but few firms have standard weights of sufficient size, and even when these are obtained, the cost and difficulty of handling sufficiently heavy weights for a large testing machine are prohibitive.

A good method is to use copper crushing cylinders, but a standard tension test bar may also be employed.

This is stressed within the elastic limit on the machine to be tested, and on a standard machine, and the extensions in each case are measured by means of an extensometer.

A calibrating lever is usually supplied with the Werder machines, and a system of levers and weights by Messrs. Riehlé, for the same purpose.

The accuracy of a testing machine naturally varies according to its age, treatment, and condition, but the following remarks may be taken as illustrative of current practice.

A 25-ton machine, is usually graduated to read to $\frac{1}{100}$ ton on the vernier, and this is sufficiently accurate for most commercial purposes. If correctly made, however, it should easily move with the application of 4 to 8 ozs. to the top grip holder. Of course, the accuracy when loaded will be considerably less, but this gives some indication of the sensitiveness of the machine.

Kennedy * gives the following table for the sensitiveness of knife-edges under various loads :—

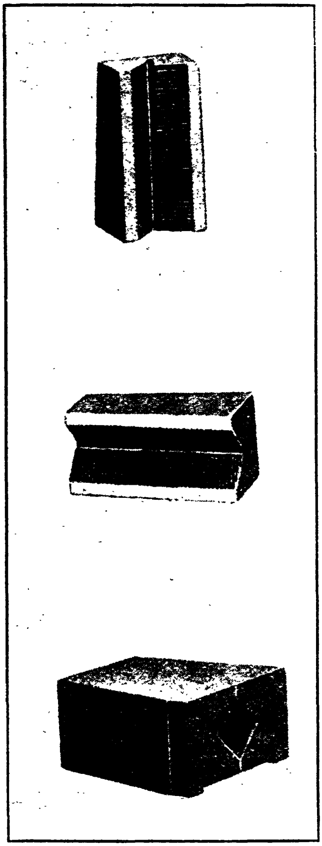
Total pull on test piece.	Addition to pull that caused first visible falling of steelyard.	
P lbs.	p lbs.	$\frac{P}{p}$
5,000	4·0	1,250
10,000	5·0	2,000
15,000	5·5	2,728
20,000	6·0	3,333
30,000	7·0	4,286
40,000	8·0	5,000
50,000	9·0	5,555

---

* "The Use and Equipment of Engineering Laboratories," by Sir A. B. W. Kennedy, Inst. C. E., 1887.

In special cases, when loose weights or subdivided poises are used, the divisions on the steelyard scale may be very much finer. Thus, the 300-ton machine in the laboratories of the University of Birmingham reads on the vernier to 10 lbs.

The accuracy of a testing or weighing machine is considerably influenced by the position of the centre of gravity of the steelyard and poise. If this is above the line connecting the two knife-edges, the steelyard is said to have "top weight" and is lively and unstable. If it is below the knife-edge line, it has "bottom weight," and is slow and sluggish. No gauge is sufficiently accurate to test the knife-edges of a testing machine, but the oscillation of the steelyard when the poise is at zero, reveals much to an experienced observer.



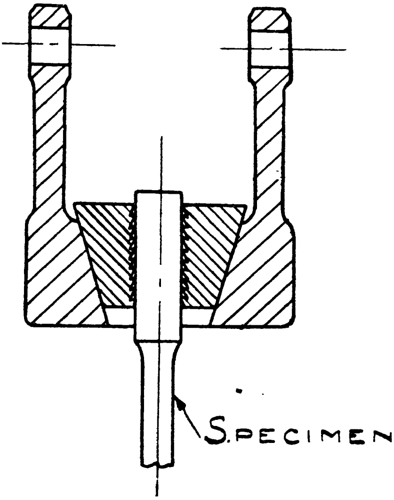


Fig. 16.—Wedge Grips and their action.

The correctness of the indications is obviously entirely impaired unless the poise weight is correct. It is usual to check this by standard weights in a large weighing machine before it is put into use. It is impossible to cast these weights correctly, and therefore, they are generally provided with "pockets," into which molten lead is run to correct the weight. This must be done after filling and painting, as otherwise the weight of the additional coating will make the poise too heavy. The inspector's stamp is usually put on the lead filling so that this cannot be altered purposely or accidentally without the fact being obvious.

Grips.—The most convenient method of gripping a tensile test piece is by means of the wedge grips shown in Fig. 16. It will be seen from this diagram that, as the pull on the specimen increases, the holding power of the grips becomes greater. The insides of the grip wedges are serrated, or file-cut, to increase the "bite" of the grips, and to prevent the specimen from slipping. Loose wedges are apt to be awkward and inconvenient, but the grips shown in Figs. 17 and 18 are worked by means of a handle and "keep plate" on inclined guides. These are so arranged (lower grip holder) that the upward movement of the handle moves both grips simultaneously downward, and at the same time causes them to open, allowing the specimen to be inserted. The subsequent downward movement of the handle causes the wedges to move upward, and grip the specimen ready for testing. This saves a considerable amount of time and is very useful for rapid tests of light capacity such as wire tests.

The upper grip holder has two handles so that a downward pressure may be used both in inserting and extracting the specimen. This is convenient as the top holder is mounted on a universal joint, and so is not rigid. The taper of the grip wedges used for holding test pieces, is a matter of some importance. If the angle of taper is very small, the range of test pieces that can be gripped by a single pair of wedges is small, and the wedges are liable to stick in the holder at the end of the test, making detachment of the broken test pieces a matter of some difficulty.

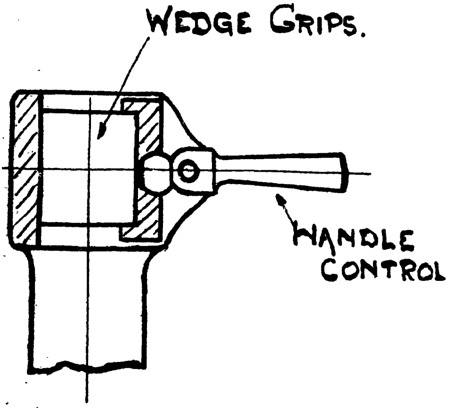


FIG. 17.—Handle-controlled Wedge Grips.

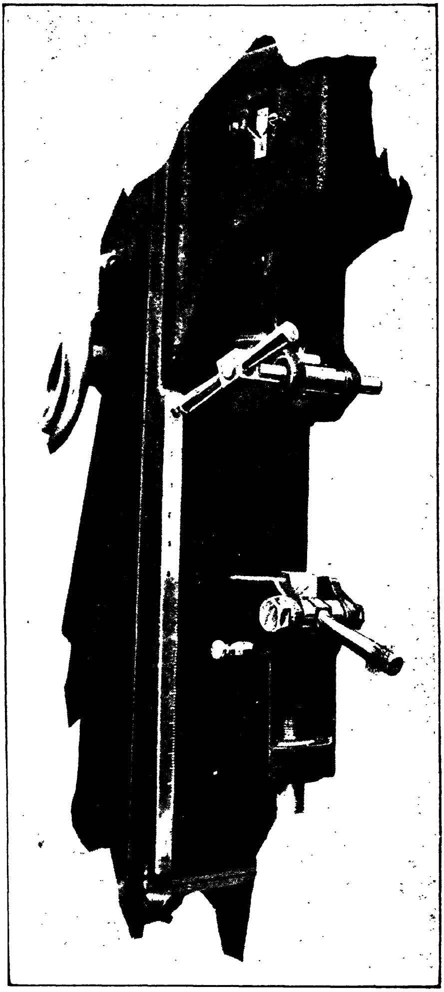


FIG. 18.—Handle-controlled Wedge Grips in position.

A useful taper for the sides of the wedges is 1 in 6, and this is often adopted in testing machine practice.

It is also advisable to make the wedges as short as possible, so that short test pieces may be held conveniently.

The grip holders have a considerable bursting stress to sustain, and in the case of large machines (10 tons and upwards), should be made of steel castings or forgings. For smaller machines cast or malleable iron may be used.

Some steels are too hard to be held in this way, and specimens of this kind are made with shoulders at the ends as shown in Fig. 19. These shoulders pull on split collars (which are preferably made with spherical seats) which transmit the load to the grip holders.

For light aluminium alloys of small section, where the elongation before breakage is small, wedge and shoulder grips do not ensure sufficiently exact axial loading to prevent bending and premature breaking of the specimen.

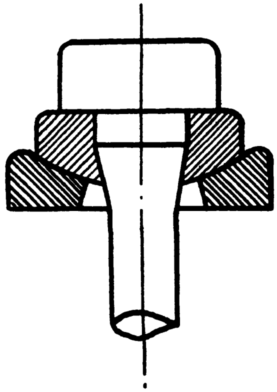


FIG. 19.—Collar Grips for Tensile Specimens.

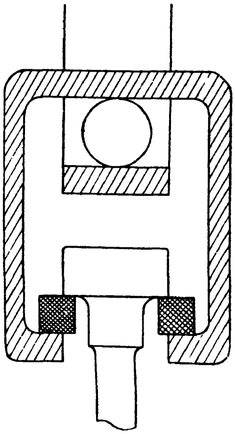


FIG. 20.—Ball-seated Grips for Brittle Specimens.

In such cases it is necessary to apply the load by means of ball joints, as shown in Fig. 20.

Screwed grips are also supplied for holding the ends of test pieces, but these are seldom used, except for very short specimens, as it is difficult to ensure that the pull is applied along the centre of the specimen. Spherical seatings assist this, but are not entirely to be relied upon.

Pendulum Indicators.—These are among the most convenient automatic load indicators and are extensively used in Continental practice.

The top grip holder is attached to a strip or chain that passes round a quadrant. This is pivoted on ball bearings, and is extended on the other side to form an arm on which the pendulum weight is fixed. A rubber tester working on this principle is shown in Fig. 21. As the load is applied, the quadrant is pulled down, giving a constant leverage, but the pendulum weight, rising on the other side, moves further and further away from the fulcrum as the load increases and so automatically balances the load, and indicates its magnitude on the large quadrant scale at the end of the pendulum arm. The quadrant arm has a saw-toothed rack cut in its upper surface, and a stepped pawl engages in this, sliding freely over the teeth as the pendulum moves outward, but immediately resisting any return movement. This keeps the pendulum in position when the specimen breaks, and enables the breaking load to be read easily.

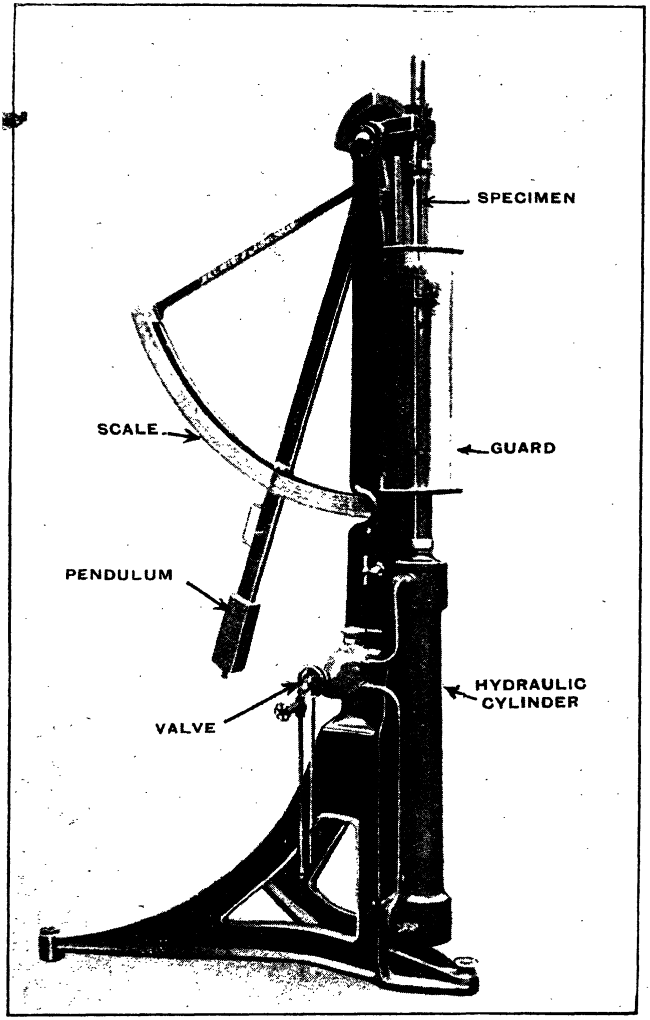


Fig. 21.—Rubber Testing Machine with Pendulum Indicator. Capacity 200 lbs.

The objections to the pendulum system are uncertainty and inaccuracy. The correctness of the readings is entirely dependent on the constancy of the distance between the load and the fulcrum. The actual point of contact in the case of ball bearings is an uncertain factor, and varies from time to time, so that the calibration of the machine is a variable quantity.

As the pendulum moves in a circular arc, the leverage increases at a much faster rate when near zero than it does at greater loads. This means that the scale is very open at low loads, and close at high loads, and makes the machine awkward to graduate and mark. It also makes the readings at high loads less accurate than those at small loads. Pendulum indicators cannot be used for high-capacity machines on account of the large weight required and the difficulty of calibration.

By placing the weight in a different position on the arm, or preferably by putting on a smaller or larger weight, the capacity of the machine may be varied. In this case a different scale for each capacity must be employed, as the practice used in lever machines of multiplying the scale reading by a constant, is not readily applicable to quadrant indicators.

Hydraulic Indicators.—The practice of using a calibrated pressure gauge connected to the straining cylinder, for reading the load on a specimen is open to many objections, chief among which is the fact that the gauge indicates only the force applied to the ram. Part of this is absorbed in overcoming the friction of the machine, piping, packings, etc., and it is not known what proportion of the load is actually absorbed in this way. It has not even the merit of being a constant quantity, as the friction will vary with the condition of the ram and leather packings, and with the length of time that the machine has been lying unused. This system, therefore, can only be used for approximate tests. The authors have used it for testing the buckling pressures of pressed springs and washers of special forms, where the limits of accuracy are fairly wide. The advantage in this case is increased speed of working.

The load is applied by a screw to the washer which is inserted in special dies, placed on the top of a hydraulic ram. The pressure exerted is transmitted by the ram to a cylinder of oil, and is indicated by a gauge graduated to read the total pressure on the ram.

At the buckling point the washer gives way and the indicator falls. Thus, the highest load indicated gives the buckling pressure.

Instead of a ram and cylinder, hydraulic diaphragms are often used in connection with pressure gauges as indicators.

The chief disadvantages of these are the diaphragm joints, and the inaccuracy of the gauges. It is difficult to make a diaphragm joint free from leakage, and if slight leakage does occur, the diaphragm will collapse in time. This trouble may be overcome, but the inaccuracy of the gauges it is impossible to remove. Generally gauges are too uncertain and prone to error for use on a testing machine pretending to any degree of accuracy, and for this purpose they are best avoided. The authors have made repeated trials with new and tested gauges, but in every case, it was found that, as compared with lever machines, they were very unreliable. The diaphragm machine made by Messrs. Emery for the Watertown Arsenal (500 tons) is immune from this difficulty, as the load is taken by a large diaphragm (see Fig. 22), and the pressure is transmitted to a smaller diaphragm from which the load is transferred to a small lever weighing arrangement. This combines the convenience of the diaphragm with the accuracy of the lever. It is noteworthy that the lever weighing device is not fitted with knife-edges, but with thin strips of steel pressed hydraulically into position. These act quite well and perform the same functions as the knife-edges on other machines.*

A similar Emery machine constructed for the Bureau of Standards at Washington, has a capacity of 600 tons, and the small diaphragm is $\frac{1}{50}$ the area of the large one, so that the weighing arrangement is of 12 tons capacity only. This was calibrated by a special machine and is claimed to be correct to 1 lb.†

The Amsler machine indicates the pressure applied to the ram of the straining gear, by means of a pendulum-actuated pressure gauge. Errors due to friction between the ram and the cylinder are avoided by allowing some of the oil pumped into the cylinder to escape in a constant stream past the ram. The pressure of oil applied to the ram causes the pendulum to swing away from the vertical position. This movement automatically balances any fluctuations of the load, and is transmitted to the gauge pointer by a rack and pinion movement. The pendulum rod can be suspended from different points to vary the sensitiveness of the machine.

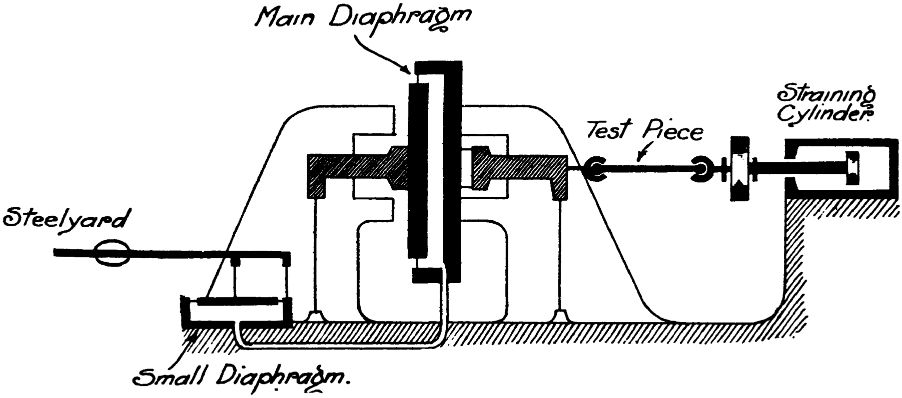


FIG. 22.—Emery Type Testing Machine at Watertown Arsenal.

Compression and Bending

Compression tests are seldom made in commercial engineering work, except in the case of special materials such as tubes, timber, or building materials which are dealt with elsewhere.

Compression tests on small specimens are made on similar machines to those already described in connection with tensile tests, except that special tools are added in place of the wedge grips, flat surfaces being generally used in the compression platens.

Long specimens, such as aeroplane struts, cannot be tested in most vertical machines, as the latter do not usually accommodate specimens of greater length than 30 inches.

---

* *Engineering*, vol. xxxvi, p. 147. "Report of U.S. Board of Testing," vol. ii, 1881.

† Unwin, "Mechanical Properties of Materials," *Proc. Inst. Mech. E.*, November, 1918.

Such specimens, therefore, must either be tested in a special compression testing machine, or in a horizontal machine.

The great difficulty in testing long specimens is to obtain a truly axial load. If the line of thrust does not coincide with the axis of the test piece, the latter is liable to fail by bending. As a rule, the length of compression specimens should not exceed 1½ diameters.

The machines most conveniently arranged for compression and bending tests are those of the multiple-screw type (preferably with two or four screws).

It is important to make sure that the platens are truly parallel, so that one side of the test piece may not fail by local crushing. The stirrup hanging from the top knife-edge, and supporting the lower compression platen must be perfectly free, as any guiding introduces friction which upsets the weighing indications.

Beyond the applications mentioned above, compression tests are only used in research work, and will not be dealt with fully at this stage.

In many testing machine outfits, bending tools are incorporated with the compression tools, but outside a few special applications, these are not greatly used.

Cast-iron bars are tested in special bending machines (" Bar Testers ") ; timber is tested with special bending tools, but beyond these two items few bending tests are made on Mechanical Engineering materials.

The dogs upon which the specimen rests should be readily adjustable to different centres and should have cylindrical seatings, so that they can readily adapt themselves to the angle of inclination at the ends of the test piece when deflected.

The usual length of beam allowed for, is 3 feet, but in some cases, special beams up to 5 or 6 feet long are made.

Very large machines such as the 300-ton testing machine at the University of Birmingham are specially made to test built-up girders in bending, and columns in compression.

This machine will accommodate girders of 20 feet span and 30 feet deep. The advantage of such large machines is that tests on models of constructional work do not always correctly indicate the conditions in the full-scale work, and valuable information is given by tests made on the latter.

The only objection to the use of such machines is the expense of preparing and handling the specimen and of making the test. In large work, however, this may be very small when compared with the total cost of the job.

In testing steel bars of smaller diameter than ⅝ inch, a bend test is often specified, as the size of such bars is too small for the standard impact test piece to be cut from them. Such tests are usually made by bending the specimen round a bar of twice its own diameter.

A steel of reasonably good quality should bend round such a bar until the sides of the specimen are parallel, without showing signs of cracking. The angle through which the specimen will bend depends upon the ductility of the material.

In some cases, bend tests are performed on carbon steels instead of impact tests, and in this case, the test pieces are ½ inch or ¾ inch diameter. The authors consider an impact test to be preferable for bars ⅝ inch diameter and upwards.

Further references to bend tests of this kind are made in Chapter XIX.

Torsion Tests

Torsion, or twisting tests have never seriously been taken up by designers or engineers, although their advantage in connection with various classes of work, is obvious.

Several kinds of machines have been designed for making torsion tests, but all work on similar principles to those used in the tension testing machines already described.

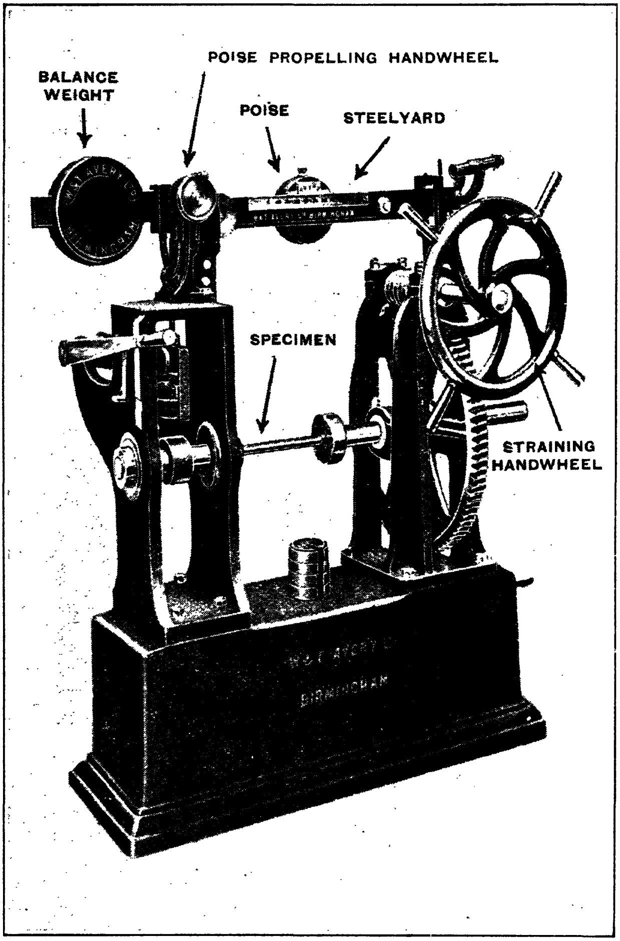


Fig. 23.—Torsion Testing Machine. Capacity 10,000 inch-lbs.

A typical instance is the " Avery " machine shown in Fig. 23. The torque is applied to one end of the test bar, by a worm wheel and worm which is driven by a hand wheel on the front of the machine.

The worm wheel has ninety teeth and the hand wheel four spokes, so that as each spoke comes to the top of the wheel, the specimen is twisted through 1 degree. The total amount of twist is indicated by a circular scale mounted on the worm wheel. This is graduated up to 360 degrees of twist, and is easily set to zero when required.

The other end of the specimen is attached to an arm and pair of levers, the last of which is connected to the steelyard.

The scale on the steelyard is graduated to read up to 10,000 inch-lbs. torque on the specimen, but by bringing into operation an alternative pair of knife-edges, this may be reduced to 5,000 inch-lbs.

The ends of the specimen are turned with a taper to fit in the grips. The insides of the grips have two keys which fit into corresponding keyways in the ends of the specimen and take the shearing forces when the specimen is twisted.

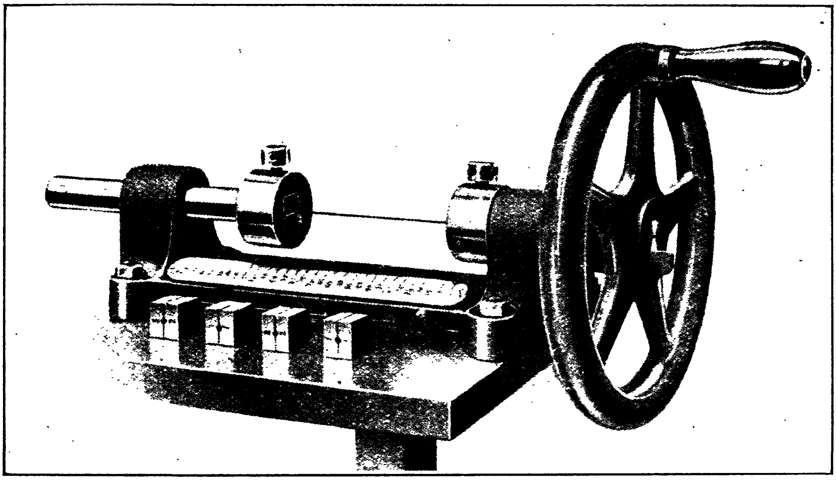


Fig. 24.—Wire Torsion Tester. Capacity 140 twists. Specimens up to 8 S.W.G. and 8 inches long.

The straining end of the machine has a sliding shaft, which transmits the twisting moment from the worm wheel, but is free to move endways to take up the shortening of the specimen as the angle of twist increases.

The test is made by twisting one end of the specimen and balancing the twisting moment by running the poise along the steelyard, until the latter is in equilibrium.

By taking readings of torque and the corresponding angles of deflection, stress strain (or load extension) diagrams may be drawn as in the case of the tension test.

Twisting tests are also made on small wires to indicate the number of times the wire may be twisted in a given length before breakage. The simple machine illustrated in Fig. 24 takes specimens 8 inches long, and indicates up to 140 turns.

This kind of machine is largely used by wire-rope makers. The number of twists sustained is automatically indicated by the finger which moves along the scale in front of the machine.

Fig. 25 shows a photograph of a shaft which broke by twisting and gives a typical torsion fracture. It will be seen that in this case, the fracture started from the end of a keyway, and also illustrates the gradual propagation of the crack after its inception.

The torsional properties of materials have been very little investigated, and in view of the frequent application of torsional stresses in designs, there is little doubt that a systematic study of these properties would be of great assistance to designers and engineers.

Fatigue.—The term "fatigue" has been very loosely used to indicate the cause of failures in working parts after continued service, particularly when the fractured part has been subjected to reversing or fluctuating stresses. Many engineers imagine fatigue to be a sort of "dry rot" that sets in when the material becomes "tired." Much work, commencing with the classic researches of Wohler, has been done for the purpose of discovering the cause of, and remedy for, this peculiar trouble, but there is still a great deal of confusion on the subject, and the various authorities are by no means agreed.

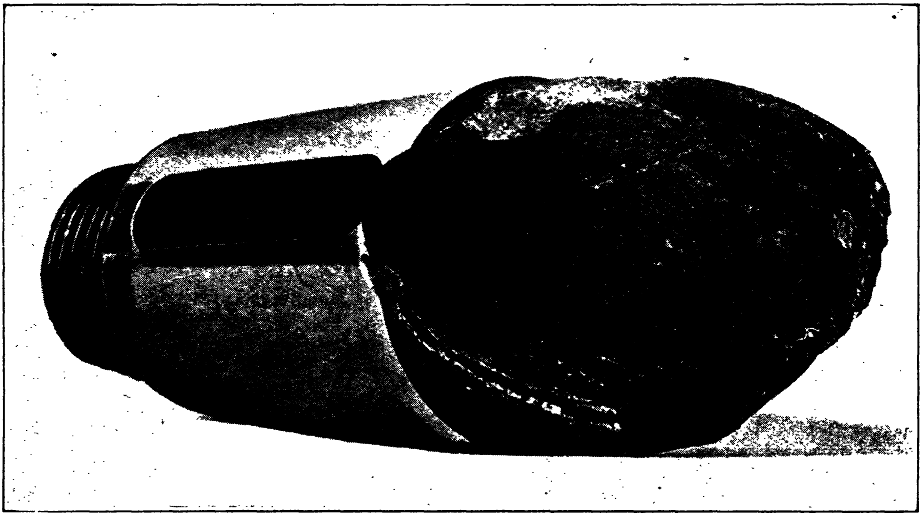


FIG. 25.—Shaft broken in Torsion, through end of keyway.

It has been definitely established, however, that many such failures are not due to any intrinsic property of the material itself, but are caused by the condition of the surface, particularly when this is machined.

In impact testing, the sharpness of the notch in the test piece, has a very marked effect upon the results obtained, and, for this reason, the standard notch has a bottom rounded to a definite radius. A machined surface, however, is full of small notches left by the tool. Some of these have infinitely sharp ends, and, although very minute, cause concentrations of stress, so that the local stress exceeds the elastic limit of the material, although the section would appear to be ample for the load it has to sustain. The continued application and removal of this force, causes the crack to spread very gradually until it becomes perceptible to the naked eye, and ultimately fracture results. Similar failures are also caused by cracks forming at the roots of hair lines, and the latter are therefore a great source of danger in highly stressed parts, such as crankshafts. Sharp corners and small radii lead to concentrations of stress, producing premature fracture, and are therefore dangerous. Even when the radius is of reasonable dimensions, there is a tendency in the machining to finish these off much less smoothly than the parallel part of the shaft, with consequent danger of cracking in heat treatment or in subsequent working.

One of the most marked features of " fatigue " tests is the effect of scratches or machine marks on the surface of the test pieces. This is referred to by Dr. B. P. Haigh in a paper read before the Institute of Metals, September, 1917.* He emphasises the advisability of finishing off with great smoothness the surface of highly stressed parts which are subjected to alternating stresses (*e.g.* crankshafts and connecting rods).

Many kinds of machines have been designed and made for the purpose of testing the " fatigue " properties of materials, but none of these have been adopted to any extent in practical work, and most of them are of academic interest only.

Fatigue testing machines may be divided into four classes :—Tension and compression machines. Bending machines with rotary motion. Bending machines with reciprocating motion. Impact machines.

Repeated Tension or Compression Machines.—A typical example of a machine for testing materials in repeated tension is described in the paper by Dr. Haigh mentioned above. The stress is applied by means of an electro-magnet which is excited by alternating current, so that the load is very rapidly applied and removed (2,000 cycles per minute). The advantage of a machine of this type is that the large number of applications of stress required to break a specimen may be made in a comparatively short time. This type of machine may also be used for applying stresses of other kinds (*e.g.* compression or bending).

Bending Machines with Rotary Motion.—The best known instance of this kind of machine is that used by Wohler. The load may be applied to the end of the specimen by a spring or dead weight, the specimen being fixed at the other end in a rotating shaft.

Bending Machines with Reciprocating Motion.—In the machine designed by Captain Sankey, the specimen is bent backwards and forwards by hand until fracture takes place. One end of the specimen is attached to a spring, the deflection of which indicates the bending effort applied to the specimen. The spring and specimen are bent by means of a hand lever through a definite angle (about 45 degrees on each side), and the deflection of the spring and number of bends sustained before fracture are automatically indicated on a diagram drawn by the machine. The specimen is $\frac{3}{8}$ inch diameter by 4 inches long, and the free length for testing purposes is $1\frac{3}{4}$ inches.

The Upton-Lewis machine is similar in principle but is belt-driven through a clutch. The specimen is held in two grips, the lower of which is oscillated by

---

* " Experiments on the Fatigue of Brasses," by B. P. Haigh, Inst. Metals, September, 1917.

means of an adjustable crank. The top grip is controlled by adjustable springs, which, by means of a recorder, indicate the load applied to the specimen. The speed can be varied in four steps from 100 to 500 revolutions per minute, and the specimen is $\frac{3}{4}$ inch by $\frac{3}{4}$ inch or 1 inch by $\frac{3}{4}$ inch section, and 6 inches long. The free length between the grips is $\frac{1}{10}$ inch to $\frac{1}{4}$ inch. The authors prefer, however, to use round test pieces, as these are easier to prepare, and may be smoothly finished. Some difficulty is experienced in preventing such test pieces from slipping in the grips, and special means must be adopted to prevent this, otherwise the tests will be useless.

Characteristic diagrams drawn by the Upton-Lewis machine when testing different materials are shown in Fig. 26. The width of each diagram represents the intensity of the bending moment on the specimen, and its length indicates the number of reversals before fracture. The area of the diagram, therefore, gives some indication of the ability of the material to resist alternating stresses, but the results are purely comparative, as no standards have yet been established with this machine. Curves are shown for Gun Metal, Phosphor Bronze, Manganese Bronze, Duralumin, and Steel. Owing to the length of some of the diagrams it is impossible to reproduce them entirely, and therefore the ends only are shown in Fig. 26. The point marked B in each case indicates the breaking point of the material and it will be seen that brittle and ductile materials give characteristic forms of diagram. The diagrams are all drawn to the same scale so that their widths in each case are comparable.

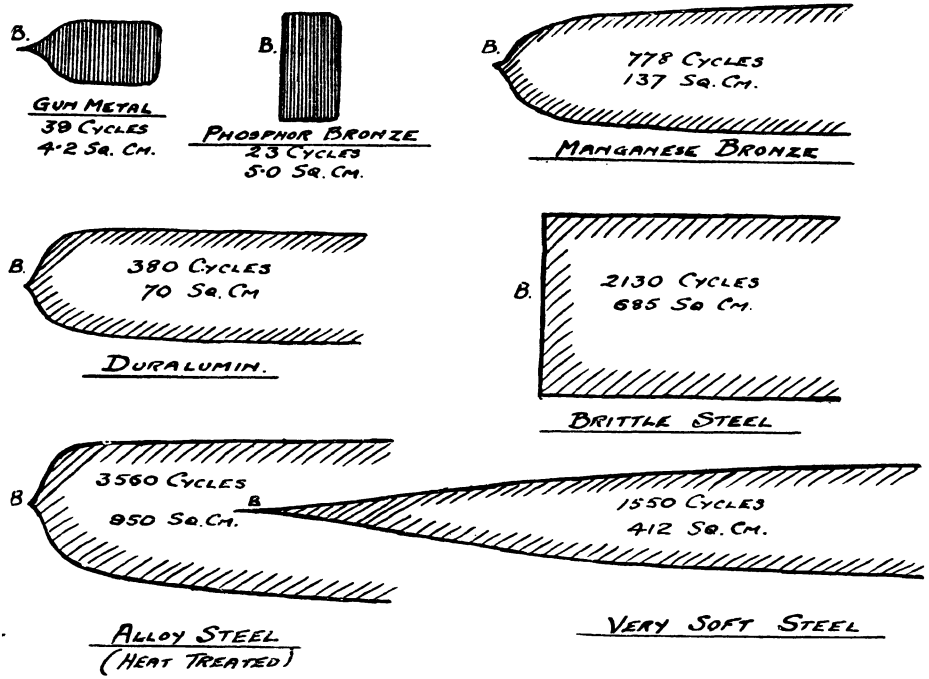


FIG. 26.—Upton-Lewis Fatigue Diagrams (end portions only are shown).

Mr. H. C. Hall * states that he has used successfully test pieces ½ inch diameter with 1 inch between grips and a crank throw of 1¾ inches. With these constants, the same springs can be used for steel, brass, and other materials and diagrams are obtained up to 2½ inches high and up to 12 inches long. Large test pieces are apt to give diagrams too wide for the paper and of unwieldy length in the case of tough steels.

Tests made by Prof. G. Upton on 0·8 carbon steel at 530 cycles per minute showed that with four rest periods of ½ hour, short, 24 hours, and 18 hours respectively, the life of the specimen was increased from 25,000 cycles (non-stop run) to over 50,000 cycles.

The arrangement used by Professor Arnold has a test piece ⅜ inch diameter and 5 to 6 inches long. One end of this is clamped in a vice and the other bent through a distance of ⅜ inch on each side of the vertical. The distance between the fixed end and the point of application of the load is 3 inches. The number of reversals is 650 per minute. This machine does not measure the bending effort on the specimen, but indicates only the number of reversals sustained before fracture.

Repeated Impact Tests.—The best known types of repeated impact testing machines are the "Eden-Foster" and "Stanton" machines. For the sake of convenience, the latter is briefly described in Chapter V, but the former will be described here.

The Eden-Foster repeated impact testing machine, Fig. 27, consists of a hammer (of known mass) which is raised to a given height, and then allowed to drop directly on to the specimen which is supported horizontally beneath it.

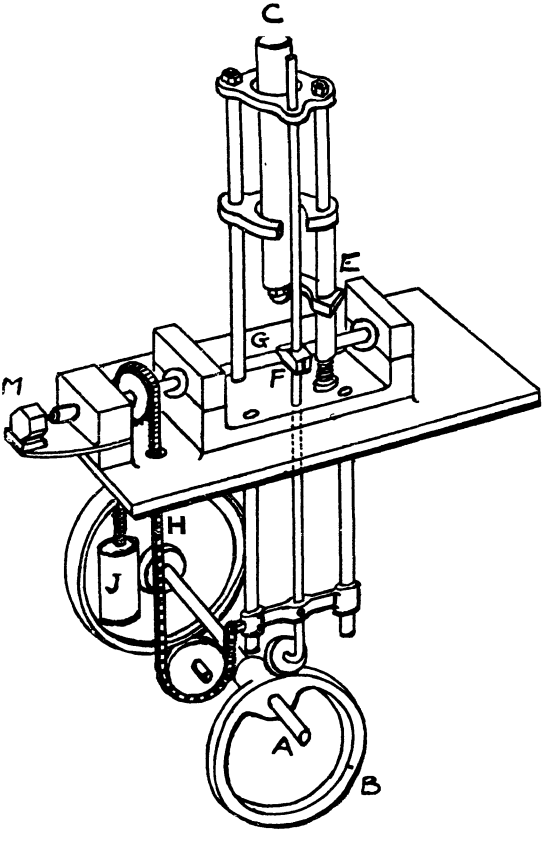


Fig. 27.—Eden-Foster Repeated Impact Testing Machine.

The machine is operated by the main shaft A, on which a large cam B is mounted. This cam, as it rotates, raises the hammer C which is held at the desired height by a catch E, until at the right moment a tripping arrangement F releases it. At the same time the cam also operates the rotating

---

* Discussion on "Mechanical Properties of Steel," *Proc. Inst. Mech. Eng.*, May, 1919.

arrangement by which the specimen G is engaged, the chain H being used for this purpose. Each time the hammer is lifted, the chain, acting against the weight J, causes a free wheel sprocket to rotate 180 degrees, thus turning the specimen by this amount, and as the cam allows the lifting arrangement to descend, the free wheel, coming into action, leaves the specimen in position ready for the hammer blow which follows almost immediately. Thus the specimen is stationary at the time the hammer drops.

The specimen is supported in bearings (which almost amount to knife-edges), placed at a fixed distance apart, and these, together with the coupling for rotating, are so arranged that the specimen simply floats on these two edges, the hammer striking it in the centre. The rotating arrangement is connected to a revolution counter M, which thus registers both the revolutions and the number of hammer blows. The machine is also provided with a declutching lever, placed under the specimen and the whole mechanism stops as soon as the latter breaks, the weight of the hammer being sufficient to release this lever. The essential feature is, that the stress is applied suddenly, thus giving the "shock" effect, but as the specimen is rotated half a revolution between each two blows, a reversal of stress throughout the cross section of the specimen takes place. Further, the hammer, having no attachments, is allowed to drop freely, and as the whole mass is arranged symmetrically above the point of impact, the true energy can be calculated with accuracy. Also, the design is such that the rigidity of the support for the machine is of little importance, good results being obtained on either a poor foundation, or a good one, a fact which cannot be said for other machines of this class.

CHAPTER IV

STRAIN MEASURING APPARATUS

Strains.—The measurement of strains produced during testing is as important as the measurement of the stress, but such measurements can be divided into two classes which are widely different in magnitude, require different apparatus for their measurement, and are used in different classes of work.

These are :—

1. Plastic deformations.
2. Elastic deformations.

The latter are deformations that occur at stresses below the elastic limit, and being usually very small in magnitude require very delicate apparatus for their measurement, except in the case of soft yielding materials such as rubber, where the elastic deformations are measurable with fair accuracy by ordinary measuring devices.

As these measuring instruments (called " extensometers ") are very sensitive, their range is comparatively small, and they have to be removed when the yield point is reached, or very shortly afterwards.

Such tests are very slow, and tedious, but they have the merit of great accuracy, and reveal many important facts in the behaviour of materials under stress. It must not be forgotten that the elastic range is the working range of the material, and its properties in that state are of great importance to engineers.

The delicacy of the instruments used and the time occupied by a single test makes their use prohibitive in commercial practice. It is usual, therefore, in works tests, to pay particular attention to the plastic properties of the materials, and for this reason consideration will first be given to the methods of measuring, and indicating plastic deformations.

Plastic Deformations.—At the conclusion of any tensile test, it will be found that the measured part of the test piece (indicated by two centre dots) has increased its length, and this increase can be measured fairly correctly by putting together the broken ends, and measuring with dividers the new distance between the centre dots. The increase in length, divided by the original length, and multiplied by one hundred, gives the percentage extension of length during the test. Also, the reduction of area at the broken end may be measured by a micrometer on the reduced section, subtracting the reduced area from the original area of the section, dividing by the original area and multiplying by one hundred. Thus :—

$$\text{Original Area of test piece} = A$$

$$\text{Reduced Area after breakage} = a$$

$$\text{Percentage reduction of area} = \frac{A-a}{A} \times 100$$

If a standard diameter of test piece is used, such as 0·564 inch (0·25 square inch area) as is generally the case, tables of reduction of area corresponding to each reduced diameter may be drawn up,* and will save a considerable amount of time when routine tests are being made. A series of experiments was made by Professor Dalby, F.R.S., with the object of analysing the elongation produced by the stressing of a test bar beyond its elastic limits. No less than six gauge points were made on the bar, and the distance between each two points was measured at various stages of the test up to the breaking point. Up to the period at which the maximum load was obtained, the various sections stretched equally, but, after this point, the total extension was the sum of two terms :—

1. A general uniform extension of the specimen as a whole.
2. A much greater local extension in the neighbourhood of the fracture.

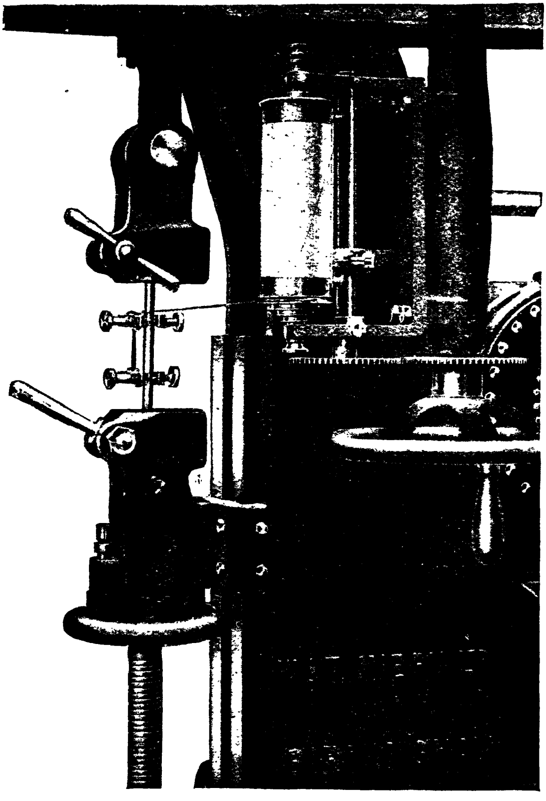


Fig. 28.—Stress-Strain Recording Apparatus.

As most of the elongation that takes place is very close to the point of fracture, the term "percentage elongation" has no meaning unless the measured length is stated upon which the elongation is taken. Thus, bar material is usually tested on a gauge length of 2 inches, but for some purposes 8 or 10 inches is taken.†

For most classes of work, 2 inches will be found a very convenient length, as it involves a minimum waste of material, is handy for purposes of observation, and does not stretch so much as a longer test bar, thus reducing the time occupied by each test. The cost of preparing and machining the test pieces is also less.

The best method of observing the plastic deformation of a test piece is by means of the Autographic Stress-Strain Diagram, or, as it should be called, the Autographic Load Extension Diagram.

The arrangement of apparatus for drawing this diagram is shown in Figs. 28

---

* See Table I.

† With round specimens it is usual to vary the length and cross-sectional area in a manner that $\frac{\text{length}}{\sqrt{\text{area}}} = \text{constant}$.

and 29. Two clips are attached to the test piece at a fixed distance apart, corresponding to the length over which the elongation is to be taken. A cord or flexible wire is fastened to one of the clips, passed over a roller or pulley on the other clip and round the drum of the recorder. Any extension of the specimen therefore rotates the drum. A screw parallel to the axis of the drum is rotated by gearing from the shaft which propels the poise along the steelyard. This rotation of the screw, moves a nut up or down according to the direction of rotation, so that the pencil mounted on the nut moves parallel to the axis of the drum, and the extent of its movement is proportional to the load on the specimen. As the test proceeds, the pencil first describes an approximately perpendicular line on the paper surrounding the drum (see Fig. 29), but at the Yield Point ("elastic limit") the drum rotates slightly, causing a horizontal or jagged line on the curve. This is followed by a curve showing the extension of the specimen as the load increases, and this part of the curve gives a useful permanent record of the plastic behaviour of the material. Such curves for

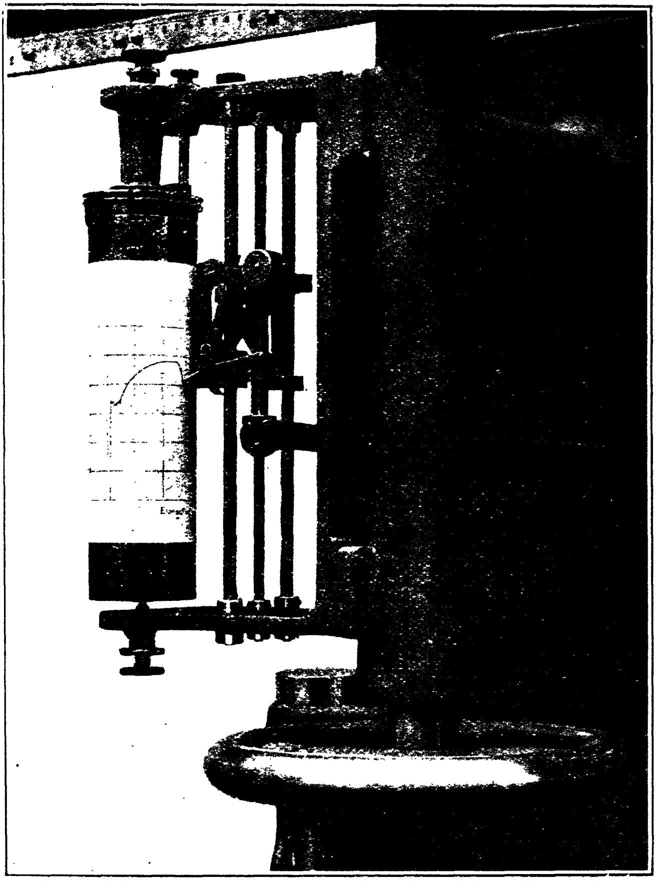


FIG. 29.—Autographic Stress-Strain Recorder.

different materials are shown in Figs. 31 to 41. Different kinds of steel have characteristic recorder diagrams, and much information regarding the properties of the steel being tested can be obtained from the diagram.

With an ordinary testing machine it is difficult to get a true record, as the poise must be run back very rapidly to keep the steelyard always in balance at the yield point, and immediately before fracture. Electric controlling devices are not sufficiently sensitive for this purpose, but an ingenious arrangement for obtaining correct diagrams is embodied in the machine shown in Fig. 30.

This can be used as an ordinary testing machine, but in addition to the usual apparatus, the long end of the steelyard is supported by a spiral spring. When a diagram is required, the poise is run out to the end of the scale, thus stretching the spring to a definite extent. As the load is applied to the test piece, the spring is thus relieved of more and more of the weight so that it shortens, and allows the steelyard to rise in proportion to the load on the test piece. The end of the steelyard is attached to the pencil on the drum, so that the ordinates of the curve are drawn by the movement of the steelyard instead of by the movement of the poise. Thus the fluctuations of the load are faithfully and automatically followed, and a correct diagram can be obtained.

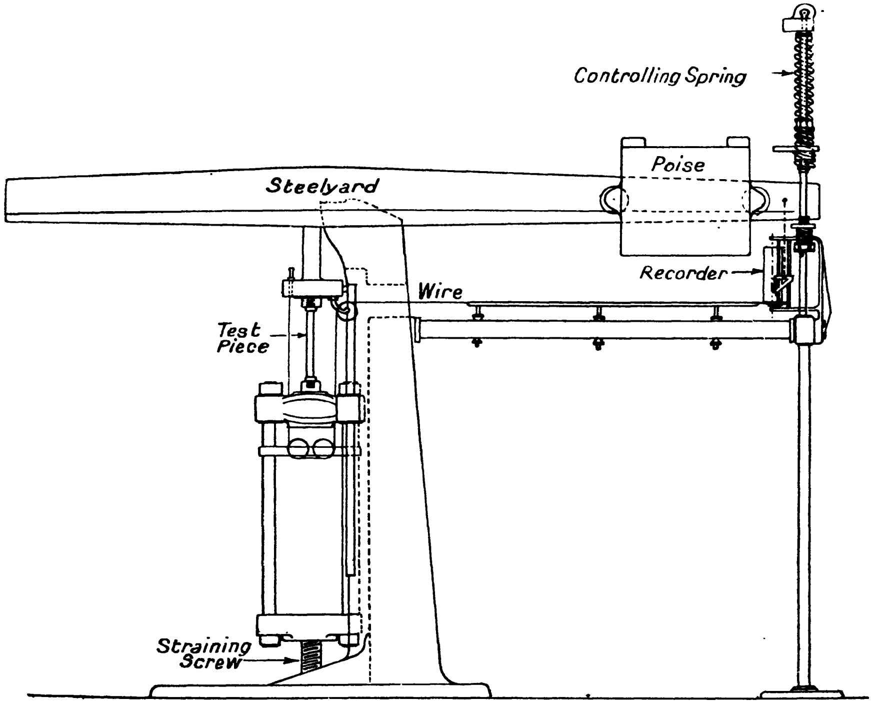


FIG. 30.—Testing Machine fitted with Patent Autographic Recorder and Spring-controlled Steelyard.

The only objection to this arrangement is the fact that the diagram cannot be obtained when the test is made in the ordinary manner by moving the poise to keep the steelyard floating. The diagram should not take the place of the ordinary test, but is a very valuable accessory to it.

Diagrams can also be obtained by photographing the movements of a beam of light from a mirror or other arrangement suitably connected to the testing machine, but this method, though perhaps the most accurate, is too delicate and complicated for use in most works. For research and laboratory work, however, it is quite useful.

Typical Recorder Diagrams.—The forms of diagram obtained when testing specimens of material are so characteristic that not only the quality of material, but some of its previous history may be deduced from the curve.

Typical load extension curves are given by Professor W. E. Dalby,* and some of these, with the results obtained are reproduced in Figs. 31 to 41.

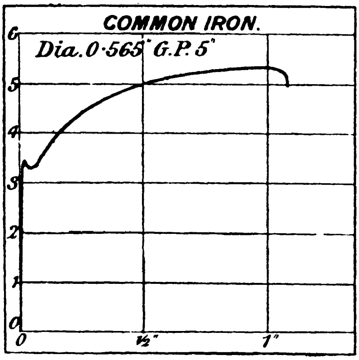


FIG. 31.—Recorder Diagram (common Iron).

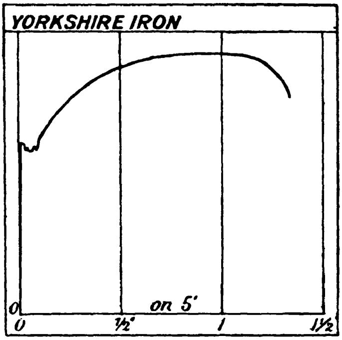


FIG. 32.—Recorder Diagram (Yorkshire Iron).

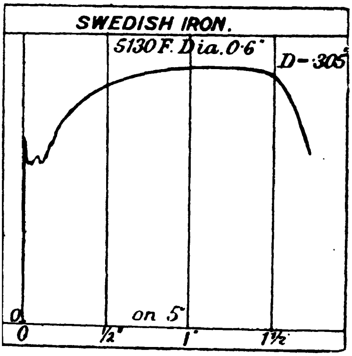


FIG. 33.—Recorder Diagram (Swedish Iron).

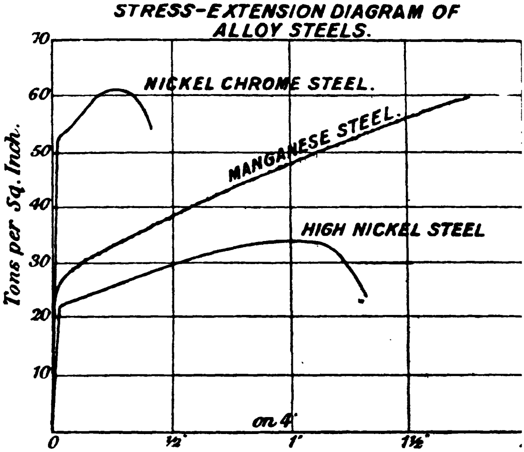


FIG. 34.—Recorder Diagram (Stress-Extension of Alloy Steels).

---

* "Researches made possible by the Autographic Load Extension Indicator," by W. E. Dalby, F.R.S., Institute of Metals, May, 1917.

There is a great difference between the recorder diagrams taken on iron and steel, and on the non-ferrous metals and alloys. The former, as is shown in Figs. 31 to 34, have a distinct break in the curve at the yield point, and some of the diagrams show very decided "oscillations" at this point, but the non-ferrous metals give practically continuous curves.

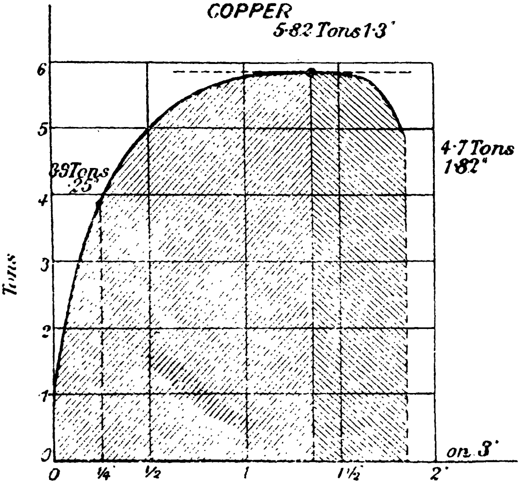


Fig. 35.—Recorder Diagram (Copper).

The load extension curve of copper, shown in Fig. 35, illustrates this point, but in the case of this metal the effects of annealing, or heat treatment, and the purity of the metal have very little influence in the form of the diagram.

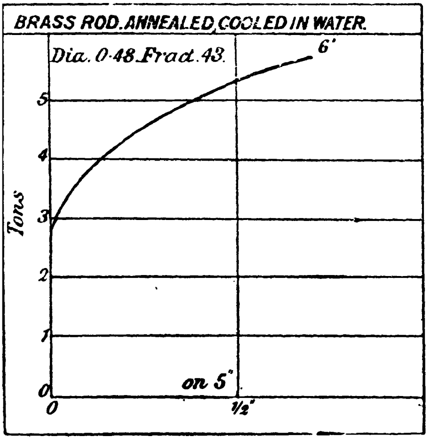


Fig. 36.—Recorder Diagram (Brass Rod annealed, cooled in water).

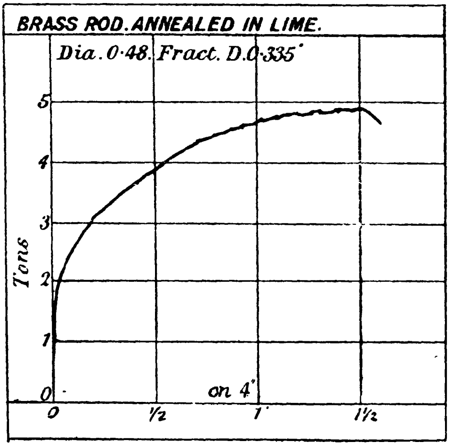


Fig. 37.—Recorder Diagram (Brass Rod, annealed in lime).

Brass, on the other hand, gives very decided indications of its past history. This is shown in Figs. 36 and 37, where the effects of cooling in water or annealing in lime are indicated by the shape of the curves.

A characteristic of brass is the peculiar wavy form of the curves near the breaking point. This appears in each of the three diagrams in spite of the effects of annealing.

Diagrams for phosphor bronze are generally similar to that shown on Fig. 39 and resemble those obtained on rolled brass. The curve shown in Fig. 40 is characteristic of gun metal, while Fig. 41 shows the diagram obtained on a light, strong aluminium alloy, the shape of which is peculiar to this material.

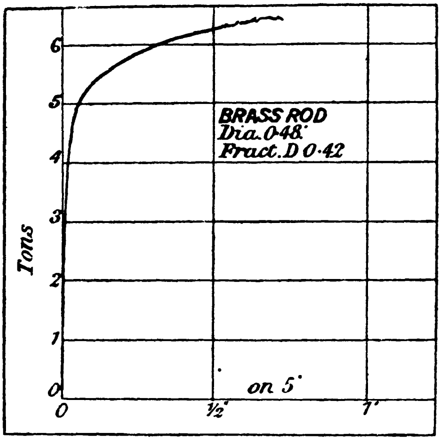


Fig. 38.—Recorder Diagram (Brass Rod).

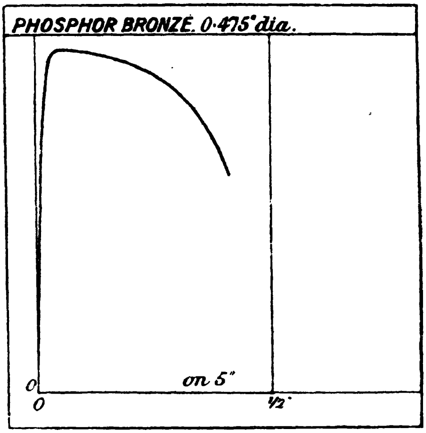


Fig. 39.—Recorder Diagram (Phosphor Bronze).

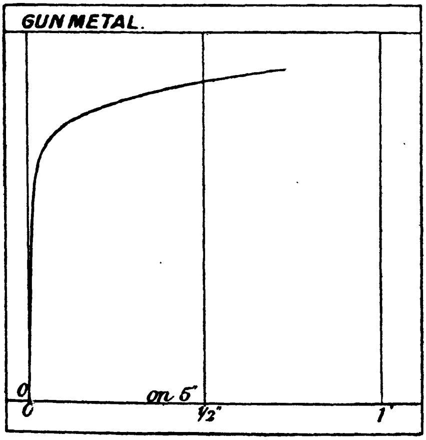


Fig. 40.—Recorder Diagram (Gun Metal).

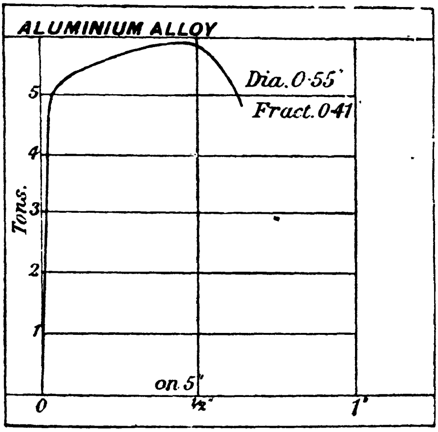


Fig. 41.—Recorder Diagram (Aluminium Alloy).

The curves shown for iron and steel in Figs. 31 to 34 are the most interesting, as on these metals the diagrams indicate more than any other.

In Fig. 31 the common quality of the iron is shown by the small extension after the attainment of the maximum load, the Yorkshire and Swedish irons shown in Figs. 32 and 33 being superior in this respect. Curves taken from very brittle materials such as cast iron, need a very high magnification of the elongation, as the extent of the latter is very small. For this reason the top of the drum is sometimes made into a stepped pulley, so that several degrees of magnification may be obtained with the same recorder.

The diagrams given by very mild steels (about 0·1 per cent. carbon) are very similar to those obtained from wrought iron, except that the yield point is much more marked in the case of steel.

As the percentage of carbon increases, the yield point becomes less marked, and the elongation diminishes considerably.

Alloy steels show no break in the curve at yield point, but the angle of the curve alters more or less abruptly as shown in Fig. 34, being similar in this respect to the non-ferrous metals.

The curve for manganese steel showed that the metal yielded in a series of steps and broke off short without local contraction.

The nickel chrome steel shown in Fig. 34 had a breaking stress of 54 tons per square inch, and at this stress it drew out and broke like mild steel. In some alloy steels the elastic limit and breaking stress are very close to one another, and the curve rises in a straight line and then bends over, exhibiting a form similar to the phosphor-bronze curve (Fig. 39).

Elastic Deformations.—For some purposes, it is necessary to measure the deformations of a material under stresses which do not reach its yield point. This is also necessary where it is desired to obtain the elastic limit accurately, as the drop of the steelyard which takes place at, or about the yield point, is only an approximation to the correct value.

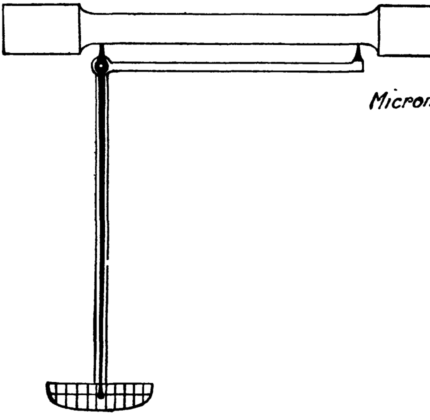


Fig. 42.—Kennedy Extensometer.

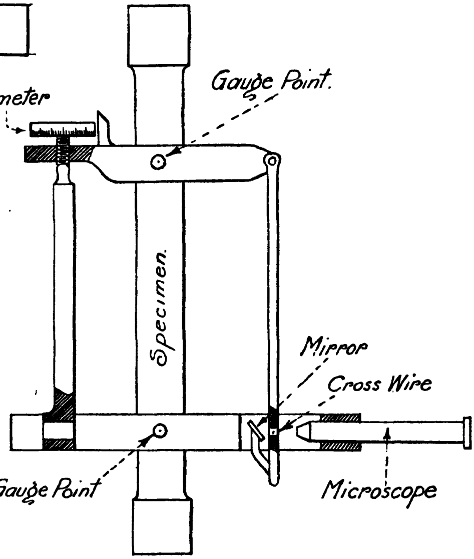


Fig. 43.—Ewing Extensometer.

A handy instrument for measuring small extensions with reasonable accuracy is shown in Fig. 42. This may be rapidly clipped to a specimen, and will enable the yield point to be readily observed, but must be removed before plastic deformation takes place to any serious extent.

A more complicated and expensive extensometer, giving considerably greater accuracy, is shown in Fig. 43. This is Ewing's Extensometer, and its accuracy is about $\frac{1}{50000}$ of an inch. As will be seen from the diagram, the readings of the scale (viewed through a microscope) are calibrated by the micrometer screw shown at the top of the apparatus, and readings accurate enough for most types of research work, can be made with this extensometer.

Many other types of extensometer are made, including optical and photographic instruments, but as they are not of great importance for commercial testing, the reader is referred to standard works on the Testing of Materials, for fuller description of these.*

Special mention may be made, however, of the instrument used by Professor Dalby, for indicating the load applied by the straining gear of a testing machine. In this case the test piece, instead of being connected to a lever indicator, is fastened to a standard bar in which the stress is always below the elastic limit. The extensions of this bar are therefore always proportional to the load, and with a suitable indicating device, photographic or otherwise, the load applied to the test piece may be read off by observing the increase in length of the standard bar.

Test Pieces.—These may be divided into two classes, viz. materials too hard to be held in friction grips, and those sufficiently soft to be so held.

Hard materials must be tested by means of headed test pieces and collar grips as described in Chapter III. Heat-treated test pieces must pass through several stages before assuming the final form, and these stages of machining are shown in Fig. 44. The test piece, which in this case is a combined tensile and impact test piece, is first turned to the form shown at (*a*), when it is ready for carburising. After this has been done, the carbon is turned off so that the test piece will be machinable after quenching, and it then assumes the form indicated at (*b*). When the specimen has been heat treated, it is turned to its final form (*c*). In these specimens it is essential that good radii are provided at the shoulders, as otherwise, the test pieces are liable to break prematurely at such points. Also in the case of hard or brittle specimens it is necessary that all tool marks are removed from the parallel part of the specimen, as these are very liable to start cracks when the piece is being pulled, and so to weaken the test piece. To allow for the testing of small sections, it is advisable to have several standard diameters and, in view of the influence of the ratio of length to diameter upon the test results obtained, standard lengths of test corresponding to each diameter must be fixed at the same time.

The following standard sizes were adopted for Air Board Tests :—

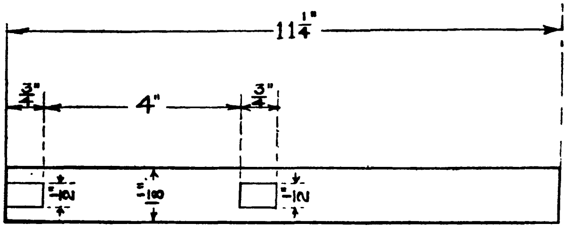
Diameter of bar.	Diameter of specimen.	Distance between centre punch marks.	Area.
$\frac{5}{8}''$ and upwards .	0·564″	2″	0·25 sq. in. = $\frac{1}{4}$ sq. in.
$\frac{15}{32}''-\frac{39}{64}''$	0·424″	$1\frac{1}{2}''$	0·141 sq. in.
$\frac{9}{32}''-\frac{29}{64}''$	0·282″	1″	0·0625 sq. in. = $\frac{1}{16}$ sq. in.
$\frac{7}{32}''-\frac{7}{64}''$	0·125″	0·443″	0·0122 sq. in.

---

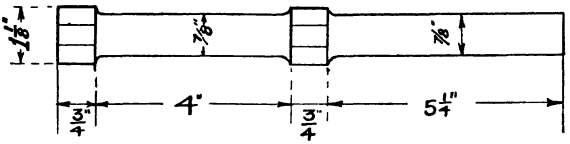
* See " A Handbook of Testing Materials," by C. A. Smith. " Testing of Materials," by W. C. Unwin, etc.

A series of experiments made by Professor Dalby on shouldered test pieces, proved that comparative figures could be obtained on geometrically similar specimens, but that short specimens not only showed considerably greater percentage elongation, but also higher tensile strength.

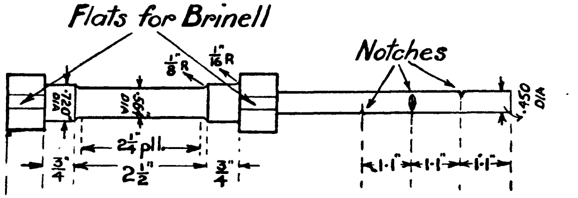
In the experiments referred to, a steel giving 30 tons per square inch and 16 per cent. elongation with a distance of 3 inches between the shoulders, showed a tensile strength of 40 tons per square inch, and an elongation of 27 per cent., when the distance between shoulders was reduced to ¼ inch.



(a) Test Piece for Carbonising.



(b) Test Piece for Heat Treating



(c) Finished Test Piece for Tensile, Impact, and Brinell Tests.

Fig. 44.—Stages of Machining for Tensile Test Pieces.*

This measured length is much shorter than would be used in ordinary practice, but the same tendency holds good in a less degree for variations in length.

Test pieces with plain cylindrical ends for holding in wedge grips, are convenient for machining from plain bar material, and are also cheaper to make, as there is less material to machine off than in the case of headed specimens.

In some instances it is only possible to obtain short specimens for testing

---

* In Fig. 44 the flats for Brinell Test are shown in the first stage of machining (*a*). As Brinell tests are useless on case-hardened surfaces it is preferable to grind these flats in the finished test pieces (*c*) deeply enough to penetrate below the case to the core.

purposes, so that neither headed nor straight shank test pieces can be made. In this case threaded ends are generally used, as they can be screwed into adapters and allow a reasonable length between the grip holders for observing the yield point during the progress of the test.

A suitable form of screwed test piece is shown in Fig. 45.

Test pieces for brittle materials such as cast iron must be very carefully made, as they are liable to break at the shoulder, or at the change of section. Thus the radii should be very large, and should blend well with the parallel part of the test pieces, special care being taken not to undercut at this point.

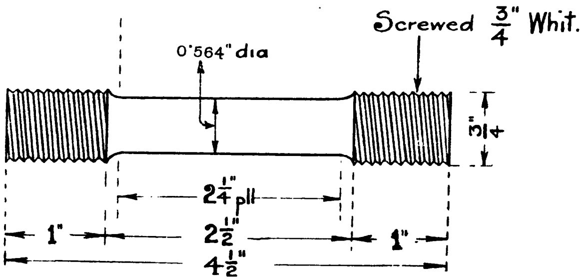


FIG. 45.—Screwed Test Piece.

Thin steels used in aeronautical work are usually machined to a width of $1\frac{1}{4}$ inches, and tested over a gauge length of 4 inches, so that the overall length of specimen is about 10 inches.

Admiralty specifications for section steel used in ship construction, and also for ship plates and sheets, require the elongation to be taken on a measured length of 8 inches.

The British Standard, Lloyds, and Bureau Veritas Specifications for Iron and Steel for ship-building purposes also specify a measured length of 8 inches on all test pieces. On steel castings and forgings for ship and engine work, the Bureau Veritas calls for a gauge length of 4 inches.

Unwin * gives the following table for plate test bars, basing the gauge length on Barba's Law, which states that the percentage elongation on two different test pieces of the same material will be identical if $\frac{l}{\sqrt{A}}$ is the same. (Here l = gauge length, A = sectional area of test piece.)

Gauge Length.	Width.	Thickness.	Area.	$\frac{l}{\sqrt{A}}$	Elongation per cent.
8"	$2\frac{1}{2}$"	$\frac{1}{4}$"	0·625	10·0	27·5
8"	$2\frac{1}{2}$"	$\frac{5}{16}$"	0·781	9·1	29·1
8"	2"	$\frac{3}{8}$"	0·750	9·2	29·2
8"	2"	$\frac{1}{2}$"	1·0	8·0	28·0
8"	2"	$\frac{3}{4}$"	1·5	6·5	26·5
8"	2"	$\frac{7}{8}$"	1·75	6·1	26·1
8"	$1\frac{1}{2}$"	$1\frac{1}{4}$"	1·875	5·8	25·8
8"	—	$1\frac{1}{2}$"	2·25	5·3	25·3

---

* The experimental study of the "Mechanical Properties of Materials," by W. C. Unwin, LL.D., F.R.S., *Proc. Inst. Mech. E.*, October, 1918.

The Engineering Standards Committee also specify a gauge length of 8″, and maximum widths of 1½″, 2″, and 2½″ for thicknesses over ⅞″, ⅜″ to ⅞″, and under ⅜″ respectively. For round specimens, the following diameters and gauge lengths are selected :—

Diameter.	Area.	Gauge Length.
0·564″	¼ sq.″	2″
0·798″	½ sq.″	3″
0·977″	¾ sq.″	3½″

In French and other Continental specifications the elongation is usually expressed as a percentage on a measured length of 100 millimetres.

Note.—Recent recommendations of the Commission Permanente de Standardisation (French Standards Committee) in connection with Tensile, Impact, and Hardness tests, and specimens are discussed in a paper by Prof. Guillet, "Testing Materials for Shipbuilding," read before the Institution of Naval Architects, July 6, 1922.

CHAPTER V

IMPACT TESTING

Origin and Development.—In the early years of engineering development, when the tensile test was practically the only indication of the physical properties of materials, many failures occurred for which there was no obvious reason, and the need for some other kind of test became apparent.

The property of "Toughness," which is vitally necessary in machines and structures that are subject to vibration or shock (and these form the great majority of engineering designs), is not indicated with any certainty by the results of the tensile test. It is true that this property is shown, to some extent, by the percentage elongation and reduction of area of the tensile test piece, but these can by no means be relied upon to do so.

A popular and rough form of workshop test which was often made, and is still used to a large extent for some classes of work, is to cut a nick or notch in the material to be tested, and break the piece across with a hammer. The readiness with which the two halves of the material separate, and the character of the fractured surface, give very useful indications of the toughness of the material, and its ability to withstand shock or vibration.

This crude form of "Impact" or shock test is now used for estimating the properties of materials where no great stresses have to be borne, or where it is difficult or impossible to cut test pieces from the article under observation.

It suffers, however, from the disadvantage that the results cannot be expressed in figures or definite quantities, and cannot be embodied in specifications for material, in other than vague terms. It is also dependent, for its success, on the experience of the observer, and so is liable to differences of opinion on the part of different inspectors.

The Impact Testing Machine has removed this difficulty, by providing a definite standard, allowing the shock resistance of materials to be expressed in terms which admit of no dispute.

The development of Impact testing in this country is largely bound up with that of aeronautical engineering, and therefore practically dates from the beginning of the War. It is true that the design and manufacture of impact testing machines originated many years ago, and the use of drop tests for steel tyres, etc., is also old, but the systematic testing of materials in this way for general mechanical engineering purposes, and the embodiment of impact tests in material specifications is comparatively recent.

The Impact Test.—The method of performing the test is to subject a specimen of the material under examination to a sharp blow, or series of blows, the impact value being expressed in terms of the energy absorbed in breaking the test piece, or the number of blows required to fracture the specimen.

The impact test may therefore be referred to as a "dynamic" test, to distinguish it from the static tests hitherto described.

In most of the single-blow impact testing machines, the specimen is notched for the purpose of testing, standard forms of notch being adopted for different types of machine.

The object of the notch is to increase the sensitiveness of the test, as it was found in the early experiments that the difference between tough and brittle materials was much more marked in the case of notched specimens than when these were left plain.

The form, size, and depth of the notch has a decided influence on the results obtained, so that in machining impact specimens it is very necessary to use gauges to which all test pieces should be prepared.

The test pieces used on different kinds of machine are of different shapes and sizes, and as tests made on different areas are not comparable, it is necessary to adhere to one standard form of test piece for each type of machine.*

Impact tests are of many kinds, as shocks can be applied to a specimen in different ways, but for the sake of convenience the "Impact-Bending" test, which is the type most generally in use, will be called the "Impact" test, the others being described as the "Impact Tensile" test, etc.

Impact testing machines may be divided into the following classes :—

1. Single-blow Machines.
    - (*a*) Pendulum weight with "cantilever" specimen ("Izod" machine).
    - (*b*) Pendulum weight with beam specimen ("Charpy" machine).
    - (*c*) Drop weight ("Amsler" machine).
    - (*d*) Rotating weight ("Guillery" machine).
2. Multiple-blow Machines.
    - (*a*) Pendulum weight ("Stanton" machine).
    - (*b*) Drop weight (various machines).

Izod Impact Testing Machine.—This is the form of impact test most frequently used and specified in this country, and is included in most of the Government specifications. It is applied by means of a swinging pendulum hammer, which applies a blow of definite and known energy to the test piece which is held at the lowest point of its path. The kinetic energy of the hammer is usually sufficient to break the specimen, and to allow the pendulum to traverse the lowest point of its swing and to rise to some distance on the other side. The energy remaining in the pendulum can be measured by the length of its swing after breaking the test piece. The energy lost in breaking the test piece is thus the energy originally imparted to the pendulum *minus* the residual energy after breaking the test piece (see Fig. 46).

If W= Weight of pendulum hammer,

H= Height of fall,

h= Height to which pendulum hammer rises after breaking test piece,

then—

$$\text{Energy required to break specimen} = W(H-h)$$

This energy can be expressed in terms of the angle of swing, and is generally measured by a loose pointer, which is moved over a graduated scale by the pendulum, and, being left behind on the return swing, indicates the farthest point reached by the pendulum after breaking the specimen.

---

* A British Standard Specification has now been issued detailing the form and sizes of small specimens in cases where the standard 10 millimetre specimen cannot be used.

The weight of pendulum in standard Izod machines is 60 lbs., and the height of fall 2 feet, so that the capacity is 120 ft.-lbs.

As some steels absorb more energy than this in breaking, machines have been constructed for steel makers with a capacity of 150 ft.-lbs. In this case the height of fall is 2·5 feet.

The pendulum is mounted on ball bearings to reduce friction to a minimum, and the suspension is made very light, and rigid, to concentrate the striking weight as far as possible in the "tup" or "bob." The tup is fitted with a hardened tool steel knife-edge, which strikes the specimen at a point 22 mm. above the surface of the gripping dies. The knife-edge is slightly rounded to avoid chipping and damage.

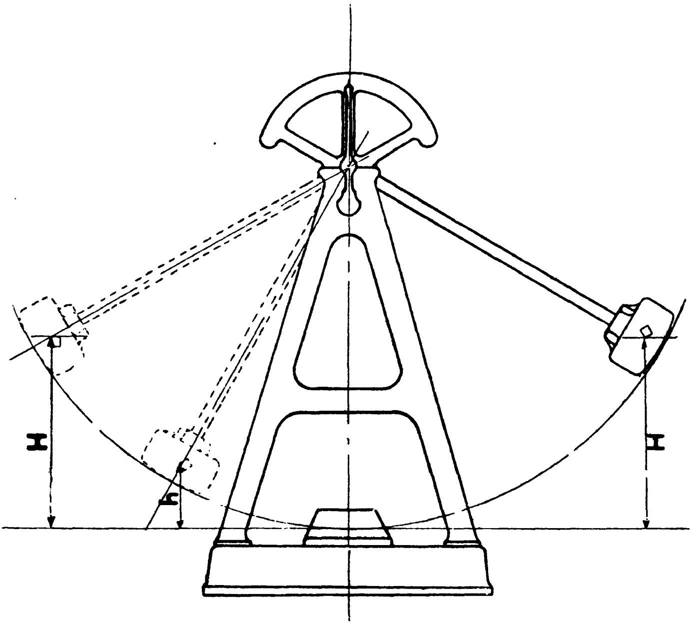


Fig. 46.—Izod Impact Test. Total energy available = WH ft.-lbs.; Energy absorbed = W(H−h) ft.-lbs.

In Fig. 47 the pendulum is shown in position for starting the test, and is released for its downward swing by a hand lever on the projecting arm of the machine.

The method of holding the specimen is shown in Fig. 48.

The cast-iron anvil has a gap in the top, and into this, two tool-steel dies are fitted. The left-hand die has a recess which positions the specimen, and the right is pulled up to grip the specimen by means of a screw-operated wedge. The screw is worked by the round nut at the bottom, into the recess of which a tommy bar is inserted. As the thread has a large angle, one movement of the tommy bar will grip or release the specimen.

The standard specimen is square, being 10 mm. by 10 mm., with a notch

2 mm. deep. This notch has an included angle of 45 degrees, and is rounded at the bottom with a radius of 0·25 mm. (25 S.W.G. wire).

This can be machined by means of a shaping tool ground to gauge, but a milling cutter is better.

As square specimens are slow and costly to make, an alternative practice is to use round specimens. These are turned to a diameter of 0·45 inch and have a notch milled or turned to standard dimensions. Milled notches are 0·13 inch deep, have an angle of 45 degrees, and a radius of 0·01 inch at the bottom of the notch.*

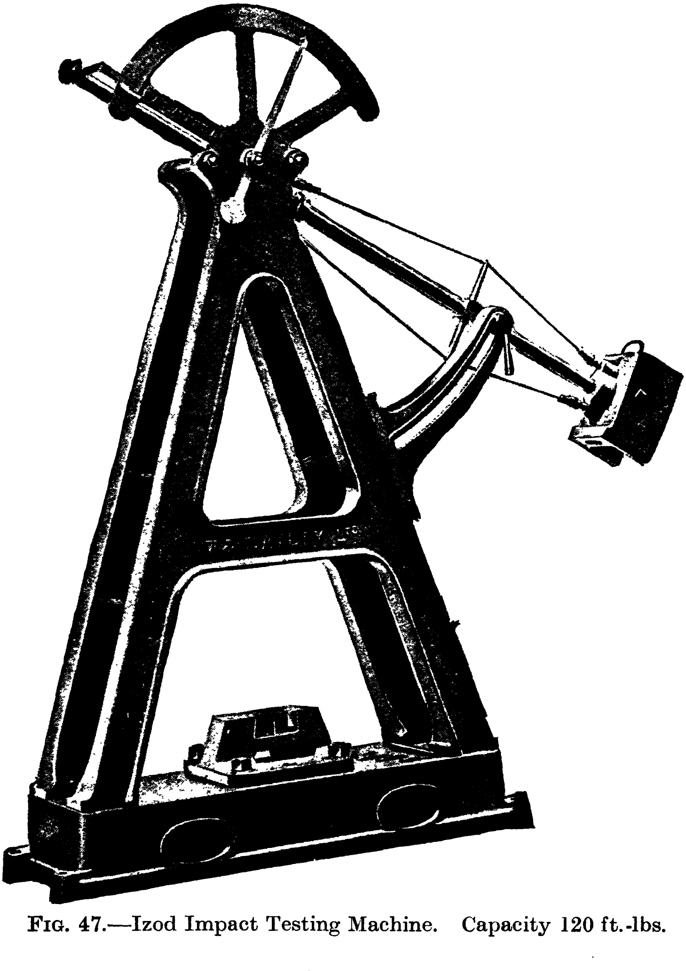


FIG. 47.—Izod Impact Testing Machine. Capacity 120 ft.-lbs.

This may be checked with a wire of 25 S.W.G.

---

* The notches in round specimens do not encircle the specimens, but are turned or milled on one side only. For full details see "Engineering Standards Specification" (Engineering Standards Committee, 28, Victoria Street, London, S.W. 1)

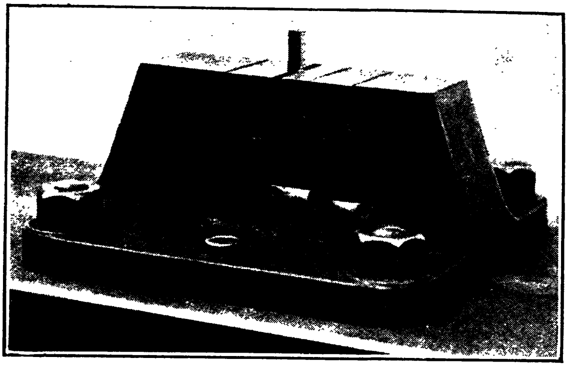


FIG. 48.—Method of holding Test Piece in Izod Impact Testing Machine.

Turned notches have a maximum depth of 0·12 inch and are of the same form as the milled notches.

Formed turning tools, which retain their shape when reground, are used for machining these notches. Four pieces are machined at a time on a special "jig."

Test pieces with three notches, 1·1 inches apart, are often employed. In this case the notches are cut at right angles to one another, so that the impact strength of the material is read in three directions. Thus, the *mean* shock strength of the material is obtained.

A smaller size of Izod machine (23 ft.-lbs. capacity) was formerly made, but is of little value for testing steel, as the section of the specimen is very small ($\frac{3}{8}$ inch by $\frac{3}{16}$ inch). It may become useful, however, for testing the impact values of light alloys, using the standard size of specimen (0·45 inch diameter) for this purpose.

The more open graduations of the small machine give the latter a considerable advantage over the 120 ft.-lbs. machine, in the case of materials having small impact strengths.

Charpy Impact Testing Machine. — The principle upon which this machine works, viz. the pendulum hammer, is similar to that of the Izod machine, but the details of the test are very different. The pendulum has a considerably greater angle of swing and is quite different in form from that of the Izod machine. A large Charpy machine of 250 kg. metres

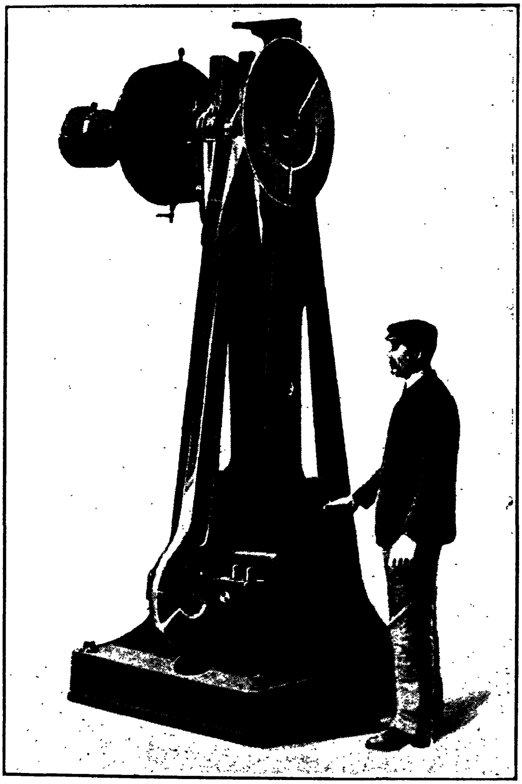


FIG. 49.—Charpy Impact Testing Machine. Capacity 250 kg. metres.

capacity is shown in Fig. 49, and a smaller size (25 kg. metres) in Fig. 50. The hammer of the large machine is raised to the striking position by means of a motor, and that of the small machine by the handle shown in Fig. 50. The hammer swings on ball bearings, and the angle of swing after the specimen is broken, is indicated by a loose finger as in the case of the Izod machine. The form of the specimen, however, is the principal difference between these two kinds of impact test. The Charpy test piece is placed in the horizontal

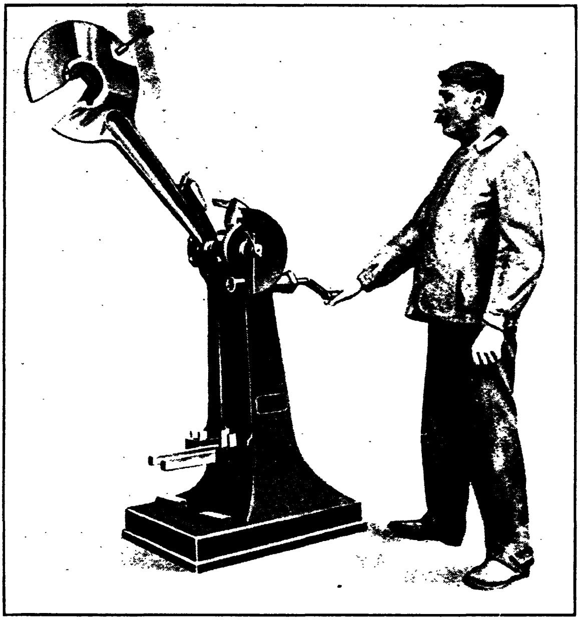


Fig. 50.—Charpy Impact Testing Machine. Capacity 25 kg. metres.

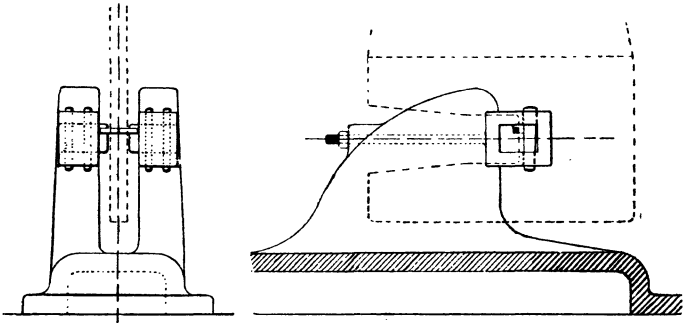


Fig. 51.—Method of holding Charpy Impact Test Piece.

position, supported at both ends, as shown in Fig. 51, and the hammer strikes it in the centre, on the opposite side from the notch. To enable it to pass between the supports, the hammer is made very narrow, and the knife-edge is placed in the vertical plane as shown in Figs. 50 and 51, and coincides with the centre of percussion of the hammer, so that there is a minimum of vibration when the test piece is struck. A hand-operated brake brings the hammer quickly to rest on the return swing. As the pendulum is mounted in ball bearings, there is very little loss due to friction, whereas this is a somewhat serious point in connection with some falling weight machines.

Tables are issued giving the energy absorbed in friction by the swing of the pendulum, and also by the broken test pieces for each angle of swing after fracture. These are shown in the form of a curve in Fig. 52.

The form of notch used with the Charpy machines, is that recommended by the Congress of the International Association of Testing, and is often called the "Copenhagen" notch. It consists of a drilled hole connected by a saw-cut to the outside surface of the specimen. This hole should be drilled in a jig to make sure that it is always at a fixed distance from the edge. The most usual sizes of test pieces are as follows :—

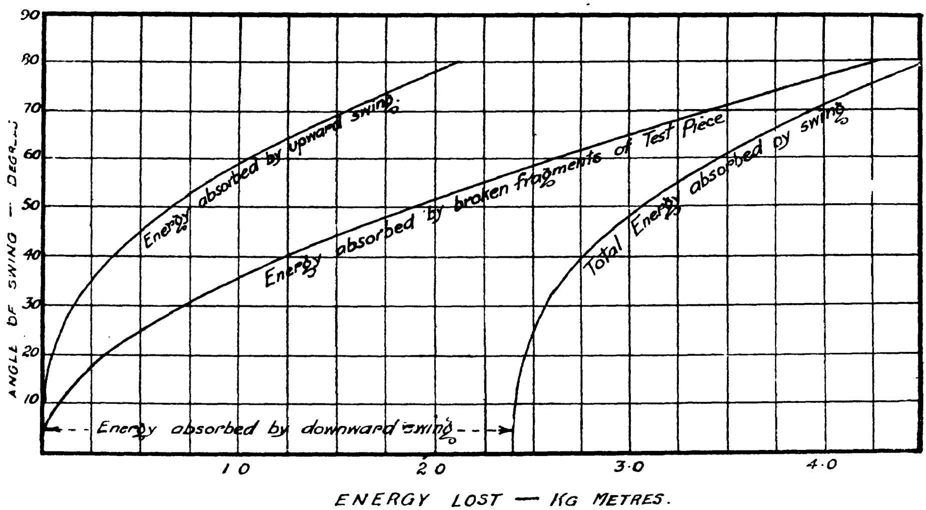


FIG. 52.—Charpy Impact Tester. Energy lost in Friction.
Weight of pendulum = 72·865 kg.
Height of fall = 3·052 metres.

160 × 30 × 30 mm. Notch 15 mm. deep. Radius of notch 2 mm.
60 × 10 × 10 mm. Notch 5 " " " 2 "

Distance between points of supports are 120 and 40 mm. respectively.

Broken Charpy test pieces are shown in Fig. 53.

The knife-edge at the striking point has a radius of 2 mm. and is machined to an angle of 30 degrees.

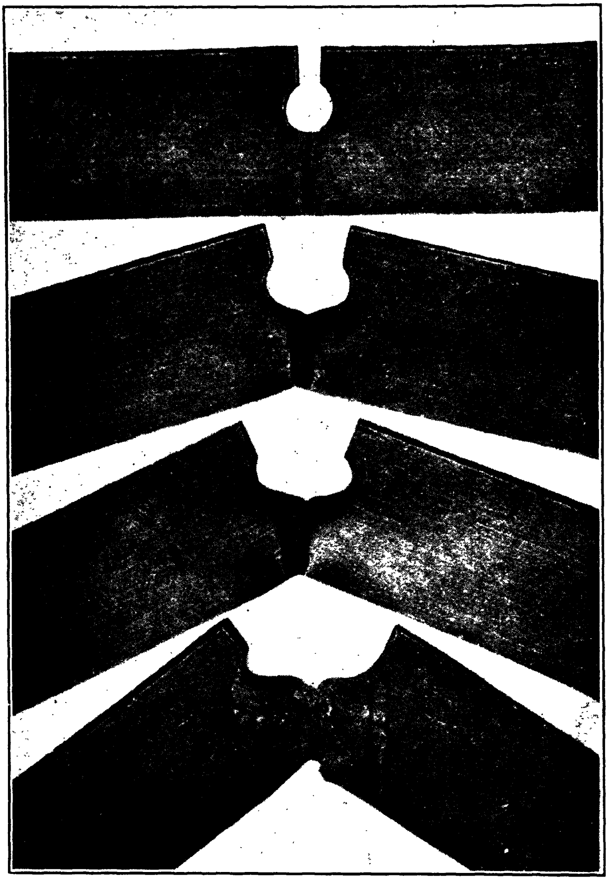


FIG. 53.—Broken Charpy Impact Test Pieces.

The following sizes are made :—

Capacity.	Weight.	Fall.
Kg. metres.	Kg.	Metres.
250·0	85·0	2·94
200·0	66·7	3·0
75·0	33·0	2·28
25·0	20·0	1·25
10·0	8·2	1·22

Drop Weight Machines.—The drop test is performed by a fixed falling weight or " tup," which is dropped from a given height upon the centre of a test piece, supported in a suitable manner at each end. This type of machine is similar to a pile driver, with the exception that the " monkey," instead of falling on a pile, hits the test piece and breaks it.

The early experiments of Frémont were made on a machine of this kind, having a tup weighing 10 or 15 kg., with a knife-edge, falling through a distance of 4 metres. The energy remaining in the hammer after impact was measured by the compression of a spring or springs. This is not very accurate, and the " Amsler " machine has a device which indicates graphically the velocity of the tup before, and after fracture, so that the work done in breaking the test piece can easily be deduced.

Another machine of this type was described * by Messrs. Blount, Kirkaldy, and Sankey, for testing specimens in impact-tension, but it could be used equally well for any other form of impact test. The energy in the tup at the moment of striking the test piece, was calculated from the height of fall. The velocity immediately after breaking the specimen, was calculated by observing the time interval between the breaking of two contacts, one placed immediately below the test piece, and the second 10 feet lower down.

The energy absorbed in breaking the specimen is :—

$$\mathrm{W}\left\{\mathrm{H}-\frac{1}{g}\left(\frac{h}{t}-\frac{gt^2}{2}\right)\right\}$$

where H = Height of fall before striking specimen.
h = Height of fall between anvil contact and second contact.
W = Weight of tup.
t = Time interval between first and second contacts.

The record of these times was taken by a pen which made a continuous line on a moving paper band. When the contacts were opened, the pen was deflected, and the distance between the two deflections gave the time of fall. A second recording pen, vibrating at about 40 per second, marked a wavy line on the paper, and provided a time scale to which the diagram was read.

A speed of 5 inches a second was found to be a suitable speed for the paper in this instance.

Rotating Weight Machines.—These are seldom used in this country, but the best known and most convenient machine of this type is the Guillery Impact Testing Machine.

This machine is illustrated in Fig. 54.

The striking edge has an angle of 45 degrees, and is carried on a flywheel rotating at about 302 revs. per minute. At this speed, the energy contained in the larger size is 275 metre-kilogrammes (2000 ft.-lbs.) and in the smaller size 60 metre-kilogrammes (440 ft.-lbs.).

By pressing a stud, the knife is forced into the " out " or striking position for breaking the test piece. The absorption of energy for this purpose, causes the speed to fall, and the reduction is immediately shown on the tachometer tube in energy units.

---

* " Comparison of the Tensile, Impact Tensile and Repeated Bending Methods of Testing Steel," *Proc. Inst. Mech. E.*, 1910.

A centrifugal pump driven by bevel gearing from the spindle of the machine, forces coloured liquid into this tube, and the height to which the liquid rises is an indication of the speed of the machine.

An adjustable float in the centrifugal pump enables the operator to set the reading to the full capacity of the machine when at rest, so that a zero reading will be obtained at full speed.

A hand-operated brake is provided for stopping the flywheel when the tests are completed, and an automatic device is fitted to prevent the wheel being turned in the wrong direction. A safety arrangement is also provided to prevent the door enclosing the test piece being opened while the flywheel is rotating with the knife in the "out" position.

The type of test piece is the same as that used in the Charpy machine, but the scale does not take into account the energy absorbed by the projected fragments of the test piece after fracture.

Stanton Impact Tester.—This is a multiple-blow machine in which the hammer falls repeatedly on to the centre of the specimen.

The latter has a groove turned in the middle and is rotated half a revolution after each blow, so that the hammer strikes it on each side alternately, until fracture takes place. The general arrangement of the machine is shown in Fig. 55.

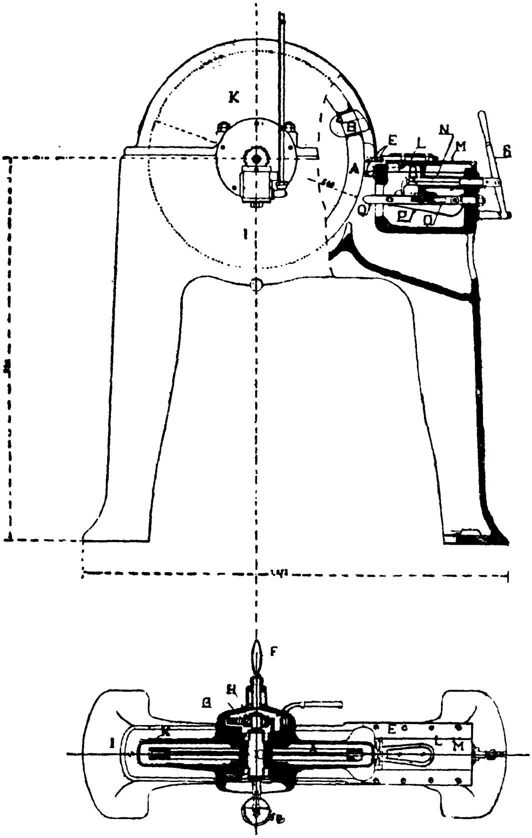


FIG. 54.—Guillery Impact Testing Machine.

A roller mounted on a movable support serves as fulcrum for the hammer, and may be moved backwards or forwards along the hammer shaft, to increase or decrease the lift of the hammer (see Fig. 56).

The groove cut in the specimen is 0·05 inch deep, and the test piece is about 6 inches long and $\frac{1}{2}$ inch diameter. It is supported on knife-edges $4\frac{1}{2}$ inches apart. The fall of the hammer can be adjusted to a maximum of $3\frac{1}{2}$ inches, and the speed is 70–100 revs. per minute. The resistance of the specimen is measured by the number of blows sustained from a given height before fracture. The machine stops automatically when the specimen breaks, so that the number of blows sustained can be read on the counter. The power absorbed by the machine is small, being only about $\frac{1}{10}$ H.P.

Falling Weight Machines.—These are similar to the Drop-weight machine already described, except that the specimen is too large to break at one blow and is therefore fractured by a succession of blows. This test has been in use for railway material for many years, and is included by the Engineering Standards Committee in their Standard Specifications for material used in the construction of Railway Rolling Stock.

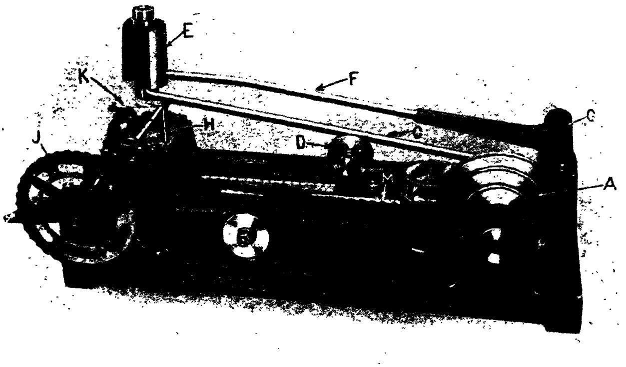


Fig. 55.—Stanton Impact Testing Machine.

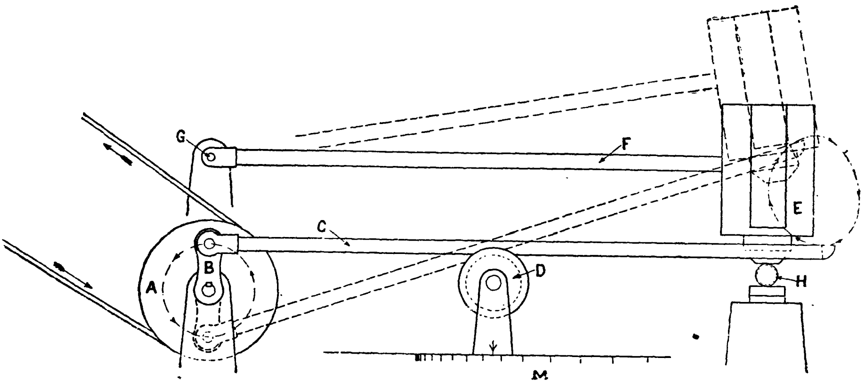


Fig. 56.—Hammer and Lifting Gear of Stanton Impact Testing Machine.

It is particularly used for important steel forgings such as axles and tyres. For testing axles the weight of the hammer is large, being about 1 ton, and the height of fall up to 35 feet. The distance between the points of support of the axles varies from 3 to 5 feet for axles of 4 to 6 inches diameter. The axles have to stand five blows at a height of fall specified for each diameter, and are turned through an angle of 180 degrees after the first and third blows.

Locomotive, Carriage and Wagon Tyres are also tested with a weight of

1 ton, the tyre being placed with the tread resting on a block of metal not less than 5 tons weight, supported on a rigid concrete or other solid foundation. The weight falls freely on the tread from heights of 10, 15, 20 feet and upwards, until the deflection of the tyre reaches a fixed amount.

This deflection under shock must be sustained without fracture of the tyre.*

Some Practical Considerations

There has been considerable opposition in many quarters to the increased use of Impact Test Clauses in Steel Specifications, but in spite of this, the impact test is becoming more and more popular in engineering and metallurgical work.

One of the chief reasons for this, is the fact that the impact test is a valuable guide to the correctness of Heat Treatment. A good impact figure almost invariably indicates that the heat treatment has been properly carried out, and cases of bad material giving a good impact value are practically unknown. Poor impact tests are nearly always accompanied by a crystalline fracture, while fibrous materials give good impact results.

This does not mean, however, that the impact test is the sole criterion in judging the quality of any material. It must always be considered in connection with, and in addition to, the yield point and tensile strength of the material.

It has been urged that the position of the notch relative to the crystals of which the material is composed, makes the results of impact tests erratic. While this may be so in the case of castings or other material in which the crystals are large, forged or rolled material has a structure that is small, relative to the size of the notch, and in this class of work, the position of the notch is immaterial.

The energy absorbed in the impact test is expended in two ways :—

1. To start and extend the crack.
2. To deform the material adjacent to the notch and crack.

The practice of using notched test pieces is condemned by some engineers, as being remote from practice, but as all tool marks are potential notches, and convenient starting points for cracks, the conditions in the impact test piece are reasonably close to those existing in practice.

Some authorities express the opinion that the sharpness of the notch, and the tightness with which the specimen is gripped in the Izod test considerably affect the results obtained. With the latter the authors are not in agreement, and as the standard form of test piece has a fixed radius at the bottom of the notch, the first point is of no practical importance.

The tightness of gripping the test piece is probably not important provided the grip is sufficient to prevent any spring of the component parts in the anvil.

It is advisable, therefore, to design the latter so that a fairly uniform pressure can be applied for successive tests, even when different men are working the machine. To avoid these difficulties and also to make the anvil as solid as possible (and so to avoid spring) the arrangement shown in Fig. 48 was designed, and has proved successful.

Some impact machines have been designed with swinging anvils, so that the energy absorbed by the latter when the specimen breaks, is indicated by the movement of the anvil. This, the authors consider, is inconsistent with the

---

* See also the Eden-Foster machine described in Chapter III

principle of the impact test, as it allows a longer period during which the knife-edge of the pendulum is in contact with the specimen, than when the specimen is rigidly held. It thus partakes more of the nature of an accelerated loading than of a shock, and so is not so true a test of the impact properties of the material. Further, with very tough material, the period of contact will be considerably longer than with brittle material, so that this difference is by no means a constant quantity. As the addition of fresh variables still further complicates the conditions, the authors think it advisable to make the holding appliances as rigid as possible, and to bolt the machine itself down to a good foundation.

Cases have been observed where impact testing machines have been placed on the floor without any holding-down bolts, and have moved considerably every time a test was made. This obviously detracts from the accuracy of the test and should be avoided.

The frame of the machine should also be as stiff as possible, to avoid loss of energy in vibration.

The position of the test piece itself relative to the direction of rolling or forging is also a very important matter. It is evident that the impact strength of a test piece cut *across* the fibres will be very much less than one cut *along* the fibres. This point is discussed in greater detail in Chapter X.

Large forgings (*i.e.* forgings of heavy section) are not likely to be uniform throughout the section when heat treated, and therefore such forgings should not be passed or condemned on the results of a single impact test. The position of the test piece in this case also is a matter of importance.

It is also found that some kinds of steel are susceptible to cold, and that impact or bending tests made at low temperatures on such steels are apt to give much lower results than when the tests are made at the ordinary atmospheric temperature.

This may be important in the case of aeroplane or airship steels, where the structure has to ascend to high altitudes and is therefore subjected to low temperatures.

It must be understood clearly that isolated impact tests, used alone, may be misleading, but that by using them as a supplement to the data obtained by other methods of testing, they give very valuable information. While there is no uniform relation existing between static tensile tests and notched bar impact tests, the combination of these two methods supplies most of the information necessary for deciding the suitability or otherwise of a material for any engineering work. Where possible, however, it is desirable to take two or three impact tests from the same bar, to eliminate any accidental sources of error that may creep in through neglect or inadvertence.

Limits of Accuracy.—One of the most serious accusations levelled against the impact test is, that it cannot be relied upon to give consistent results, and that differences of 100, 200, or 300 per cent. in successive tests are common. This statement has been effectually met by MM. Charpy and Cornu-Thenard in a paper read before the Iron and Steel Institute in 1917.*

If irregularities occur in the impact test readings on successive notches of the same bar, the discrepancies can only be due either to the unreliability of

---

* "New Experiments on Shock Tests and on the Determination of Resilience," by G. Charpy and A. Cornu-Thenard, *Proc. Iron and Steel Institute*, Sept. 1917.

the test itself, or to irregularities in the material tested. As the latter is usually steel, the subsequent remarks will be limited to that material.

It must be understood that the shock test on notched bars is very sensitive —much more so than any static test—so that an accuracy of 5 per cent. is quite reasonable. If a series of tests can be made on the same steel, in which the divergence of results, up or down, does not exceed 5 per cent., it is evident that any abnormal discrepancies must be due to the steel itself, or to the preparation of the specimen.

In the preliminary experiments, it was found that unnotched bars, when deformed to a well-defined bend without fracture, gave practically identical results when tested in the impact machine, the average divergence of readings on each side of the mean value being less than 1·5 per cent.

The notched bar test pieces were carefully prepared from the centre of a large ingot, the section used for their preparation being $\frac{1}{1800}$ of the volume of the ingot.

Brinell tests and analyses were taken, and a micro examination made of the whole surface of the section to detect any local irregularities which might vitiate the results obtained.

The test pieces were then cut from this section, annealed, machined, and heat treated. After finishing and notching, the impact values showed an average divergence of about 40 per cent. The lateral faces of the other test pieces treated under the same conditions were then planed away to the extent of 1, 2, and 3 mm. with the result that the irregularities were reduced to 21, 13, and 8 per cent. respectively. It therefore follows that to get consistent results on heat-treated work, it is necessary to remove at least 3 mm. from the outside surfaces before testing. In all the above tests, the difference shown by the Brinell tests was not more than 2 per cent. in any series, so that this is no guide.

It was also found that the effects of rolling temperatures could not be removed completely by heat treatment. Pieces of the same ingot were rolled at 1200° and 800° respectively, normalised at 900° C., heat treated, machined and notched. The divergence on bars rolled at 800° C. was 20·5 per cent., as compared with 5·2 per cent. for bars rolled at 1200° C. In these experiments, the Brinell tests showed a difference of less than 2 per cent., and micro examination could not detect any difference between the structure of the cold rolled metal and that of the hot rolled metal.

From these results, the desirability is apparent of having as large a crop as possible from the ends of rolled bars, to eliminate the effects of abnormal cooling.

In the experiments upon the different forms of impact test, these sources of error were eliminated, and variation in heat treatment was avoided by treating each series together in a single quenching frame.

In the subsequent experiments, the variation in results was not more than 3·6 per cent. for steel and 4·6 per cent. for copper. Some of the experiments were made on nickel and nickel-chrome steels, the latter being taken from a small ingot of 2·5 tons weight. This shows that consistent results can be obtained by the impact test over all ranges, even when the weight of the original ingot is comparatively small.

The various curves shown in Chapters X., XI., XII. and XIII., showing the relation between heat treatment, temperatures, and impact values for different steels are examples of consistent results which the authors obtained on a standard Izod machine under works testing conditions.

Influence of Variables in Impact Testing Machine

Velocity.—The effect of varying the height of fall, and consequently the velocity of the pendulum, on a standard machine was also investigated by MM. Charpy and Cornu-Thenard. The size of test pieces used was 30 by 30 by 160 mm., and the height of fall was varied from 6·45 to 2·2 metres. The velocity of the pendulum immediately after striking the specimen varied in the ratio of 12 to 1 after various tests, but in the case of steel and copper, it was found that this did not seriously affect the results obtained. The duration of test varied from 0·0015 to 0·0062 sec.[*]

Size of Machine.—In a further series of tests, the effects of testing similar specimens in different sizes of machine was investigated. The machines used were of 307 and 30 kg. metres capacity, and had pendulums weighing 96·25 and 22·31 kg. respectively. The specimens were 15 by 15 by 80 mm. and the supports in each case were 60 mm. apart. The difference in the results obtained on the two machines was only 3·9 per cent. on the highest figure recorded.

Thus, within the limits of accuracy of the test, the effects of height of fall, weight of pendulum, and size of machine are negligible in the case of the Charpy impact test.

Type of Notch.—The preceding tests were all carried out on notches of the "Copenhagen" type. The same experimenters also made a series of tests with different notches as follows :—

A. Copenhagen notch. Residual section 10 × 5 = 0·5 sq. cm.
B. " " " " 10 × 7 = 0·7 "
C. Angular notch. " " 10 × 7 = 0·7 "
D. Blunt saw-cut. " " 10 × 9 = 0·9 "

Comparing A, B, and D, the resistance per square centimetre doubles in high impact steels, when the depth of notch is reduced from 0·5 to 0·1 cm. The angular notch gives results equal to a deeper round notch.

The steels tested in this way were carbon, nickel, and nickel-chrome steels, and the divergence in all cases did not exceed 4·2 per cent.

These experiments established the important practical facts that the depth and size of notch are very important, and that there is no connection between the results obtained in different sectional areas of test piece.

In other words, *the expressions "foot-lbs. per square inch" or "kg. metres per square cm." have no meaning unless the size of test piece and shape of notch are definitely stated.*

A series of experiments was also made by Mr. J. J. Thomas at the Watertown Arsenal on a Charpy machine, to determine the effect of altering the shape of the notch. A round-bottomed notch 1·3 mm. wide and 5 mm. deep was

---

[*] Mr. J. C. W. Humfrey, in discussion on "Mechanical Properties of Steel" (Inst. Mech. Eng., May, 1919), considers the likelihood of slow bending tests with autographic diagrams giving results similar to those obtained by impact tests. This has also been stated by other observers, but the weight of evidence in its favour is not yet sufficient to justify any definite statement on the subject.

used, and the sides were cut away to various angles up to 90 degrees. The result indicated that if the sides of the notch were cut away to any angle up to 30 degrees, the results were unaffected, but above this point the resistance to shock and the angle of bend before fracture were greatly increased.

Dimensions of Test Bar.—It was found that as the dimensions of the test bars increased (in steel or copper), the impact strength per square centimetre also increased, and that the law of similitude did not apply in the case of shock tests on notched bars.

All these results were repeated at the Conservatoire des Arts et Metiers, with substantial agreement in each case.

Comparison of Different Types of Impact Test.—A series of tests was made by MM. Charpy and Cornu-Thenard, to ascertain whether any comparison could be drawn between the results obtained on the Charpy, Drop Test, and Guillery machines.

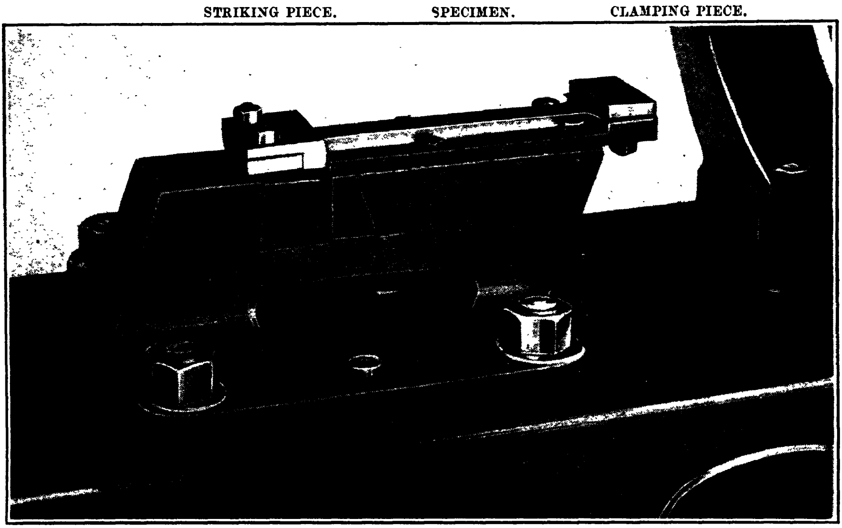


Fig. 57.—Impact-Tensile Test for Flat Strips.

The tests on the Charpy and Vertical Drop Test machines were made on specimens 30 by 30 by 160 mm. and the results obtained differed by 7·1 per cent. in the two cases. The type of machine used for making the drop tests was the Amsler machine already referred to.

The comparative tests on the Charpy and Guillery machines, were complicated by the fact that the principles, shape and dimensions in the two cases were entirely different. Tests were made on the 30 and 300 kg.-metre Charpy machines and 60 and 275 kg.-metre Guillery machines with the following results :—

Charpy	30 kg.-metre.	Results 19·01–18·24.	Variation 1·3 per cent.
Guillery	60 „	„ 18·9 –18·0	„ 1·9 „
Charpy	300 kg.-metre.	Results 19·64–18·21.	Variation 2·4 per cent.
Guillery	275 „	„ 21·78–19·78	„ 3·5 „

It will be seen that the results obtained on the two types of machine are substantially in agreement, and that they are both very regular in degree of accuracy.

The Impact-Tensile Test.—This test has not been used to any great extent in commercial practice, but with the increasing use of small highly stressed parts, it is likely to become useful in cases where the ordinary impact-bending test cannot be made.

Fig. 57 shows an arrangement of the Izod machine for testing steel or aluminium sheet in this way. The specimen is clipped to the anvil at the right-hand side, and has a striking piece firmly bolted to its left-hand extremity. The pendulum knife-edge comes into contact with the striking piece, and the energy of the blow is sufficient to stretch and break the test piece.

Fig. 58 shows the arrangement used on the Charpy machine for testing bar material in impact-tension. In this case the test piece is screwed to the pendulum and travels with it until the cross-piece screwed on the end of the test piece meets the stops mounted on the frame of the machine. The front end of the test piece is pulled onwards by the pendulum with such force that the test piece breaks, the energy absorbed being measured by the swing of the pendulum in the usual way.

One objection to this method of making the test is the fact that the moving weight before fracture includes the weight of the specimen and cross piece, and after fracture the cross piece and half the test piece are left behind. Thus the swinging weight is not constant during the test and varies with each class of material tested.

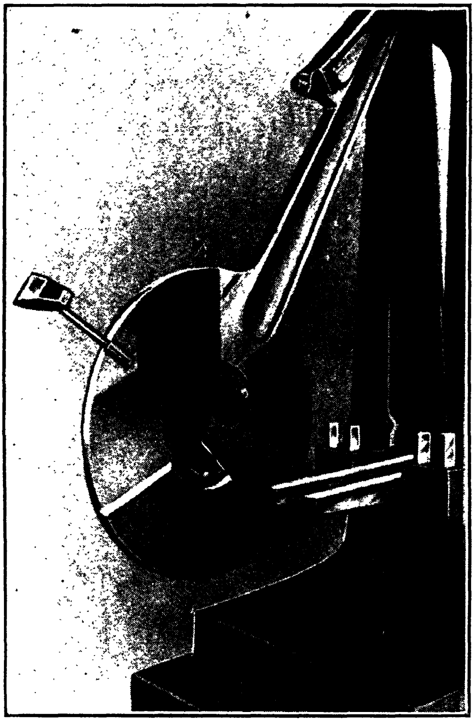


Fig. 58.—Charpy Impact-Tensile Test for Round Bars.

Note.—The attention of interested readers is directed to a series of papers read before the Inst. C.E., 1920:—

"Effect of Overstrain on Impact Figure of Steel."—Jones & Greaves.
"Notes on Single Blow Impact Test on Notched Bars."—Greaves & Moore.
"Shock Tests and their Standardisation."—Hadfield & Main.
"Characteristics of Notched Bar Impact Tests."—Stanton & Batson.

CHAPTER VI

THE MEASUREMENT OF HARDNESS

Hardness.—Before the various methods in practical use for measuring hardness can be discussed, it is necessary to define the meaning of this important property. Many attempts have been made to do this, but although every engineer has a very definite idea of what is meant when he uses the word "hardness," the exact meaning of the term is still in dispute. This is due to the fact that different engineers approach the subject from different points of view. In general terms, the property of hardness indicates the ability of a material to resist the continued action of a force for a long time, but as the nature of the forces and their direction of application vary considerably, different properties of the material are brought into play. It is probable, therefore, that hardness is not a simple property, but the combination of different properties in varying degrees, to produce certain well-known and recognised results.

The most usually accepted and best known definition of hardness, is "resistance to deformation," or "resistance to permanent deformation." This implies the existence of a deforming agent, which must itself have a standard or measurable hardness, to enable comparisons to be made.

The above definition corresponds to the yield point of the material, but not necessarily the *tensile* yield point. As the definition of hardness is frequently limited to "resistance to penetration," the latter principle is usually employed in measuring hardness. During a penetration test, the particles of the material tested are pressed closer together directly below the penetrating medium, so that the resistance of the material is assisted by a certain amount of "backing" that is not present in the tensile test.

Therefore, although the results of hardness tests are often proportional to the tensile yield point, this is not always the case, and the ratio of the hardness value to the tensile yield stress varies in different materials.

In ductile materials, the yield point is often roughly proportional to the breaking stress, and in brittle materials the yield and the breaking stress are practically identical, so that the ratio of the hardness value to the breaking stress, will be subject to a further variation with the ductility of the material that is being tested.

The engineer's definition of hardness, however, is frequently only indicative of "resistance to wear, or abrasion." This introduces a further variable. When a pure penetration test is employed, the material under the penetrating body becomes "work hardened," and so the resistance becomes greater as the depth of penetration increases. The effect of abrasion is to remove continually particles of material from the surface, so that the abrading body is constantly working on a fresh surface, and this increased resistance with depth of penetration does not exist to anything like the same extent. It is true that the rubbing and polishing of the surface creates a " skin hardness " that helps the wearing properties considerably, but the two properties thus measured are fundamentally different, and considerably complicate the conception and definition of hardness.

Professor Turner,* under the heading "Resistance to Wear," divides materials into two categories :—

1. *Hard* materials, in which the particles on the surface are not readily *displaced.*

2. *Plastic* materials, in which the particles on the surface are not readily *removed.*

For a good wearing metal, both of these properties are necessary. A purely hard material will disintegrate readily, although it offers a high resistance to pressure, and a purely plastic material will flow readily and provide a good running surface, but has not sufficient resisting power to support a normal force for any length of time.

The good wearing properties of Manganese Steel are due to a useful combination of these two properties, the steel itself being naturally resistant to pressure, and the particles displaced from its surface do not come away as a powder, but are plastically spread over its surface, and thus are capable of being repeatedly displaced before finally disappearing.

These two conceptions of hardness are those which interest engineers most, and the remainder of this chapter will therefore be devoted to the different methods in use for measuring these properties, and to the discussion of their relative usefulness and values.

Penetration Tests.—The methods of measuring hardness by penetration may be divided into two classes :—

1. Static tests, or slow penetration.
2. Dynamic tests, or rapid penetration.

When considering the influence of the time element in hardness testing, it must be remembered that all solids can be made to flow to a greater or less extent under pressure.

A hard body penetrates a soft body by causing the material of the latter to flow from beneath the former, so that when the penetrating body is withdrawn, an impression is left in the softer material. The depth of this impression is dependent upon the amount of flow that has taken place, and this in its turn varies with the intensity of the pressure between the two surfaces.

But the existence of flow necessarily involves the property of " viscosity." A freely flowing liquid such as water, takes much less time to change its form than does a thick or " viscous " liquid such as treacle. The same condition occurs in the case of solid bodies, and therefore the time allowed for flow to take place is an important factor in penetration tests.

Where plenty of time is allowed, as in the case of the Brinell test, the impression assumes its final form, but with a dynamic test, such as the scleroscope or impact hardness tests, the time of contact is so small that flow is not complete at the conclusion of the test.

The most important forms of static penetration test in general use are the Brinell or ball test and the Ludwik or cone test.

---

* " Hardness and Hardening," Institute of Metals, September, 1917.

Many kinds of dynamic tests have been devised, but the best known are the Shore scleroscope and the Impact Hardness machine, one form of which was recently described by Professor Edwards.* The latter has not been used to any extent in engineering practice, but is included on account of the amount of research which has been done with it, and because of the light thrown by that research upon the relation between dynamic and static test results.

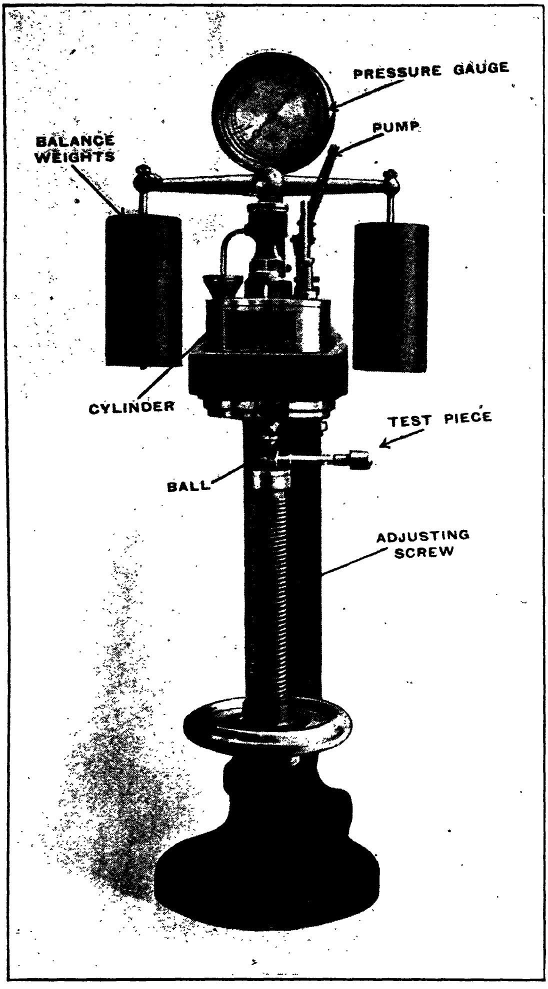


FIG. 59.—Brinell Hardness Testing Machine.

Brinell Hardness Test.—This was the first form of hardness test to meet with any practical success, and its success was due to the fact that the Brinell test first enabled figures to be given, which expressed with reasonable accuracy the comparative hardness of different materials.

The Brinell test is performed by pressing a hardened steel ball into the surface of the material under test, and measuring the diameter of the impression produced.

For this purpose it is convenient to fix a standard size of ball, and a standard pressure between the surfaces. The ball mostly employed is 10 mm. in diameter, and is the kind generally used in ball bearings, and the standard pressure adopted for iron and steel is 3,000 kg. In some cases the use of this pressure would distort the articles tested, so that occasionally pressures of 2,000, 1,500, or 1,000 kg. are used. For soft materials such as brass, or other alloys, 500 kg. is the customary pressure.

To ensure the completeness of the test, the pressure is kept on in the case of hard materials for 15 seconds and in the case of soft materials for 30 seconds.

The machine is illustrated in Fig. 59. The specimen is placed on the small platen, and is brought into contact with the ball by means of the screw and

---

* *Proc. Inst. Mech. E.*, May, 1918.

handwheel shown. The pressure is then applied by pumping oil into the cylinder at the top of the machine and thus forcing the plunger downwards. The ball is fixed in a screwed holder at the bottom of the plunger, and is pressed into the surface of the specimen.

A pressure gauge connected to the cylinder, indicates the load on the ball, but this is not sufficiently accurate to be used as a sole guide. A second plunger is held down by the cross-bar and weights shown, and when the pressure reaches the predetermined amount (say 3,000 kg.), the resistance of the weights is overcome, and the plunger rises. This, therefore, acts as a safety valve, and prevents overloading and consequent incorrect results.

If the pumping is too rapidly performed, however, the inertia of the plunger and weights may cause the pressure to rise momentarily above 3,000 kg., and so give a slightly larger impression. Care should be taken, therefore, not to raise the pressure with too great rapidity.

When the load has remained on the specimen for the specified time, the knurled nut at the top of the cylinder is rotated. This opens a release valve, which relieves the pressure in the cylinder, and allows a spring to pull the main plunger back to its starting position.

The platen upon which the specimen rests, has a spherical seat which enables a true test to be taken when the upper and lower surfaces of the specimen are not quite parallel.

The diameter of the impression made in the specimen is then measured by a microscope, with a scale graduated in millimetres, and the corresponding hardness number can be read off on a table provided with the machine. This microscope gives readings correct to $\frac{1}{25}$ millimetre, and its accuracy is quite sufficient for all practical purposes. A table of hardness numbers for the Brinell test is given in Table II.

The Application of the Brinell Test.—Although the Brinell test is a very simple one to apply, it presents several pitfalls for the unwary.

The standard times (15 seconds and 30 seconds), during which the load should be maintained on the specimen, are of serious importance when many tests have to be made, and a reduction of these periods is absolutely necessary in many cases, to enable a reasonable amount of work to be done in the day. The authors have made numerous experiments on several different classes of steel, hardened and unhardened, and have found that for periods ranging from 3 seconds to 60 seconds, there is no appreciable difference in the diameters of the various impressions. These measurements were taken with the ordinary microscope supplied with the machine, and so are quite accurate enough for all practical purposes.

A series of tests made at the Hadfield Research Laboratory showed practically no difference between the results obtained with a load applied and released quickly, and one sustained for 60 seconds.*

Mr. R. G. C. Batson,† at the National Physical Laboratory, made a similar series of experiments on Mild Steel with the following results :—

Time, seconds	2	3	5	15	60
Impression, mm.	5·45	5·48	5·49	5·50	5·50

Both these series of measurements were made with a microscope of much

---

* Discussion on "Hardness Tests," *Proc. Inst. Mech. E.*, October, 1918, p. 511.

† *Ibid*, November, 1918, p. 570.

greater accuracy than those usually employed, and it therefore follows that a period of 5 to 10 seconds is ample for work on steel.

A much greater source of inaccuracy is the speed of pumping up the pressure. If this be taken up very rapidly, the inertia of the plunger and weights causes a momentary rise in pressure above 3,000 kg. and consequently a larger impression.

Mr. G. Stanfield * has shown that the error due to careless pumping can be, and often is, very much in excess of anything due to an insufficient period of sustaining the load.

Another possible source of inaccuracy is the flattening of the ball itself. This is particularly serious in the case of hardened steel, where the hardness of the specimen approaches that of the ball. The distortion of the ball makes the Brinell test difficult to apply to materials whose hardness exceeds 600 Brinell, and above this hardness it is advisable to test by some other means.

Sir R. Hadfield † found that the permanent distortion of the balls varied from 0 to 0·0025 inch, but came to the conclusion that it was impossible to use the deformation of the balls as a measure of the hardness of the specimens, as the compression of the different balls varied more than the hardness of the test pieces.

The extension of the material round the edge of the Brinell impression also introduces a variable which may be important in the case of soft materials, as it creates a false edge of larger diameter than the true indentation. This may be avoided to a certain extent in accurate work, by measuring the depth of the impression, but this is also liable to error, as the radius of the impression is different to that of the ball, and varies in different materials.

Batson ‡ gives a series of results obtained on three steels, showing the difference between the radii of the ball and the impression for dynamic and static tests. The results were as follows :—

Steel.	Nature of Test.	Radius of Ball.	Radius of Impression.
Nickel Chrome	Dynamic	5·0 mm.	6·5 mm.
,,	Static	5·0 ,,	6·27 ,,
Manganese	Dynamic	5·0 ,,	5·57 ,,
,,	Static	5·0 ,,	5·69 ,,
Carbon (Rail)	Dynamic	5·0 ,,	5·15 ,,
,,	Static	5·0 ,,	5·37 ,,

In practical tests, Brinell impressions should not be taken upon case-hardened surfaces, particularly of gears or other parts that have to resist shock or vibration. Impressions taken in this way are invariably surrounded by a crack, and this forms the starting point for other cracks which spread over the surface and ultimately cause the case to flake off. Also such readings are not reliable owing to the crushing effect of the load on the soft core underneath.

Brinell tests are often taken to indicate the condition of the core in case-

---

* Discussion on "Hardness Tests," *Proc. Inst. Mech. E.*, October, 1918, p. 542.

† *Ibid.*, October, 1918, p. 586.

‡ *Ibid.*, November, 1918, p. 575.

hardened parts, and for this purpose it is necessary to grind the case away from a small patch in order to obtain a true reading. Care should be taken to get well below the case, as otherwise incorrect readings will be obtained.

Even when this precaution is taken, however, the results obtained are not always reliable.

A shaft $1\frac{1}{2}$ inches diameter, made of Mild Case Hardening Steel, was treated in this way, and it was found that though the Brinell impression at the surface was 3·5 mm. diameter, the shaft when turned down to $\frac{7}{8}$-inch diameter brinelled 4·4 mm.

Another shaft brinelling 3·7 mm. on the outside diameter, had a Brinell impression of 4·6 mm. when turned down to $\frac{1}{2}$ inch diameter.

This shows that on mild case-hardening steel the impressions taken near the surface are not always to be relied upon and are apt to cause work to be rejected unnecessarily.

A similar test made on an oil-hardening steel (Nickel Chrome) showed a difference of 0·1 mm. only between the outside and inside of a 2-inch bar. The presence of nickel or chromium in steel makes the carbon change very sluggish, so that comparatively heavy sections can be hardened right through.

The surface of the specimen that is to be tested by the Brinell method must always be as smooth as possible. The presence of tool marks, makes it almost impossible to read correctly the diameter of the impressions, and it is therefore necessary for these to be removed by filing or grinding. It is then advisable to finally smooth the surface with fine emery cloth.

The surface should also be as flat as possible. Any curvature causes the impressions to be elliptical, instead of round. Where this is inevitable, the mean of the maximum and minimum diameters may be taken for the purpose of obtaining the hardness number, but this is only an approximation, and should be avoided wherever possible.

Effect of Departure from Standard Test Conditions.—A special machine is made for applying the Brinell test under very heavy pressures, and is capable of applying loads up to 50,000 kg. In this case a ball 19 mm. ($\frac{3}{4}$ inch) diameter is used.

For soft metals, thin sheets, saw blades, etc., a small machine is made to apply loads up to 100 kgs. with a 2·5 mm. ball.

These departures from the standard size of ball (10 mm.), and standard pressure (3,000 kg.), make it necessary to calculate the Brinell hardness number instead of referring to a table for it. The method of obtaining the hardness number is as follows :—

P = Load on specimen in kilogrammes.
A = Area of spherical surface of indentation.
r = Radius of ball.
a = Radius of indentation.
H = Brinell hardness number.

Then $$H=\frac{P}{A}$$

and $$A=2\pi r(r-\sqrt{r^2-a^2})$$

Therefore $$H=\frac{P}{2\pi r(r-\sqrt{r^2-a^2})}$$

While this formula gives results that are generally sufficiently accurate for practical use, it must be pointed out that the Brinell hardness number varies with (*a*) the size of the ball used, and (*b*) the applied load.

These points are fully discussed in a paper by Mr. R. G. C. Batson,* and the following conclusions were arrived at :—

1. The true hardness number for any size of ball can be calculated from Moore's formula if two different impressions are made. As follows :—

$$\text{Moore's hardness number} = \frac{16\text{PD}^{n-2}}{\pi(2d)^n}$$

where n is a constant varying between 2 and 2·5 for different materials.

If P = First load in kg.,
d = Indentation obtained under load P,
P_1 = Second load,
d_1 = Second indentation,

Then,
$$n = \frac{\log \text{P}_1 - \log \text{P}}{\log d_1 - \log d}$$

To obtain the Brinell hardness number from Moore's hardness number, divide the latter by 1·0718.

$$\text{Then, Brinell hardness number} = \frac{1}{1{\cdot}0718} \times \frac{16\text{PD}^{n-2}}{\pi(2d)^n}$$

2. When the applied load is varied, the first part of the load-depth diagram is curved, so that the larger loads give higher hardness numbers than do impressions taken at low loads. Thus, to obtain correct indications under small loads, care must be taken that the load applied is situated on the straight part of the curve for that material.

It has been pointed out that the best and most accurate way of applying the Brinell test, is to measure the pressure required to produce a standard diameter of impression, but this is difficult to do with the present apparatus. The indications now in use are probably sufficiently accurate for all practical engineering purposes.

Ludwik Hardness Test.—The difficulties arising from the fact that the indentations in the standard Brinell test are geometrically dissimilar, may be avoided by adopting the Ludwik test. The same machine is used, but in this case a right-angled cone is substituted for the steel ball. The radius and depth of indentation are therefore equal, and a special plunger and mercury scale are attached to measure the indentation without a microscope and without removing the specimen from the machine.

Ludwik's hardness number is obtained by dividing the load by the conical area of indentation.

Thus, Hardness number = L,
Load = P,
Radius or depth of indentation = a,

Then
$$\text{L} = \frac{\text{P}}{\pi a\sqrt{2}}$$

---

* "The Value of the Indentation Method in the Determination of Hardness," *Proc. Inst. Mech. E.*, October, 1918.

The relation between the Brinell and Ludwik tests has been fully discussed by Professor Unwin * in his Thomas Hawkesley Lecture (1918) and to this the reader is referred for further information.

The Ludwik test, although probably the most rational of all static indentation tests, has never been adopted to any great extent in this country, and as the Brinell test became very widely adopted during the war, it is not likely to be displaced by the Ludwik test in the near future.

"Scleroscope" Test.—This is the best known and most widely used of all dynamic penetration tests. A small steel hammer, weighing $\frac{1}{12}$ oz. is allowed to fall freely from a height of 10 inches on to the smooth surface of the article to be tested. The hammer has a diamond striking point, the face of which is curved to a definite radius (see Fig. 60).

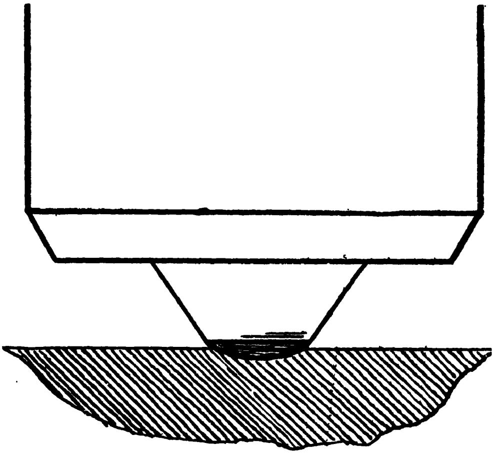


FIG. 60.—Magnified view of Hammer Point.

When the hammer falls on to a soft surface, it penetrates that surface to some extent before rebounding, and so produces a minute impression. In so doing, part of the energy of fall is absorbed, and the energy available for rebound is comparatively small.

If the hammer is dropped on a hard surface, the size of the impression is much smaller, so that less energy is absorbed in making it. The rebound of the hammer in this case is therefore much higher than before, and the height of the rebound is taken as a measure of the hardness of the material.

The instrument itself is shown in Fig. 61.

The hammer falls in a glass tube, the inside diameter of the tube being 0·002 to 0·003 inch larger than the maximum diameter of the hammer. This allows the hammer to fall freely without friction. The hammer is drawn up to the top of the tube by the suction from a rubber bulb connected to the instrument, and is held at the top of its travel, by two small steel hooks. When the bulb is again pressed, the hooks are caused to contract by means of a piston and cam mechanism, and the hammer falls freely on to the surface of the specimen, which is held in a clamp at the foot of the instrument.

The height of rebound after striking is noted, and the hammer drawn up again by pressing the bulb.

The scale is graduated into 140 divisions, a rebound of 100 being equivalent to the hardness of martensitic high carbon steel. Under these conditions, the area of contact between the hammer and the specimen is only about $\frac{1}{2500}$ square inch, and the pressure exerted is about 220 tons per square inch.

It will be seen from these figures, that, notwithstanding the lightness of

---

* "The Experimental Study of the Mechanical Properties of Materials," by W. Cawthorne Unwin, LL.D., F.R.S., *Proc. Inst. Mech. E.*, October, 1918.

the hammer and the smallness of the apparatus, the forces exerted in all cases are sufficient to overcome the resistance of the hardest materials used in engineering practice. The impressions produced are so minute that they do not seriously impair a running surface, and consequently, the scleroscope is very useful for testing finished surfaces.

Standard steel blocks giving readings of 100 and 40 degrees respectively, are provided with the instrument for checking its readings from time to time.

A magnifier hammer is also provided for use on soft materials. This has a larger point area than the universal hammer, and therefore gives higher readings, thus magnifying small but significant variations of hardness.

Charts are provided for resolving readings of the magnifier hammer into the standard degrees of the universal hammer.

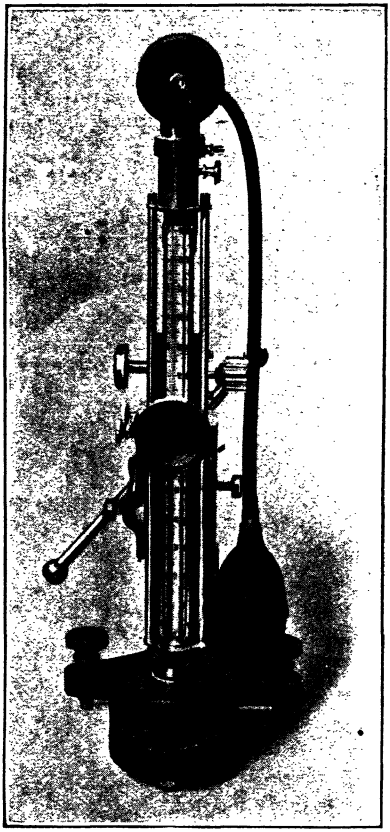


FIG. 61.—Shore Scleroscope.

Scleroscope Maintenance and Use.

The following are a few of the troubles that may be experienced with the scleroscope. In most cases the remedies are obvious.

Low Readings.—Dirt in bore of tube or on outside of hammer. Air cushion under hammer due to clogged vent holes. Glass tube too small or too large. Diamond split or loose. Instrument not vertical. Specimen not horizontal or level. Chip or dirt stuck to face of diamond.

High Readings.—Wear on diamond point.

Hammer does not Fall when Bulb is pressed.—Catch hooks too far apart, or too close together. Edges of hooks out of centre. Hooks not operating properly. Plunger in pneumatic cylinder not moving full stroke.

Hammer does not Catch on Hooks when sucked up.—Hooks too far apart or too close together. Spring tension not flexible enough. Suction too weak.

Hammer does not Rise to top of Tube.—Split or leaky bulb, tube, or air connections. Wet, or oil-soaked bulb.

Readings Erratic.—Bore of glass tube too large. Diamond loose.

Of the above, dirt or oil in the glass tube is the most prevalent trouble, and it is advisable to check the instrument frequently when in daily use, and to pass a piece of clean cotton-wool through the tube when the readings become low.

The results obtained by means of the scleroscope can be very misleading, unless proper precautions are taken, and the following points should be observed :—

(*a*) All tests must be made in different spots, and must be at least $\frac{1}{32}$ inch apart, more if possible.

(*b*) All test pieces should be mounted on a solid foundation wherever possible.

(*c*) A bench vice must always be used when the instrument is mounted on the swing arm.

(*d*) Small pieces should be mounted in a jig when a large number of similar articles are to be tested.

(*e*) Castings and other articles having large crystals or patchy surfaces, must be tested by taking a number of readings.

(*f*) The illumination on the hammer should always be inclined *downward* as the readings are taken at the *top* of the hammer.

(*g*) Rounded surfaces must be mounted truly below the centre of the hammer, otherwise it will strike a glancing blow and give low readings.

(*h*) The surface to be tested must be very smooth. Any tool or rough file marks cause the readings to be low. Dry grinding should be avoided as it tends to draw the temper.

(*k*) When balls are being tested, they must not be supported in a conical depression, but must have a support directly under the centre of the balls.

The makers claim that a mass of 1 lb. is necessary in the specimen and support to resist the shock of the hammer. They give the following figures for smaller masses :—

Mass of specimen.	Reduction in height of rebound.
½ lb.	½ to 2 per cent.
¼ lb.	2 „ 4 „
1 oz.	20 „ 40 „

Methods of clamping must be used to counteract the lack of inertia in the object tested—surface plate support is useless.

The scleroscope is a very useful instrument for testing the hardness of ground case-hardened surfaces (it is necessary for the case to be at least $\frac{1}{64}$ inch thick), but for this purpose it is advisable to take many tests over the surface, as a good deal of variation often exists in such instances. The good quality of the scleroscope is also its main defect—the area tested is so small that it does not give anything like an average value of the hardness of a surface, and the results obtained with it may be erroneous unless taken with care and discrimination. Standard scleroscope readings for various purposes are shown in Table III.

Relation between Penetration and Tensile Tests.—It has already been stated (p. 72) that there is an approximate relationship between the hardness of materials as obtained by the penetration test, and the tensile strength of the material.

This being so, the Brinell and scleroscope tests form convenient methods of estimating the tensile strength of machined or other parts, where it is impossible to cut out a test piece, or to ascertain the properties of the material in any other way.

Tables and formulæ for calculating the tensile strength of steel from the

Brinell or scleroscope readings are often given in books and pamphlets, and are blindly accepted by engineers who have not the necessary time or facilities for investigating their correctness for themselves.

In the first place, it must be emphasised that the ratio between the Brinell number and the breaking strength of steel is not a constant quantity.

Attempts are often made * to express this ratio in the form of formulæ connecting together the Brinell, scleroscope, and tensile strength values for different classes of steel.

The following is one of them :—

Low Chrome Nickel Steel:

$$\text{Tensile strength} = 0{\cdot}304\ B - 9{\cdot}8,$$
$$\text{where}\quad B = \text{Brinell number.}$$

On working out this formula with known test results, the actual tensile strength was often found to be 10 tons per square inch lower than that calculated from the equation.

Thus, formulæ of this kind should be used with extreme caution, particularly in the case of alloy steels.

The figures given for carbon steels are usually fairly reliable, but they cannot be applied to alloy steels, nor do they invariably give correct results.

The authors have found that the following factors may be applied with reasonable accuracy to steels :—

$T=$ tensile strength—tons per square inch.
$B=$ Brinell number.
For Carbon Steels $T=0{\cdot}24\ B$ to $0{\cdot}25\ B$.
For Nickel Chrome Steels $T=0{\cdot}22\ B$ to $0{\cdot}23\ B$.

Also, it should be remarked that there is no safe relation between the Brinell readings and tensile strengths of steel at the higher ranges (90 to 120 tons). Some steels with a Brinell impression of 2·9 mm. give a tensile strength of 100 tons, while others, very slightly different in composition give 110 to 115 tons for the same size of impression.

The reason for this is the tendency of the Brinell ball to flatten when a pressure of 3,000 kg. is applied to a specimen of about 500 Brinell hardness. A series of experiments made by A. F. Shore † showed that with material of over 500 Brinell hardness, the use of a new ball for each test gave hardnesses from 100 to 150 *lower* than when the same ball was used twice. With very hard materials, it was found that there was a marked tendency for the flattened ball to give the same diameter of impression irrespective of the varying hardness of the material.

By using a diamond sphere under a pressure of 750 kg., this tendency was eliminated, and a smooth curve connecting the scleroscope and Brinell readings was obtained.

This, of course, is not possible commercially, as the indentations thus obtained are very small and difficult to measure, and the first cost and loss of diamonds through breakage makes the method very costly.

---

* See paper read by Messrs. H. S. and J. S. Primrose before West of Scotland Iron and Steel Institute, February 15, 1918 (Table III.). Also Bullen's " Steel and its Heat Treatment," pp. 270, 327, 361, etc.

† Paper on " Hardness Testing," read before Iron and Steel Institute, September, 1918.

Subject to the foregoing remarks, the following table prepared by Sir Robert Hadfield in connection with the above paper, and giving average results for different classes of steel, may be found useful:—

COMPARISON OF BRINELL BALL AND SCLEROSCOPE HARDNESS NUMBERS WITH COMPRESSION STRENGTH, ALSO YIELD POINT AND TENACITY OF STEEL.

Prepared by Sir ROBERT HADFIELD.

This table represents the average of a large number of tests on all types of steel, and is intended as an approximate guide. Individual results vary considerably from the average.

Zones of Hardness F to A.	Approximate Scleroscope Hardness Number.	Brinell Ball Hardness Number.	Tensile Strength.				Compression on Specimens 0·564 in. diameter and 0·70 in. in height.		
			Yield-point.		Maximum Stress.		Elastic Limit and 0·25 per cent. Compression.		Compression per cent. (100 tons per sq. in.) (160 Kg. per sq. mm.).
			Tons per sq. in.	Kg. per sq. mm.	Tons per sq. in.	Kg. per sq. mm.	Tons per sq. in.	Kg. per sq. mm.	
F	—	150	20	31	36	57	17	27	49·0
	—	175	26	41	41	65	19	30	40·0
	34	200	32	50	46	72	21	32	35·0
E	38	225	38	60	51	80	23	36	31·0
	42	250	44	69	56	88	26	41	27·0
	46	275	50	79	61	96	30	47	23·0
	50	300	56	88	66	104	34	54	19·0
D	54	325	61	96	71	112	38	60	15·2
	57	350	67	105	76	120	43	68	11·3
	61	375	73	115	81	128	49	77	8·0
	64	400	79	124	86	135	55	87	5·6
C	68	425	84	132	91	143	61	96	3·8
	71	450	90	142	96	151	67	105	2·4
	75	475	96	151	101	159	74	116	1·3
	78	500	102	161	106	167	81	127	0·6
B	80	525	107	169	111	175	87	137	0·23
	84	550	113	178	116	183	94	148	0·21
	86	575	—	—	121	190	101	159	0·20
	89	600	—	—	126	198	108	170	0·18
A	92	625*	Not determined		131	206	115	181	0·16
	95	650			136	214	122	192	0·14
	99	675			141	222	129	203	0·13
	101	700			—	—	136	214	0·12
A2†	—	725	Not determined		Not determined.		144	227	0·11
	—	750					151	238	0·09
	—	785					159	250	0·08
	—	800					166	261	0·07

* Glass-scratching hardness commences here.

† Owing to want of data, but little is known about this extremely high zone of "superhardness."

From those figures the curves shown in Figs. 62 and 63 have been plotted. The ratios $\frac{\text{Tensile strength}}{\text{Brinell number}}$ and $\frac{\text{Tensile strength}}{\text{Scleroscope reading}}$ have been called " Brinell factor " and " Scleroscope factor " respectively.

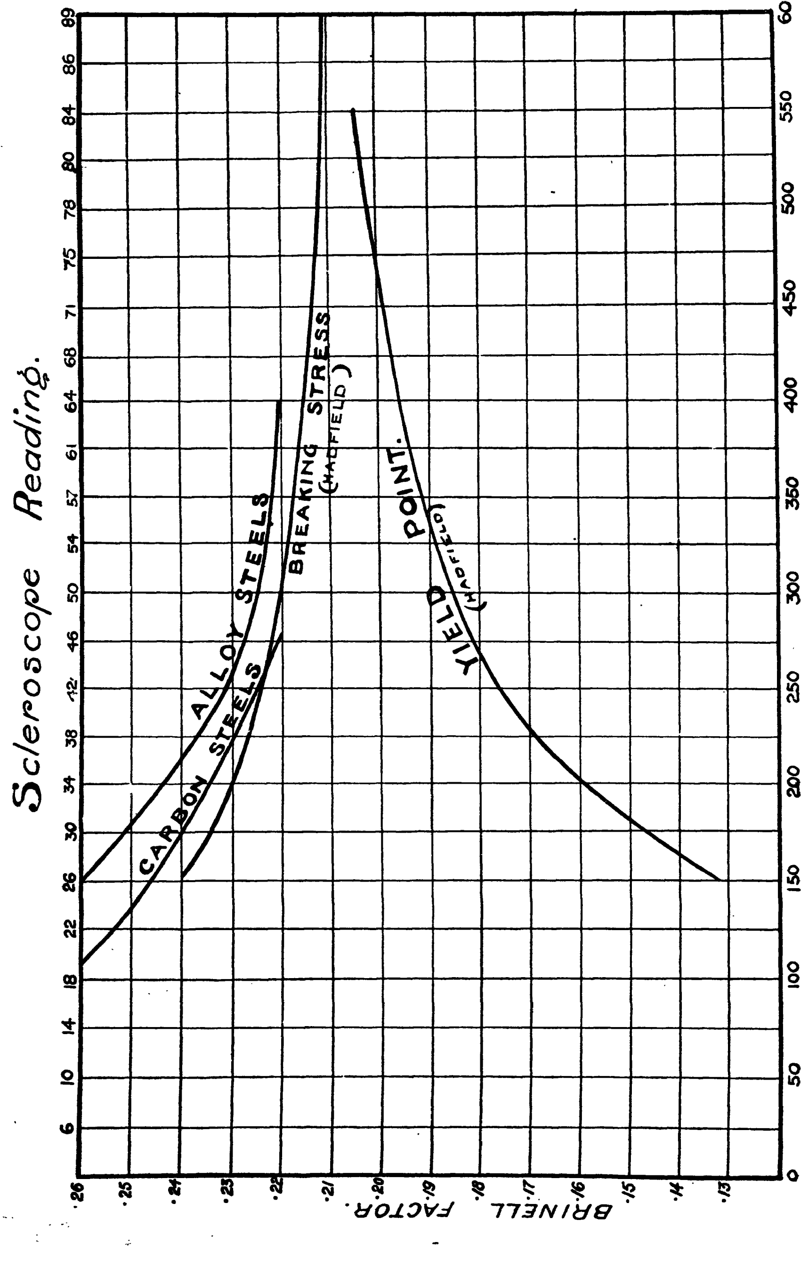


FIG. 62.—Curves showing Relation between Hardness Numbers and Tensile Strength. The upper curves for carbon and alloy steels represent the results obtained by the authors.

The following table gives the approximate relationship between Brinell numbers and tensile strengths for various kinds of material :—

Material.	Brinell Factor.		
Gun-metal	0·08 to 0·12	Average	0·099
Cast iron	0·05 to 0·06	,,	0·056
Steel Castings	0·15 to 0·25	,,	0·212
Phosphor Bronze	0·08 to 0·12	,,	0·096
Malleable Cast iron	0·14 to 0·19	,,	0·170
Aluminium (Castings)	0·07 to 0·12	,,	0·097

Approximate relationships between Brinell and scleroscope hardness numbers for other materials are as follows :—

Cast iron	B = 5·25 S.
Brass and Bronze	B = 5·25 S.
Aluminium	B = 5·0 S. to 6·0 S.
Tin (Cast and Annealed)	B = 2·1 S.

The tests made both by A. F. Shore and by J. J. Thomas show that the ratio between the Brinell and scleroscope readings is not constant, but varies with the different metals, and that considerable variation is found even in the same metal. This variation is greater in the scleroscope than in the Brinell tests, probably owing to the fact that the scleroscope measures the hardness of very small areas, and these areas vary in hardness even on the same metal.

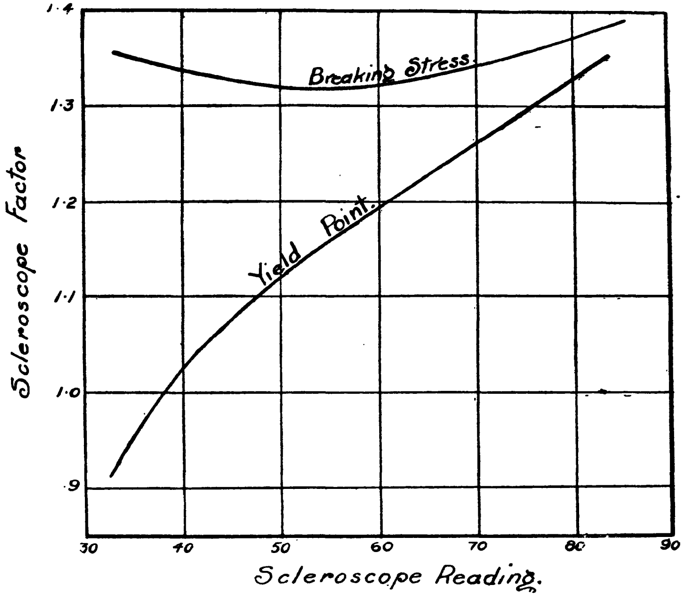


FIG. 63.—Curve showing Scleroscope Factors and Tensile Strengths for Steel (Hadfield).

The results shown in the accompanying curves have been checked by the authors, and the readings of over 350 tests in different kinds of steel are summarised in Figs 62 and 63. These figures were used in the preparation of Table II.

Other Dynamic Penetration Tests.—The readings of the scleroscope are measurements of the energy remaining in the hammer after the work on the specimen has been done. The work of Batson * shows that the volume of indentation produced by dropping a hardened steel ball or cone on to the surface to be tested, is proportional to the energy of the blow and is approximately independent of the form of the indenting tool. This confirms the findings of Lieut.-Colonel Martel in 1895 and 1900.

Advantage has been taken of this fact to produce many hardness testing machines and apparatus on these lines, but the experience obtained with such machines is not yet sufficient to enable any practical results to be given.

An elaborate series of experiments was made with one of these machines by *Professor C. A. Edwards, and the results were published in papers read before the Institute of Metals (1918) and Institution of Mechanical Engineers* (1918), *but these results have not yet been put to the test of practical application*, and therefore, at present they are of academic interest only.

It was found that the harder metals gave greater differences than the softer metals, between the static and dynamic hardness impressions, the latter giving impressions smaller in diameter than the former. The reason for this has already been explained on p. 73.

The results obtained by Professor Edwards and Mr. Willis may be summarised briefly as follows :—

1. The results obtained by a dynamic hardness test made with a 10 mm. steel ball rigidly fixed into a hammer, under known impact energy, may be converted into terms of Brinell hardness numbers.

2. The law governing the resistance to penetration of metals capable of plastic deformation, may be expressed by the equation :—

$$d = CE^{0 \cdot 25}$$

where d=diameter of indentation made by 10 mm. ball,
C=constant varying with hardness of metal,
E=total energy of impact.

3. The factor C should not be used to express the hardness of a metal, but to calculate the energy necessary to produce a standard impression.

The hardness is then expressed in terms of the energy required to produce that impression.

4. The impact test may be used satisfactorily for hard specimens.

5. The results obtained by estimating the rebound of a hammer falling from a fixed height are unreliable. A regular scale can only be expected where a standard penetration is obtained in all tests.

A practical application of the dynamic method is the "Auto Punch," made by Messrs. Rudge Whitworth, of Coventry. This is an automatic centre punch; the blow is applied by a compressed spring, the centre punch point being replaced by a ball $\frac{3}{16}$ inch diameter. The energy of the size generally used, is about 0·032 kg.-metre (0·232 ft.-lb.).

The results obtained by this handy little instrument were found by Batson

---

* "The Value of the Indentation Method in the Determination of Hardness," by R. G. C. Batson, *Proc. Inst. Mech. E.*, October, 1918.

to be approximately in agreement with the direct drop test. The indentation is small, and difficult to measure accurately, but the authors have found the instrument useful in case-hardened work, where the Brinell test was difficult to apply and the scleroscope unreliable. Table IV. gives the approximate Brinell numbers corresponding to auto punch impressions.

Other dynamic hardness-testing apparatus, such as the "Pellin" and "Boyelle Morin" apparatus, are occasionally used, but are of no great practical importance at present.*

Abrasion Tests.—The amount of wear taking place in running parts is occasionally so much more than might be expected from the results of a penetration test, that the only satisfactory guide in choosing a material for such parts is to make the parts in different materials and try them in the machine or engine itself. This "trial and error" method has the merit of conclusiveness, but it is not always possible to wait for such experiments to be made, and in the case of a new design, it is frequently impossible to make such experiments at all.

Therefore, it is necessary to have an abrasion test of some kind, the results of which can be relied upon to bear some approximate relationship to the practical running qualities of the material.

Mr. Saniter divides the frictional effects which produce wear into three classes :—

1. Dry rolling friction.
2. Pure abrasion.
3. Lubricated sliding friction.

The Report of the Hardness Test Research Committee † contains the results of tests made by rolling friction and sliding abrasion.

Tests with dry rolling friction were made on bars 1 inch diameter, which were rotated at 2,200 revolutions per minute, and supported a load of 410 lbs. This was applied through a ball race to a hardened steel bush, $1\frac{1}{2}$ inches diameter, the interior of which ($\frac{1}{4}$ inch long) was rolled into the surface of the bar. The wear was taken as the reduction in diameter of the bar in ten-thousandths of an inch, after 200,000 revolutions of the specimen.

$$\text{The resistance to wear} = \frac{1}{\text{wear}} \times 1000.$$

It was found that the resistance to rolling abrasion was roughly proportional to the Brinell hardness number of the specimens tested. The latter varied from 219 to 720.

It was also found that the Brinell number of the worn surface was the same as that on the unworn surface, but that the scleroscope readings were much higher on the worn surface than on the unworn parts.

A very important factor in abrasion tests is the presence of vibration

---

* The following papers may be consulted with advantage :—
"Use of Scleroscope on Light Sections of Metal."—Tritton, Inst. of Metals, 1921.
"Notes on Ball Test."—Baker and Russell, Iron and Steel Inst., 1920.
"A Small Ball Hardness Testing Machine."—Moore, Inst. Mech. Eng., 1921.
"Prism Hardness."—Haigh, Inst. Mech. Eng., 1920.
"Measurement of High Degrees of Hardness."—Innes, Inst. Mech. Eng., 1920.
"Hardness Testing."—H. S. and J. S. Primrose, Inst. Mech. Eng., 1920.

† *Proc. Inst. Mech. E.*, November, 1916.

This considerably increases the rate of wear, and makes an accurate alignment necessary between the driving medium and the specimen. Frequent renewal and calibration of the wearing ring is also advisable.

Many tests were also made with sliding friction, and here it was necessary to limit the amount of slip between the surfaces to $\frac{1}{4}$ inch per revolution, as if this was exceeded there was a tendency to seize. Abraded particles were removed by a strong air blast, and thus rise in temperature was prevented.

At a low pressure (100 lbs.) it was found that the wear was liable to be uneven, and that the specimen had a tendency to become elliptical. When the pressure was raised to 410 lbs., the wear was much more uniform.

No perceptible hardening of the surface was observed, *i.e.* the surface was not deformed during the test. Manganese steel, however, is an exception to this rule, as the surface hardening effect is very marked in this class of steel.

The resistance to abrasion was shown to be roughly proportional to the Brinell number in alloy steels, but not in the case of carbon steels. It was established that the Brinell hardness numbers of a miscellaneous selection of steels are not a safe guide in predicting their relative resistances to wear.

The wear which takes place in machine or engine parts is generally due to lubricated sliding or rolling friction, and in this case, the amount of wear will obviously depend upon the nature and quantity of the lubricant used, and the method of applying it to the working surfaces. If lubrication could be made perfect, the surfaces of the rotating or sliding bodies would never come into contact at all, but would always be separated by a thin film of lubricant.

In practice this is not so, and therefore the conditions obtained are a compromise between solid and fluid friction, inclining towards the one or the other as the lubrication is less or more perfect.

In this case, the relative speed of the two surfaces also has a very important effect upon the lubrication and wear, and this factor must always be taken into consideration in designing surfaces which move in contact with one another.

The curvature of the rolling surfaces is also a factor in the result. This is not usually expressed in design formulæ, but has a marked influence on the friction between the running surfaces.

" Scratch " Tests.—The abrasion test which appears to be the simplest, quickest, and most scientific to apply, is the " scratch " test.

The " Sclerometer," invented by Professor T. Turner, consists of a balanced arm, at the end of which a diamond point is fixed. This is weighted to a definite extent and is drawn across the polished surface of the specimen to be tested. The scratch thus produced is compared with a standard scratch on a surface of known hardness.

The weight necessary to produce this scratch is taken as a measure of the hardness of the material.

The difficulty of applying this method is that considerable skill is necessary to judge the standard scratch, and the readings are thus open to dispute. Further, the instrument is too delicate to be useful in the shops.

A variation of this test, used by the authors, wherein a standard weight was used and the width of scratch measured, failed to give sufficient delicacy in measurement. Also, a difficulty was experienced in getting diamonds cut to the same form of point, so that comparative readings on different machines were difficult to obtain.

A useful tool for testing ball and roller bearings is a rod of carbon steel, hardened, and ground off at right angles, the edge being used as a scraper. This does not give quantitative results, but is a good indicator of variations in extreme hardness.

Both the scratch test and the scleroscope fail to differentiate satisfactorily between *intrinsic* and *work* hardness. For a further discussion of this point see "The Effect of Cold Work on Metals and Alloys," by O. W. Ellis (*Metal Industry*, Dec. 5, 1919).

Machining Tests.—The hardness experienced by the machinist is again a somewhat different property to those measured above, but may be indicated to some extent by the Brinell test.

A more direct method of testing this property is by means of a drill test.

A standard drill is driven into the specimen at a constant speed and load. The penetration obtained for a given number of revolutions is a measure of the machining hardness of the material.

Table V. gives a rough indication of the machining hardnesses of different classes of steel. In this table, the machining properties of 25-ton carbon steel are taken as 100, and those of the other steels are expressed as a percentage of this.*

Hardness of Brass.—A series of tests on brass containing 66 per cent. copper and 34 per cent. zinc, was made at the Sheffield Scientific School of Yale University,† to ascertain the relationship between the Ultimate Strength, Brinell, and Scleroscope Hardness Numbers of that material.

It was found that the curve between the scleroscope numbers and ultimate tensile strength was parabolic for brass, and that the relation also held for the Brinell numbers obtained at 500, 1,000, and 3,000 kg. and the ultimate strength.

The curve between the Brinell and scleroscope numbers for brass was found to follow (approximately) a straight line law.

The 3,000 kg. load made very large depressions which were liable to show on the other side of the specimen.

Loads of 500 kg. gave small depressions which were not always circular, but loads of 1,000 kg. were satisfactory for all specimens of brass over 0·2 inch in thickness.

The figures obtained will be found in Table VI.

---

* Such tables should be used with caution as there is no direct connection between Brinell and machining hardness, the indentation test being merely a rough guide. However, in spite of the approximate connection the Brinell hardness is an extremely useful guide to the machinist. See "The General Properties of Stampings and Chill Castings in Brass," by O. W. Ellis, Inst. of Metals, No. 1, 1917.

† "Hardness Tests for Brass," by W. K. Shepard, *American Machinist*.

CHAPTER VII

CHEMICAL COMPOSITION AND MICROSTRUCTURE OF MATERIALS

THE influences which the constituents of a certain material have upon its properties are of considerable importance, and a clear realisation of the extent of such influences will enable the engineer to select his materials with a fuller knowledge as to their behaviour under the conditions imposed in practice.

The compositions of the various materials used in engineering work are given in their respective chapters, and reference should be made to these chapters. Mention is also made in some instances of the effect of varying the proportions of the constituents, but in this and the two succeeding chapters the influence of each element in a material will be stated as far as is possible to do so.

Commercial materials are very seldom pure, and their composition may always be divided into two main groups as follows :—

1. The main constituent or constituents.
2. The impurities.

In most cases the properties of the main constituent or constituents are well known, but when impurities exist these properties are sometimes considerably modified, but with some materials, however, the extent of such modifications is, unfortunately, a matter of conjecture, although in the case of steel, research has removed most of the doubtful points at issue.

The metallurgical operation whereby the materials are obtained from their ores usually governs the percentage of the impurities found, and in consequence a metal obtained by one process is freer from a certain impurity than when obtained by another process. The same also applies to the source from which the ores or other raw materials are obtained. Thus mild steels are classified as "acid" and "basic" steels because of the difference in the metallurgical operations by which they are produced.

Although a material may consist of the two groups of constituents mentioned above, *i.e.* the main constituent and the impurities, it does not follow that these remain in the presence of each other in their natural state. On the contrary it is usual to find them in a more or less complex state which renders it difficult to form a clear judgment as to their relative behaviour. The following diagram is intended to convey an impression as to the possible states in which the main constituents and the impurities may exist. In the case of steel it will be shown later how the carbon in it exists as a chemical compound (iron carbide) which can form a solid solution (austenite) and yet at other times an eutectoid (pearlite), while in the case of cast iron it will exist as carbon alone (graphite). The same possibilities apply in different degrees to all other materials both as regards the main constituents and the impurities.

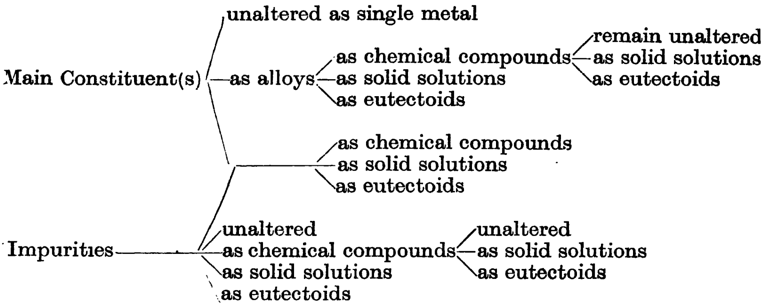


Diagram showing some Possible States in which the Main Constituents of a Material and the Contained Impurities may exist.

This diagram reveals an important fact regarding the composition of materials, and that is the possibility of the constituents assuming various physical, as well as chemical, combinations, such as " solid solutions " and eutectoids or eutectic mixtures. These physical arrangements cannot of course be discovered by ordinary chemical analysis since this only gives the final or ultimate composition: *e.g.* the analysis of steel will give the proportion of carbon it contains but will not show in what form it actually exists. Thus chemical analysis often supplies information of little or of no value. At the same time, however, the ultimate composition of a material is the only one that can be specified in actual practice, since from a practical and commercial point of view our work is mainly that of reproducing a given material and therefore whatever physical forms its constituents may assume, it is fundamentally important that the chemical composition should be the same. Starting with the same proportion of constituents each time it then becomes a physical process of some kind to obtain the properties required in the final material.

Fortunately the microscope enables a good deal of information to be obtained as to the physical arrangements, etc., of the constituents and thus supplies that which ordinary chemical analysis cannot definitely show.

The Micro-Structure of Materials

The microscope as a means for the examination of material is of immense value to engineers and, even in the smallest concern, should form part of the equipment for the inspection of materials. The information afforded by the intelligent study of a piece of metal under a high magnification is not only related to the chemical composition but is valuable in so far that the actual arrangement and disposition of the constituents are revealed, and this in great measure determines the mechanical properties of the material.

While chemical analysis gives the ultimate composition of the material it does not give any clue to the proximate composition and thus in many cases is not very helpful, whereas the proximate composition as analysed by the microscope will enable a better judgment to be formed as to the value of the material for the purpose in hand. This is very pronounced in the case of steel, for though chemical analysis may show that it contains, say 0·45 per cent. of carbon, the microscope will not only show this with fair accuracy, but will give additional information as to the *form* in which the carbon exists, *i.e.* whether pearlite, martensite, or other state, and, knowing the properties of these various forms, the properties of the steel can be judged; the presence of pearlite indicating a fairly soft and ductile material while martensite would indicate hardness and low ductility.

To the engineer it is a method for analysing materials without the necessity of mastering the slow and somewhat complicated methods of chemical analysis and by reason of its simplicity and somewhat mechanical manipulation it appeals to him.

In works practice the microscope has two definite uses: (1) to watch for certain characteristic defects in materials required for important and vital parts, and (2) to investigate causes of failure in heat treatment and the reason for the breakdown of parts while in use. Other uses will be found in connection with works practice such as the cause of machining difficulties, leakage under pressure and many more.

A number of examples where this method has shown up the cause of failure, or defects which might lead to failure, are given in Chapter IX. These represent such common faults as those due to slag and oxide inclusions in rolled bar, segregation, etc., also high forging temperatures and chemical defects due to impurities such as sulphur and phosphorus. Then in the case of castings defects such as crystallisation and segregation—porosity and other faults due to incorrect pouring temperatures are given.

It has a further important commercial use in the examination of castings, for where chemical analyses are part of the routine examination and are, by reason of their number, comparatively inexpensive, the necessity for tensile or other mechanical tests is eliminated since the microscope will reveal the structure of the material, and this in turn will enable a fair estimate to be made of such physical properties. The real importance of this lies in the fact that no elaborate arrangements need be made for casting test pieces on the actual casting (sometimes very difficult if not impossible) and no special operation for cutting off such test pieces is required.

The constituents forming the material, their arrangement or grouping, and relative dimensions can be studied in most cases and, with a knowledge of the properties that result from such combinations or groupings of the constituents, valuable comparisons can be made between *known* materials and the actual castings or other parts which, by reason of their expensive character, cannot be cut up for more elaborate tests. It is comparatively easy to remove a small piece (say ¼ inch cube) from some portion of a large casting and to examine this with a microscope.

In the study of the effects of heat treatment and for research on materials this method of examination is invaluable, and therefore, before proceeding to the chapters dealing with the constitution of materials and that on heat treatment, it will be helpful if the method and the nomenclature connected with it are understood, because reference will be made to the structure of most of the materials dealt with in this book.

Microscope and its Accessories.—The selection of a microscope and its accessories depends to some extent on whether photographic records are to be obtained. Much has been written regarding this, and the reader is referred to the many books which deal so ably with this portion of the subject. Only the principal requirements will be dealt with here, and these are as follows :—

1. Microscope with mechanical stage permitting movements in both directions across the field of view and also coarse focussing adjustment.

2. Three objectives (ordinary achromatic objectives will do) having focal lengths of 4 mm. (⅙ inch), 16 mm. (⅔ inch), and 32 mm. (1⅓ inches), giving initial magnifications (at 250 mm., the distance of distinct vision of the eye) of 43, 10, and 4 diameters.

3. Two eyepieces or oculars of magnification 5 and 10 diameters.

4. A vertical illuminator, either the prism type or the transparent reflector type, preferably the latter.

5. A source of illumination—the quality of which must be arranged to suit photography if records are to be taken. For ordinary visual work a metallic filament lamp is quite suitable, used with a condenser to concentrate the light on to the illuminator. For photographic work an arc light is without doubt the best.

This apparatus is shown in Fig. 64.

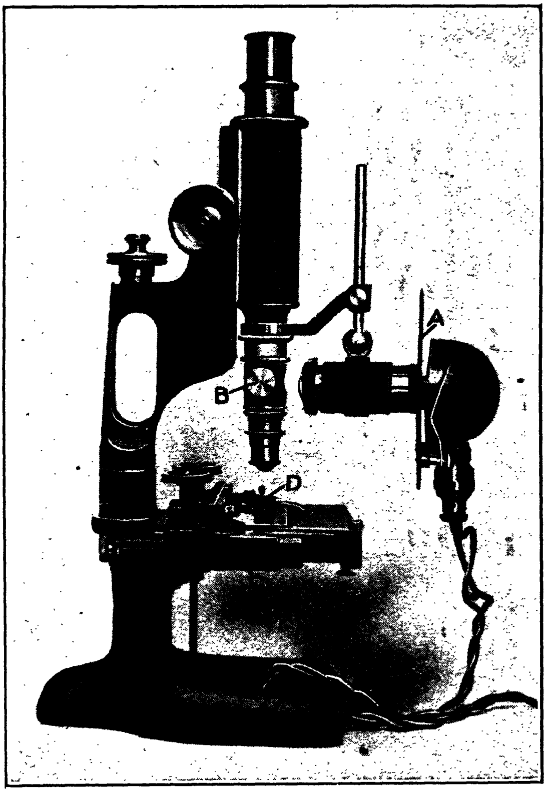


Fig. 64.—Microscope with Tassin illuminating apparatus (A); vertical illuminator (B); mechanical stage (C); carrying specimen (D).

Preparation of Specimens.—In general the specimens are easily prepared and, with suitable arrangements, very little time is required. The operations are :—

1. Cutting the rough specimen out of the piece to be examined.
2. Machining, filing or grinding a flat surface ready for polishing.
3. Polishing the flat surface.
4. Etching the polished surface.

The first operation, although not often described in works dealing with this subject, is given because it is usually one that requires careful attention. When the material is in the soft state the piece can be cut out with a saw or, when in a difficult position, a series of holes drilled round it will enable it to be removed—in other cases it may be necessary to put the work in the hands of a good machine man and leave him to cut it out. Hardened material will have to be cut with a grinding wheel unless it can be broken—a risky operation so far as the specimen is concerned.

In all cases, however, precautions must be taken to prevent heating the specimen and so altering its structural characteristics. Also the surface to be examined should not be torn or strained by the cutting off and so give an untrue " tale of affairs " to the observer.

It is essential to note in what position the specimen lay in the original piece and to decide which section should be studied. The view obtained from the cross section of a drawn or rolled bar may be very different to that obtained from a lengthwise section in which the direction of flow is shown. Similarly in the case of castings the position of the specimen relative to the centre or to the outer surface should be noted on account of the difference in the cooling rates between the centre and the outside of the casting. The examination of a piece taken from a thin web may lead to most erroneous conclusions as to the state of the main casting, unless such a fact is known and stated.

When parts are being handled in large numbers advantage should be taken of any that have been scrapped through machining faults, and a careful comparison made between the vital portions and those portions which are accessible for specimens.

The second operation should be given the same attention and the surface produced should be the result of careful light cuts and slow grinding.

The polishing of the flat surface is accomplished by various grades of emery paper, each one finer than the last, and then by finishing on polishing pads using such abrasives as jeweller's rouge, diamantine powder, or some of the artificially made powders such as P.P.P. powder.* Of course, the degree of hardness of the specimen and its composition must be taken into account, but a little experience will soon guide the operator in this matter. The quality of the polish can be judged by examination under the microscope and the process stopped as soon as a satisfactory surface is obtained. Commercially there is not the same need to obtain surfaces entirely free from scratches as in careful research work, or work for reproduction or publication ; still at the same time it must be borne in mind that such scratches may lead to a wrong conclusion on some occasions, and they are best out of the way.

The last operation is that of etching or attacking the polished surface with some chemical reagent which tends to corrode or re-act with some of the constituents of the material without acting upon or only slightly acting upon others, thus differentiating their appearance.

In some cases there is no need to etch the specimen because the constituents already appear different, *e.g.* cast iron when polished shows the graphite areas quite distinctly. Also when some constituents are harder than others they stand in relief to the softer material and are easily distinguished under oblique lighting by the shadows cast round them.

Etching Reagents †:—

Steel and Iron.—*Nitric Acid* solution, consisting of 10 per cent. of pure strong acid and 90 per cent. of absolute alcohol.

---

* Supplied by the County Chemical Co., Ltd., Birmingham.

† These are the more common ones ; many workers favour other reagents.

Picric Acid solution, consisting of 5 grams of acid dissolved in 95 c.c. absolute alcohol.

Sodium Picrate solution, consisting of 2 grams picric acid dissolved in a solution containing 24·5 grams of caustic soda dissolved in 73·5 c.c. water.

Stead's Cupric Reagent, consisting of cupric chloride 10 grams, magnesium chloride 40 grams, hydrochloric acid 20 c.c., alcohol to make to 1000 c.c. Salts to be dissolved in hot water to saturation and then alcohol added.

Copper and Copper Alloys, such as Brass, Bronze, etc.—*Ammonium Persulphate* solution, consisting of 10 per cent. pure ammonium persulphate in 90 per cent. water.

Lead, Tin, Antimony Alloys, White Metals, Anti-Friction Alloys.—*Strong Hydrochloric Acid.*

Aluminium and its Alloys.—*Hydrochloric Acid* solution, consisting of 10 per cent. pure acid and 90 per cent. water. *Caustic soda* or *Potash* solution.

The above etching liquids should not be applied until the specimen is free from grease or oil. The general procedure is to wash the specimens in ether or alcohol and then to immerse them in the desired etching liquid. This should then be followed by washing in alcohol and drying rapidly (by air blast preferably). Other methods and other ways of employing these reagents are in use, and some of these are dealt with below.

For steel and iron the most successful etching reagent is picric acid. This leaves a slight deposit which will require removing by very gently rubbing the surface on a clean smooth piece of chamois leather stretched on a flat board.

To give an idea of the use of such a reagent the following remarks concerning its performance will be of interest :—

Pearlitic Steel.—Thirty seconds' immersion should show good contrast between ferrite (and cementite) areas and the dark areas of pearlite. If there is much ferrite the grains should appear like a delicate and distinct network. This will not appear if the etching time is insufficient.

Sorbitic Steel.—This constituent etches more rapidly than pearlitic steel and 15 seconds' immersion will probably suffice. The structure will be granular and ill-defined.

Troostitic Steel.—This constituent etches more quickly than any other constituent, 5 seconds being sufficient time for immersion. A better control can be obtained by using a weaker solution, say 2 per cent. If martensite is present this short etching will not reveal it except as white patches.

Martensitic Steel.—Ten seconds' immersion will generally bring this constituent out although a high magnification (300 diams.) may be required to resolve it. Any troostite which may be present will be intensely coloured—more so than any other constituent.

With alloy steels the etching is generally much slower, and various modifications in treatment become necessary. Nitric acid acts more quickly and is preferred by some instead of picric acid, but whichever solution is used it should be adopted for general use so that all examinations may be comparable.

The sodium picrate solution is used to detect cementite and should be used boiling, 5 to 10 minutes' immersion being required. The cementite will show up brown or blackish.

Stead's Cupric Reagent is useful for showing up phosphorus areas or segregation. It is applied as a thin layer on the surface and left there for one minute and then shaken off, a second layer being placed on it. The process is repeated as often as may be found necessary, after which the specimen is washed in boiling water and then with alcohol, and dried in an air blast. Copper is deposited first on those areas which are most free from phosphorus, and as each application is made the copper coating spreads until the whole surface is covered, the last remaining patches being those richest in phosphorus.

Heat Tinting.—This consists in heating the specimens until the surface becomes coloured with oxide films. It is particularly useful in showing up phosphides in steel, iron and in phosphor bronze. It also helps to differentiate between the manganese and iron sulphide found in iron and steel.

To obtain the best results with this method the specimen should be etched to a very slight extent (only) with picric acid, and then be placed on an iron plate or on the surface of a bath of molten solder and heated.

Those portions rich in phosphorus oxidise before the purer portions and pass through a range of tints: yellow, brown, red, and purple. The purer portions also pass through these tints, but by the time they reach the yellow or brown stages the phosphorus-rich portions will have become red or purple. Further heating will cause the phosphorus-rich portions to take up a yellowish-white tint at about the time the purer portions have a blue tint. The amount of phosphorus present controls the rate at which the tints appear.

Grain or Flow of Metal.—Etching is often resorted to in determining the direction of the grain or flow in materials, especially steel. With ordinary etching reagents, the flow in a steel stamping or forging can often be distinguished with a low-power magnifying glass. The part to be examined should be sectioned or cut to expose the required plane, and this should be polished up so as to produce a surface of fair quality—not necessarily as good as for ordinary micro-examination. This surface after cleaning should be treated with a copper solution such as Stead's, and then be attacked with a dilute solution of nitric acid. By this means a very deep form of etching takes place, and the fibres or grain of the steel show up quite distinctly to the unaided eye.

Crystallisation

Growth of Crystals.—When a substance changes from the liquid to the solid state crystallisation generally takes place, the molecules tending to arrange themselves so as to form definite geometric forms such as cubes. These separate formations are crystals, and the material that behaves in this manner is said to be crystalline.

Those materials which do not crystallise are called amorphous substances, glass being a good example.

Crystals are found to split easily in one or more directions, generally parallel to one or more of the faces. This is usually referred to as "cleavage," and the directions in which it easily takes place are called the planes of cleavage.

When a metal cools from the liquid to the solid state the mass begins to solidify at several points each being the centre for the growth of a crystal. As the crystal grows it comes into close proximity with other crystals also growing, with the result that its correct external form is prevented from developing and only an irregularly shaped mass is formed. This will be understood more clearly by referring to Fig. 65,* which shows diagrammatically the growth of several crystals.

The final arrangement is a mass of distorted shapes, each of which represents a separate crystal and has all the properties of a crystal. Since, however, they are not perfectly shaped it is usual to call them " crystal grains," or more simply " grains," and thus they are differentiated from true crystals.

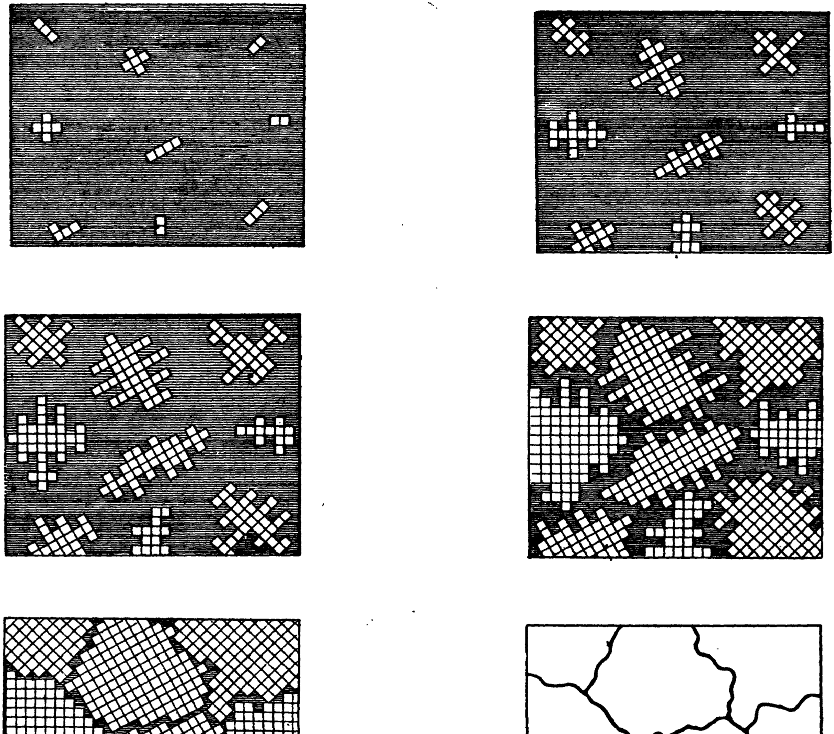


Fig. 65.—Diagram demonstrating Crystal Growth during cooling from the Liquid State into the Solid State. Note that the separate crystal grains start at several points, eventually meeting to form irregular areas or " grains."

At the boundaries of the crystal grains there are left minute spaces which, it is assumed by some, are filled by amorphous metal.

The number and size of the grains will depend on the number of centres at which crystallisation commences, and hence upon the rate of cooling and also

---

* This manner of showing crystalline growth is due to Rosenhain.

upon the purity of the material. The slower the cooling and the purer the metal the larger will be the grains.

Since the growth of the grains proceeds in all directions (until arrested) and in all planes it will be seen clearly that when a polished flat surface is prepared the natural planes of the crystal grains cut through, will be at various angles to the polished plane. This is easily proved by etching the polished surface, when the different grains will be quite distinguishable, some appearing bright while others are semi-dark and others very dark. The bright grains are so placed that their natural planes are normal to the vertical light and reflect it into the microscope while the dark grains have their natural plane at such an angle that the reflected light passes away from the microscope and, therefore, is not seen. Other grains differently oriented reflect more or less light into the microscope and appear more or less bright. This characteristic structure is shown by Fig. 66.

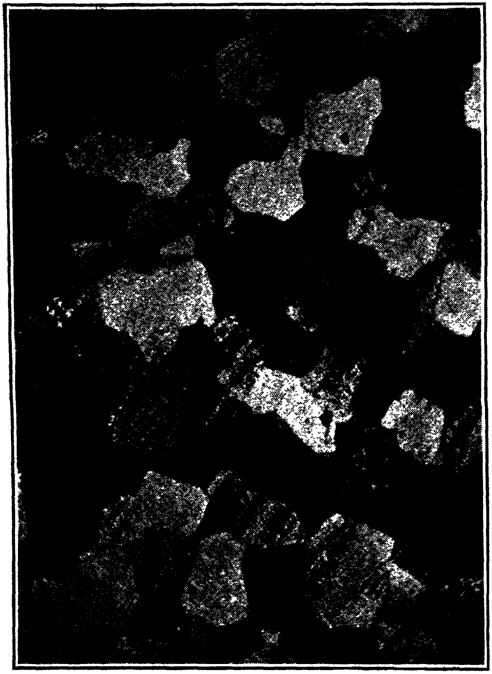


Fig. 66.—Micrograph of Special Brass showing Grain Formations and the different Orientation of the Grains. Magnification 50 diameters; etched with ferric chloride.

Boundaries of the Crystal Grains.—The nature of the material forming the boundaries of the grains has been the subject of much discussion and various theories have been put forward. From a practical point of view, however, and considering metals and alloys of the usual commercial standard of purity it may be taken for granted that as a general rule with fairly pure materials the boundaries are stronger than the crystal grains themselves, and that when rupture of a metal takes place it is generally due to the slipping or even splitting of grains along their cleavage planes, and not along the boundaries as might at first be expected.

The presence of impurities sometimes has a considerable bearing on the nature of the boundaries owing to the tendency of the material when crystallising to throw out certain foreign matters which eventually become trapped between adjacent grains and thus form part of the boundary. Such impurities will in some cases affect the quality of the material by reducing its ductility, weldability, electrical conductivity, etc., and often increase its hardness and fusibility.

Solid Solutions.—A solid solution is one in which the essential characteristics of a liquid solution are retained even after solidification. The addition of a metal or metalloid to another may result in either of the following :—(1) it may combine with some of the main metal in definite proportion forming a chemical compound, (2) it may remain uncombined. Either or both of these may then be soluble in the main metal and when solid remain in solution forming a solid solution. On the other hand either one or the other or both may be insoluble and will, therefore, be rejected by the crystal grains forming, in most cases, an "eutectic" alloy.

Metals which dissolve in each other forming solid solutions will do so in varying proportions, and the resulting solid will be so homogeneous that it is impossible to detect the presence of either, even under the highest powers of the microscope. Their identity is completely lost in the solution.

Eutectic Alloys.—This important arrangement of the constituents in a solid mass of alloy or impure metal may be defined as that alloy in a series of alloys having the lowest transformation or melting point. It is a mechanical mixture and as such is easily distinguishable under the microscope. The formation of the eutectic mixture takes place as follows : When a molten mixture of two metals, "A" and "B," is allowed to cool, a temperature is reached at which "A" will commence to separate out as a solid (*i.e.* freeze). The loss of this particular metal will make the remaining liquid richer in "B," and this increase in richness will continue as the temperature falls, more and more of the metal "A" separating out. At a certain temperature, and when the metals "A" and "B" are in certain definite proportions, the remaining liquid will freeze as a whole, although not in the form of an indistinguishable mass. The portion that freezes last is the Eutectic alloy and is usually recognised by its laminated appearance, *i.e.* by the fact that it consists of thin plates or laminæ of one metal interleaved with thin plates of the other metal. This proceeding takes place when the proportions of the metals have reached a definite ratio, and always at a definite temperature, which is the lowest freezing-point of any mixture of the two metals. This structure is shown in Fig. 97.

This also applies to compounds and solid solutions and is not confined to pure metals alone.

Eutectoids.—In some instances a similar proceeding takes place in solid solutions, but with the constituents in less definite proportions, although the final structure is much the same. The mixture is then referred to as an eutectoid to distinguish it from those really definite mixtures called eutectics that separate out from a liquid. The mixture of iron carbide and iron in steel is an eutectoid, and the laminated structure formed by these is generally referred to as pearlite. An example of this is shown in the micrograph of Cast Iron, Fig. 82.

Impurities.—The impurities found in commercial metals and alloys can be divided into two classes ; those that form solid solutions with the actual material, and those that form eutectic alloys. The former class do not influence the character or the structure appreciably except in so far that the grain size may be altered considerably.

The latter class, however, exert a very marked influence on the structure as they are usually rejected to the grain boundaries, taking with them a little of the main material and forming an eutectic alloy. Thus actual films or membranes surround each crystal grain, and are easily detected under the microscope. These membranes naturally affect the properties of the material, often reducing the ductility, etc.

Effect of Temperature.—The constituents forming the different crystal grains and their boundaries, in a material, may have different coefficients of expansion, with the result that changes in temperature such as cooling after casting will tend to cause a partial separation between one grain and another. This would account for the porosity of some materials such as gunmetal, which appear perfectly sound and without blowholes, yet are porous to liquids like water and paraffin.

This expansion and contraction of the different constituents in castings has a tendency to open out the material and to form planes of weakness.

The effect of temperature on the constituents themselves, is a different subject, and is dealt with in connection with the actual materials in later chapters.

Cold Working.—Iron, steel, copper, brass and many more materials are cold rolled or drawn into bar form for machining into bars, bolts, screws, nuts, and other parts, and it is not uncommon to find that such parts fail for some reason which is very much akin to brittleness.

The effect of working metals in the cold state, therefore, should be understood. Beilby's theory is that during the deformation of a metal the various sections of the individual grains slip along their gliding or cleavage planes, and by doing so, generate amorphous metal at these planes. Further, it is believed that amorphous metal already existing at the grain boundaries is *increased in amount* as the result of such plastic formation.

Thus, when the elastic limit of a metal is exceeded, and plastic deformation begins to act, slipping takes place along the cleavage planes of the individual crystals, resulting in a relatively high temperature localised at these slipping planes. At the temperature so produced the slipping generates amorphous metal, and this acts in the manner of a lubricant to promote slip.

The metal at the moment of slipping appears to be very mobile but does not remain so for long, passing into the hard amorphous state, which is stronger, harder, and more brittle than the crystalline. Thus, those portions where amorphous metal has been generated, are stronger than other portions where no slip has occurred, and with further deformation the metal is amorphised more and therefore becomes stronger.

It is not possible to completely amorphise a ductile metal by work; for it has been shown by Beilby in the case of wire drawing that the grains, even though enormously elongated, retain a crystalline core encased in an amorphous shell.

With bar material such as bright drawn steel the cold working or deformation effects are greatest in the outer layers, the centre being less amorphous than the outside. Thus, the outer layers are generally harder, and more brittle than the interior, and since the outer portion in the case of studs or tie bars, usually carries the thread it is evident that the stripping or breakdown of such studs or tie bars is a common possibility. In small-section bars the difference between the centre and the outer layers is not much, the bar being comparatively brittle right through, but with large sections it is quite pronounced, the centre of the bar probably giving good test results (on Izod impact) while the outer layers are poor.

Secondary Crystallisation.—It is important not to confuse the "secondary crystallisation" phenomenon that takes place when an alloy in cooling changes from a state of solid solution to one in which the constituents separate out, with the phenomenon that occurs during solidification from the molten state. This latter phenomenon may be referred to as "primary crystallisation" and is quite distinct from that which occurs with the solid solution.

With iron-carbon alloys such as steel this secondary crystallisation is of considerable importance, and because of this it is explained fully in Chapter VIII and again in Chapter X.

The effects of cold working on the grains of a metal or alloy, their distortion and ultimate recrystallisation during annealing, are factors which, until recently, have not been fully understood and even now the information available is rather meagre. One point, however, should be made clear at this stage, and that is the possibility of developing a coarse-grained structure through annealing (after cold working) at an unsuitable temperature even though this temperature may be below that at which the alloy passes into a state of solid solution. In other words, there is a state of affairs in which grain growth proceeds at a rapid pace and at quite low temperatures. The degree of distortion due to cold working influences this exaggerated grain growth which takes place during subsequent annealing, and for this reason the latter operation must be adjusted to suit the conditions produced by the cold working.

Apart from rolling and drawing operations, which in most cases only concern the manufacturer of the raw materials, there are operations which the engineer has to consider, such as pressing, both hot and cold, and it is in connection with these that the annealing process may require serious consideration. This question is dealt with in Chapter VIII under the heading of Cold Working.

CHAPTER VIII

MICRO-STRUCTURE AND COMPOSITION OF STEEL

Micro-constituents

ALTHOUGH steel is a carbon-iron alloy, its examination under the microscope does not reveal carbon as carbon. In this respect it differs entirely from ordinary grey cast iron, which if polished and examined (without etching) will show flakes of graphite (or carbon) quite distinctly (see Fig. 67). A piece of steel under the same conditions will, with vertical illumination, appear structureless, no sign of carbon being present.

FIG. 67.—Micrograph of Cast Iron, polished only, showing presence of Graphite Flakes. Magnification 150 diameters.

If the specimen is etched with picric acid, however, dark areas will be seen, the proportion and size of these depending on the carbon content and also on the heat treatment to which the steel has been previously subjected.

The nature of the dark areas will be found to vary considerably even in the same steel, if it is heat treated in different ways. The amount of carbon in the steel will also be found to influence the character of these areas to some extent.

From this it is evident that the dark areas either contain the carbon in some form or other or are influenced by it. As a matter of fact, the carbon is wholly contained in them and the white areas are simply pure iron.

Thus it would appear that the carbon is absorbed by or is in combination with the iron, and that the resultant mixture or compound is capable of assuming different forms or appearing as constituents having totally different appearances. This is the case, and it is now known that steels may contain any of the following constituents which, although a little in advance of this stage, are given together with some particulars of their properties and appearance and also their occurrence.

Austenite.—A solid solution of carbon in iron, or more probably of carbide of iron (Fe_3C) in iron, resulting from the solidification of the steel and existing only (in carbon steels) at high temperatures above what is known as the transformation point. It is very seldom found in ordinary carbon steels but appears in some of the alloy steels when suitably heat treated. Its appearance in hardened high carbon steel is as a ground mass pierced by zigzag needles and lances of martensite.

It is hard but not as hard as cementite, which is the hardest constituent found in steel.

Cementite.—This is a chemical compound of iron and carbon (Fe_3C) which remains in solution in the iron at high temperatures (above the transformation point) forming austentite, but which separates out at lower temperatures, and is found in the form of very thin plates or laminæ intermixed with similar laminæ of iron, forming what is known as "pearlite," and in the case of high carbon steels containing more than 0·9 per cent. carbon exists as a network surrounding the crystal grains, or as needle-shaped crystals running in the cleavage planes of the grains themselves.

It is also found in the form of irregular-shaped spheres and is then known as "spheroidal" cementite.

This is the hardest constituent found in steel, but its tensile strength is exceedingly low, being about 2 to 3 tons per square inch.

Ferrite.—Nearly pure iron, containing perhaps a little phosphorus and silicon but extremely little carbon. At high temperatures above the transformation range it forms part of the solid solution austentite, but on slowly cooling it separates out at the same time as cementite.

It is found in annealed or normal steels of low carbon content (0·2 per cent.) in the form of irregular-shaped masses (white in colour) intermixed with the dark "carbon areas."

It also forms part of the constituent "pearlite," taking the form of very thin plates or laminæ which are alternately arranged with similar laminæ of cementite. In medium carbon steels (0·4 to 0·5 per cent.) it usually forms a coarse network surrounding the dark "carbon areas."

It is a soft constituent having a tensile strength of about 18 to 20 tons per square inch, but is very ductile and gives an elongation figure of about 40 per cent. on 2 inches.

Pearlite.—A mechanical mixture of about six parts of ferrite to one part of cementite. It is an eutectoid mixture and is formed when austentite cools down to a certain transformation point at which cementite and ferrite are thrown out of solution in the proportions given above. It exists in slowly cooled steel in the form of very thin, clearly defined plates or laminæ of cementite and ferrite alternately arranged. The laminæ are parallel and do not intersect. It usually requires a high magnification to resolve it into its laminæ, 300 diameters being about the least at which the structure is distinguished.

Pearlite contains approximately 0·9 per cent. carbon and 99·1 per cent. iron.

It is a tough constituent having a tensile strength of about 55 tons per square inch and gives an elongation of about 10 per cent. on 2 inches.

Martensite.—This is a transitional constituent obtained during the change from austenite into its components cementite and ferrite. It occurs early in the change and in consequence is usually only found in steel which has been rapidly cooled (*i.e.* hardened).

It is distinguished by its plate or needle formation, these intersecting each other as though they ran parallel to the sides of an equilateral triangle. It is also found as small crystallites which are not often arranged in triangular order and which sometimes are so fine that they appear to be amorphous.

It is a very hard and brittle constituent, giving tool steel the hardness which results when it is " quenched " in water from a temperature above the critical range.

Troostite.—This is the second transitional constituent in the change from austenite to pearlite. It appears to follow martensite in order.

It occurs in steel which has been cooled at an intermediate rate or in hardened steel which has been reheated to just below 400° C. It then appears as irregular, fine, granular areas of indistinct form, which are much darker than the other constituents. It is usually associated with martensite.

Troostite is harder than pearlite but softer than martensite. It is not so ductile as pearlite.

Sorbite.—There is a third transitional constituent in the change from austenite to pearlite, following troostite in order. It appears to be simply a form of aggregation of the pearlite and ferrite areas, and is not a change of the same character as those mentioned above.

It occurs in steel which has been cooled moderately fast or in hardened steel which has been reheated to about 450° C. It then appears as ill-defined areas, almost amorphous in character and lighter in colour than troostite. It is tougher than pearlite although not quite so ductile, and has a very important bearing on the properties of low and medium carbon steels.

Cooling and Heating of Steel

When a piece of steel is allowed to cool slowly from a high temperature (about 1,100° C.) various changes occur and the different constituents mentioned above appear at different phases. By increasing the rate of cooling, making it very rapid, some of the constituents which generally exist only at high temperatures are retained in the cold steel and give it some of the properties which they themselves possess.

A low carbon steel upon solidification becomes the solid solution austenite and remains as such during cooling until at a definite temperature, depending on the carbon content (and to a lesser extent on other foreign elements), a complete transformation takes place and austenite ceases to exist, the iron carbide being thrown out of solution forming cementite while the free iron is recognised as ferrite. These two constituents, however, do not exist as separate areas or masses in the steel; instead the cementite will take up a definite amount of iron (or ferrite), about 6 parts to 1 of cementite, and form the constituent known as pearlite, which will collect in areas intermixed with the grains of the remaining ferrite.

This change, however (from austenite to pearlite and ferrite), does not take place in a single transition; there are several phases producing constituents which differ in their properties very considerably. The most important of these phases are (1) the formation of martensite, which is very hard, followed by (2) a change from martensite into troostite, a softer constituent, and then (3) a change of a different character but of considerable practical importance from troostite into sorbite.

As will be explained later, these changes during cooling are not sharply defined and do not occur suddenly, for, as might be expected, there are intermediate stages where two or even three phases appear to overlap and their respective constituents are present at one and the same time.

Critical Ranges.—In most commercial work the steel which has to be heat treated may be considered to be in a normal state and the various properties that have to be conferred upon it are obtained by heating it and then fixing it in the desired condition by rapid cooling or otherwise. It is therefore essential that the changes which occur during heating should be known and well understood, because they form the basis of this important subject.

These changes occur or commence at temperatures known as "Critical points" or "Critical ranges" and are denoted by the letter A followed by the small letter *c* ("chauffage," French for "heating"), or when obtained during cooling by the letter *r* ("refroidissement," or "cooling"). The first change that takes place is numbered 1, the others 2 and 3. Thus the first critical range passed during heating is denoted by *Ac*1, the next *Ac*2, and so on.

Associated with these changes there are certain physical manifestations such as the emission or absorption of heat, loss of magnetic properties, and sudden changes in the electrical resistance. Thus the study of one or more of these properties during the heating and cooling of a piece of iron or steel, will reveal when these changes occur and also their extent.

The most usual method for ascertaining the position of these change points consists simply of recording the temperature, at regular intervals of time, of the iron or steel under examination while it is being gradually and uniformly heated, and also while it is cooling under natural conditions. The measurements, when plotted as a graph with time as abscissa, form curves which are referred to as "decalescence curves" or "recalescence curves" according to whether they represent the changes during heating or cooling respectively.

Recalescence Curves.—It is not proposed to enter into a discussion of the various methods by which these curves are obtained, but for most steels the following simple method will give satisfactory results. A thermo-electric couple consisting of two wires, one of platinum and the other of an alloy such as platinum-rhodium, is inserted into a hole in the specimen of steel which is heated gradually and at an even rate in a small gas-fired or electrically-heated muffle furnace (preferably the latter). The thermo-couple should be connected to a sensitive indicator, millivoltmeter or galvanometer which has already been calibrated for the range of temperature worked. Readings of the temperature of the steel sample are then taken at intervals of a minute or half a minute (or more often in the region of the critical range temperatures), and a graph is drawn up for the heating curve. The furnace is then allowed to cool and a corresponding curve is obtained showing the cooling of the steel.

Self-recording instruments are useful for critical range determinations, but are limited to the medium carbon and high carbon steels, and to some of the alloy steels, because as a rule they are not sensitive enough to record the change points of low carbon steels. A useful and reliable type of pyrometer having a very open scale is the resistance pyrometer working in conjunction with Callendar's Electric Recorder.* This type is accurate and is easily checked and, for commercial purposes, is very serviceable.

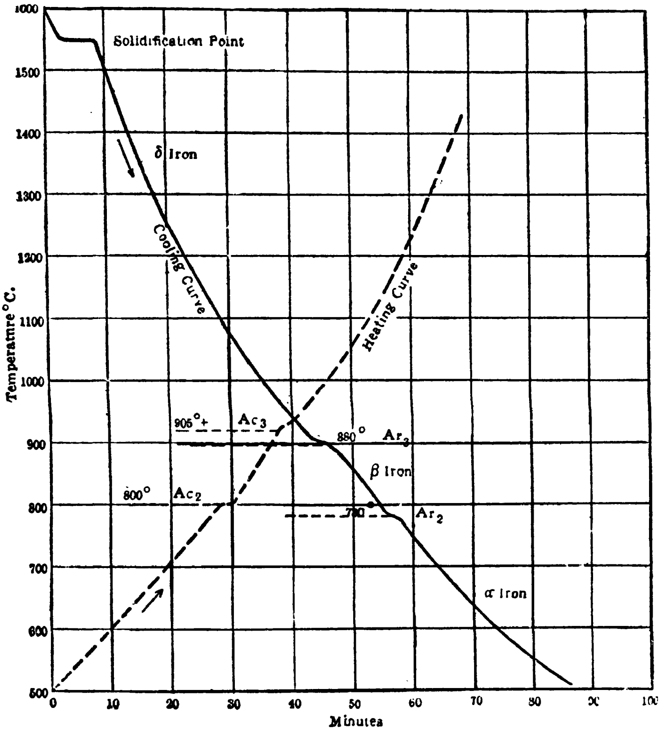


Fig. 68.—Time-Temperature Curves. Heating and cooling of Pure Iron (Goerens).

The curves obtained by the above procedure will be found to be discontinuous or broken by kinks, and it is these breaks that give the information desired. The curve Fig. 68 shows the heating and cooling of pure iron. From this it will be seen that at certain temperatures in the heating curve two breaks occur which, if studied, indicate that actual heat absorption has taken place and the rise in temperature has been arrested in consequence. During the cooling, similar breaks occur which indicate that heat has been evolved preventing the specimen cooling at the same rate as that immediately preceding this break.

---

* Made by the Cambridge and Paul Instrument Co., Limited.

Change Points in Pure Iron.—For practical purposes it may be stated that these breaks in the heating and cooling correspond to actual changes in the iron, and it is generally accepted now that these changes are of an allotropic nature, which accounts for the heat disturbances that take place, a phenomenon usually associated with allotropic changes.

The curve Fig. 68 therefore shows that pure iron undergoes two changes during heating and exists in three allotropic states which are usually denoted as the "Alpha," "Beta," and "Gamma" states. In the normal state, iron exists as Alpha iron, but on heating it passes into Beta iron, and then eventually into Gamma iron, each change being accompanied by an absorption of heat. Similarly during cooling the Gamma iron passes back into Beta iron and thence into Alpha iron, the changes being in the reverse direction and giving rise therefore to an emission of heat.

These changes during cooling are known as "recalescence" points and those during heating as "decalescence" points. They also correspond to the points known as the Ac2, Ac3, A*r*2, and A*r*3 explained below.

Change Points in Steel.—The addition of carbon to the iron to form steel brings in another change point, which occurs somewhere in the region of 725° C. in commercial steels, and it is this point that corresponds to the change from pearlite into austenite, *i.e.* when the constituents cementite and ferrite go into solution and which, like other solids, absorb heat in the process (latent heat of fusion).

Thus in a low carbon steel there are three critical change points, which, during heating, are referred to as the Ac1 due to the change into the solid solution austenite, the Ac2 due to an allotropic change of the Alpha iron itself into Beta iron, and then the Ac3 point due to another allotropic change from Beta iron into Gamma iron. These are decalescence points. During cooling the same changes take place, but in the reverse order and direction and, owing to the emission of heat, are recalescence points.

It is important to note that the changes do not occur at the same temperatures on both heating and cooling curves, but that the recalescence points (cooling) are always lower than the decalescence points (heating). This is due to an effect similar to hysteresis, but this need not be discussed here having little practical bearing on the subject.* With alloy steels this effect is increased and therefore becomes important.

It should be clearly understood, however, that steel must be heated to above the decalescence point to effect the change required. It is quite a common error, having determined the recalescence points of a steel (*i.e.* the cooling curve), to work entirely to these points without reference to the decalescence points, which may be much higher and which must be reached before the change can take place.

Now the comparison of recalescence curves for steel of different carbon contents will show that a low carbon steel (0·2 per cent.) has three change points, but when the carbon is increased only two such points are found on

---

* This statement, of course, does not apply to the high carbon steels such as tool steel, but such steels do not come under consideration in this book. With tool steels it is advisable, after heating to above the critical range (Ac1), to quench at a temperature below this but above the A*r*1 point. Such a proceeding is not a commercial one and in most cases is quite unnecessary with the ordinary classes of steel used in constructional work.

the recalescence curve. As the carbon content increases, the upper point gradually falls until at about 0·85 carbon there is only one point observed. A series of recalescence curves * for steels of different carbon content are given (see Fig. 69).

These curves have been obtained by another method based on the different rate of cooling between the steel specimen and a neutral body, both in the same furnace. The results, which were obtained by Carpenter and Keeling, have been replotted by Rosenhain according to his derived differential method.

It is evident that the amount of carbon in the steel is a most important factor and that it influences the position, and number, of the change points in a manner that requires careful attention. The connection between the carbon content in the steel and the position of the critical ranges, has been the subject of much research and, as a result, equilibrium diagrams, of which Fig. 70 is a portion, have been developed.

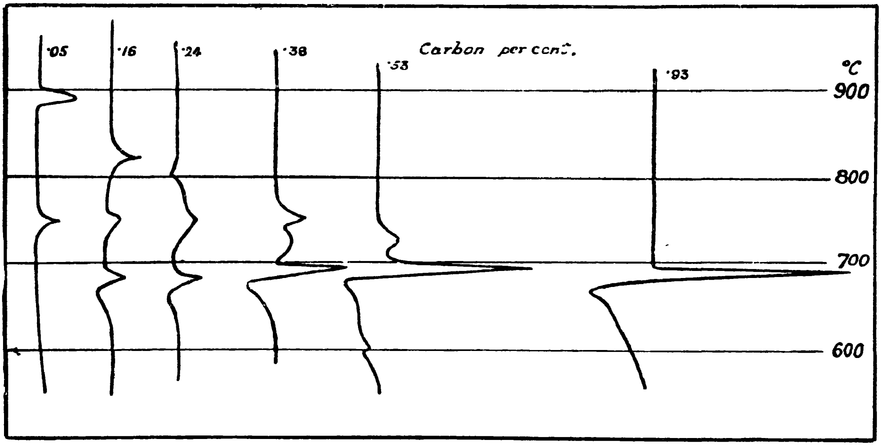


FIG. 69.—Cooling Curves for different Carbon Steels showing Change Points. This series of curves shows how the critical range diagram Fig. 70 is obtained.

For practical convenience the diagram Fig. 70 shows the approximate temperatures at which the changes take place *during the heating* of the steel. This is important, because in most heat treatment processes it is necessary to heat the steel to temperature above the upper critical range (Ac3) before cooling.

Cooling of Steel.—Reference has been made to the fact that steel when cooling from the liquid state freezes as a solid solution known as austenite, which consists of carbon (or iron carbide) dissolved in iron. This iron is in the " Gamma " state.

Consider now the effect of cooling a piece of mild steel having a carbon content of 0·2 per cent., from a temperature above the upper critical range Ar3.

The diagram Fig. 71 will now be referred to, in conjunction with the critical

---

* Plotted from data of Carpenter and Keeling (Rosenhain).

range diagram Fig. 70, to explain further the nature of the changes during cooling.

No change takes place in the austenite (except diffusion and crystallisation phenomena) until the *Ar*3 point is reached and then ferrite (iron) is set free in an amount, gradually increasing as the temperature falls. This continues until the temperature corresponds to the *Ar*1 point (see both diagrams), when the remaining austenite (solid solution) freezes and, in doing so, behaves as an eutectoid: the iron carbide (cementite) separating from the iron, but forming with it the constituent known as pearlite. This new constituent is recognised by its regular and laminated structure, which consists of thin plates or laminæ of iron carbide and iron alternately arranged. Further cooling produces no other changes of a radical character although, as will be explained later, there are several phases before the pearlite assumes its final structure as described.

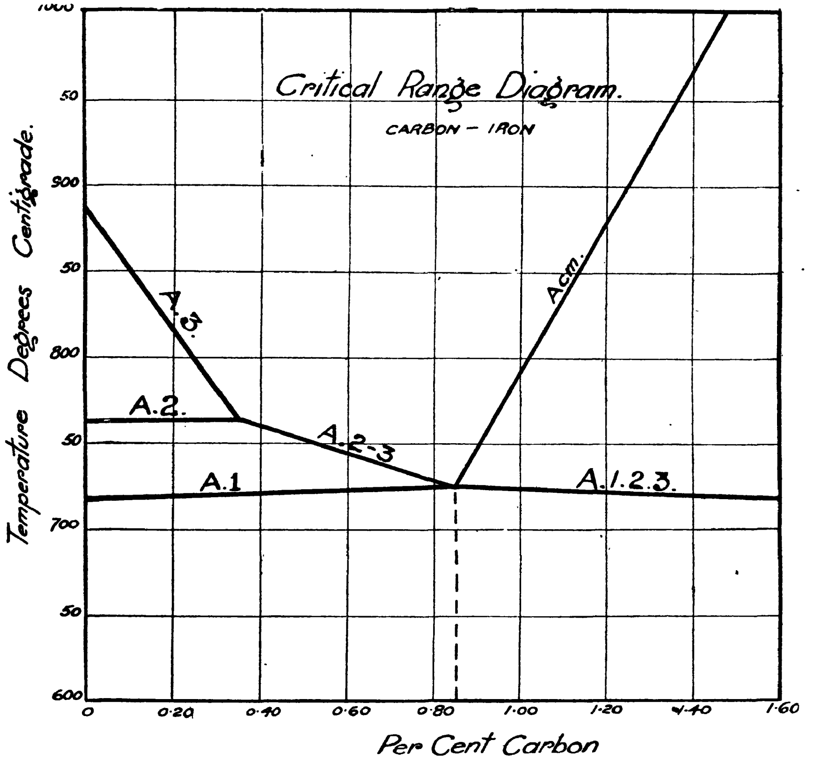


FIG. 70.—Critical Range Diagram. Carbon steels, showing relation of critical change points *during heating* and the carbon content of the steel.

During the cooling from the *Ar*3 point to the *Ar*1 point the iron, which has been set free from the solid solution as free ferrite, also undergoes certain changes, which have been described under "Change Points in Pure Iron" (see also Fig. 68). At the *Ar*3 point and just below it the iron, which was in the Gamma state in solution, is set free as Beta iron and remains as such until the Ar2 is reached, when it changes into Alpha iron. Below the Ar2 point the iron as it is set free changes presumably from the Gamma condition into the Beta and then immediately into the Alpha state and remains as such down to normal temperatures. The Ar2 point is not shown in Fig. 71, which is drawn simply to show the setting free of the ferrite from the solid solution as it cools down to its freezing point (Ar1). The diagram Fig. 70, however, shows the position of this point but *during heating* and not during cooling.

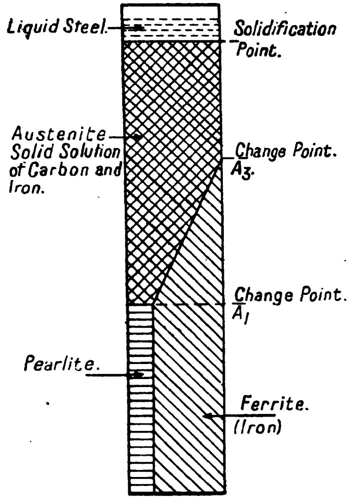


Fig. 71.—Diagram showing effect of cooling Steel of about 0·2 per cent. Carbon. The change from austenite into pearlite is shown, together with the gradual separation of the free ferrite.

Relation between Carbon and the Critical Ranges.—So far only mild steel of low carbon content has been considered, and the effect of increasing the carbon must now be considered.

Since the carbon combines with the iron to form iron carbide (cementite) it is evident that as the percentage of carbon increases so the amount of cementite will increase. Further, as the cementite takes up a definite proportion of iron to form pearlite it is clear that the proportion of the latter will increase also. Thus the micro-examination of an annealed steel will reveal approximately the amount of carbon it contains because this is proportionate to the amount of pearlite present.

Now, if steels of different carbon contents are examined (while in the annealed or normal state, see Figs. 72 to 76), it will be found when the percentage of carbon is between 0·8 and 0·9 per cent. that the dark areas corresponding to pearlite completely occupy the whole mass of the steel, or in other words, the steel is composed of pearlite only, no ferrite or other constituent

Fig. 72.—Steel containing 0·15 per cent. Carbon. Magnification 150 diameters.

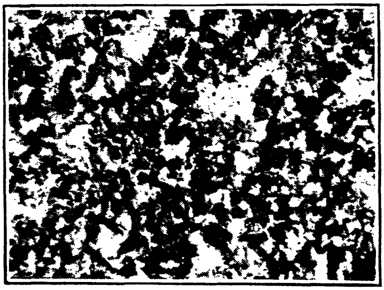


Fig. 73.—Steel containing 0·40 per cent. Carbon. Magnification 150 diameters.

being present. Any further increase in the carbon simply results in the formation of "free cementite" because there is no more ferrite for it to take up to form pearlite. This free cementite is seen in Fig. 76 forming the boundaries of the crystal grains and also as needles in the grains themselves.

Now pearlite is an eutectoid mixture, *i.e.* one that has the lowest transformation point, and is therefore, when in the form of austenite at the *Ar*1 point, a saturated solution.* That this must be so is clearly shown by the fact that any excess of iron in a weak solution is thrown out as ferrite, and any excess of iron carbide in a strong solution is thrown out as free cementite. Thus a steel which is wholly pearlitic (containing no free ferrite or free cementite) is often referred to as a "saturated" steel.

The exact percentage of carbon required to produce a eutectoid steel cannot be stated with accuracy, nor is it necessary from a practical standpoint seeing that steels are never pure but contain manganese and other elements which tend to disturb the proportions of the eutectoid mixture. Some authorities assume the percentage of carbon in pearlite to be 0·9 per cent. while others take a lower value such as 0·83 per cent. Probably the best figure is 0·85 per cent., and without going further into the discussion of this point, this figure has been adopted as the basis for the curve Fig. 70, showing the relation between the carbon content of a steel and the critical points or ranges.

Referring to this curve it will be seen at once that the temperature at which the different changes take place is dependent on the carbon content. Further, it will be noted when the carbon content reaches

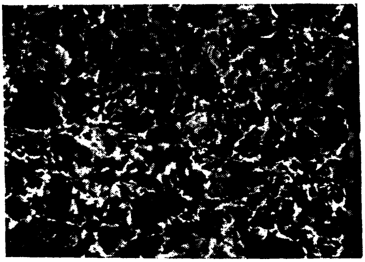


Fig. 74.—Steel containing 0·50 per cent. Carbon. Magnification 150 diameters.

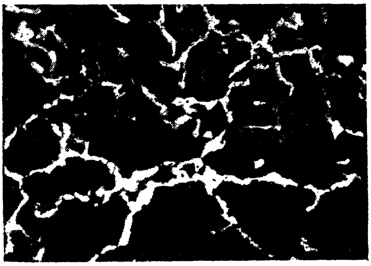


Fig. 75.—Steel containing 0·70 per cent. Carbon. Magnification 150 diameters.

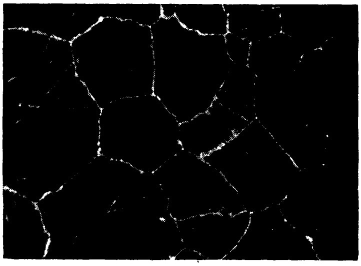


Fig. 76.—Steel containing 1·20 per cent. Carbon. Magnification 150 diameters.

---

* The use of the expressions "saturated" "unsaturated," and "supersaturated," should be avoided as they are misleading. Really all steels are saturated at some temperature or other, but in the case of a steel of Eutectoid composition the saturation temperature is at the A1 point. Above this point the steel clearly is undersaturated. These expressions, however, have been made use of in so many text-books, and have been found so convenient to describe the behaviour of the solid solution, that it is difficult to eliminate them completely in such a contracted account as this of the changes in steel.

about 0·35 per cent. that the *Ac*2 and the *Ac*3 points occur together at the same temperature, about 765° C.

Again, at the saturation point 0·85 per cent. carbon, all three changes occur at once at the temperature of 725° C. Continuing, therefore, with the study of the cooling effects in steel but taking into account different percentages of carbon, a steel containing approximately 0·35 per cent. of carbon will now be considered. In this instance a much lower temperature (about 750° C.) than in the case of the 0·2 per cent. carbon steel is reached before the iron commences to separate from the solid solution austenite, and further, this iron assumes the Alpha condition, passing, no doubt, very quickly through the Beta state in the change. Thus it would appear that the two changes (*Ar*3 and *Ar*2) that take place separately in the lower carbon steels, occur simultaneously in the 0·35 per cent. carbon steel.

Further cooling produces, as in the case of "0·20 steel" the setting free of the iron until at the *Ar*1 point the solid solution freezes and pearlite is formed. In this steel, therefore, and in others containing more than 0·35 per cent., and less than 0·85 per cent. of carbon, there are only two change points: the upper one being designated the *Ar*2–3 point, and the lower one the *Ar*1 point.

If the cooling of a steel containing 0·85 per cent. of carbon is considered it will be realised that, as this corresponds to the saturation percentage, no iron will be set free as ferrite and the whole mass of the steel which is now an eutectoid mixture will freeze at the same temperature, which is approximately 700° C. This is shown in the critical range diagram Fig. 70 (on heating) at about 725° C. This point is referred to as the *Ar*1–2–3 point because it is believed that the iron, which forms part of the constituent pearlite, does pass through the Beta phase in the change from the Gamma to the Alpha condition, but that the changes are so rapid as to appear as one single change. Thus when the steel reaches the *Ar*1–2–3 point it is converted completely into pearlite and there is no free ferrite present.

When the carbon in a steel exceeds 0·85 per cent. a new set of conditions comes into being. Such a steel may be considered as supersaturated and the solid solution behaves like other supersaturated solutions when cooling by throwing out that cementite which is in excess of the solvent power of the iron at the selected temperature. Thus steel containing 1·2 per cent. carbon will, when cooling, commence rejecting free cementite at some definite temperature (approx. 830° C.). This point is known as the *Acm* point (see Fig. 70). Further cooling causes more and more cementite to be thrown out of solution until the *Ar*1–2–3 point is reached, and then the austenite changes into pearlite in exactly the same manner as a saturated steel. The structure will consist of pearlite grains surrounded with a network of free cementite and possibly needles of this constituent running through the pearlite grains (see Fig. 76).

The Transitional Constituents.—In the change from austenite to pearlite there are several intermediate phases and for convenience each condition of the constituents has been named. Thus the first phase produces "Martensite," which changes next into "Troostite." These two phases are fairly definite and under the microscope are clearly and easily distinguished. A further change takes place: Troostite into Sorbite, but this is less definite and of a different character.

Now these transitional constituents, as they are called, are of great importance in the heat treatment of steel. The presence of one or other of them in the finally treated steel gives the steel certain physical properties. Hence their position in relation to one another, their properties when retained in the cooled steel, and the manner in which their presence is secured, are all factors of the utmost practical importance.

The following diagram,* Fig. 77, is helpful in forming a rough mental picture of what happens when a medium carbon steel cools from a temperature above the A*r*2–3 critical range. Referring to this, it will be seen that there are five constituents, and that the changes are: (1) austenite-martensite, (2) martensite-troostite, (3) troostite-sorbite, and finally, sorbite-pearlite. These constituents are described in the early part of this chapter.

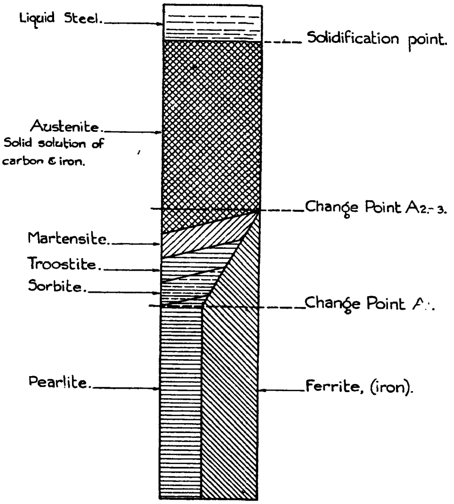


FIG. 77.—Diagram showing the Principal Constituents formed during cooling of 0·35 per cent. Carbon Steel from a high temperature.

The rate of cooling determines which of these constituents will be retained in the steel. Very rapid cooling obtained by quenching a thin piece in water or brine will arrest the steel in the martensite phase, or perhaps just at the changing point: martensite-troostite, in which case troostite also will exist in the steel.

Slower cooling will allow the steel to pass through these phases before it is finally arrested, and sorbite may be the constituent found in the steel. Still slower cooling may allow the steel to pass through all the changes into pearlite.

The change from austenite to martensite is extremely rapid in carbon steels, and even with the most rapid cooling (*e.g.* in liquid air) only a small amount of austenite is retained. The addition of certain "alloy metals," such as nickel and manganese, however, appears to lower the critical range and to retard the changes, and with such steels an austenitic structure can be obtained by ordinary quenching methods.

The changes referred to above are explained further in their connection with the practical heat treatment of steel in Chapter X.

Referring again to the critical range diagram, Fig. 70, the changes that occur in steel containing about 0·85 per cent. carbon, when cooling, are really austenite-martensite, martensite-troostite, troostite-sorbite, and sorbite-pearlite, but the duration of the changes is so brief that it practically amounts to a single change: austenite into pearlite. This explanation also applies to the merging of the A*r*2 and A*r*3 points corresponding to 0·35 per cent. carbon.

---

* This diagram is not strictly correct, but in view of the uncertain knowledge regarding these changes, it forms a very convenient way for obtaining a rough and practical notion of the behaviour of steel during cooling. The authors realise that this method of presenting the subject is open to criticism.

From the above it will now be clear why the constituents, martensite and troostite, are referred to as transitional ones.

Heating of Steel.—The changes that take place in steel during cooling also take place during heating, but in the reverse order and at higher temperatures. Thus the *Ac* points are higher than the corresponding *Ar* points. In a low carbon steel the pearlite will begin to change into austenite (solid solution) at the Ac1 point (approx. 720° C.), and as the temperature is raised this solution will absorb ferrite until at the Ac3 point the whole mass will be a solid solution. The allotropic changes in the iron will occur also, the first from Alpha to Beta iron at the *Ac*2 point, and the second from Beta to Gamma iron at the *Ac*3 point (see Figs. 68 and 70).

Crystal Grain Size in Steel.—Although the solid solution austenite does not change in character as the temperature is raised progressively from the Ac3 change point, it gradually increases in grain size, a process which is non-reversible, for on cooling the grain size does not decrease. The above diagram, Fig. 78, is intended to show the effects produced by heating the steel to progressively higher temperatures, T, T, etc. As the temperature is raised the average size of grains increases and, to make this clear, this is represented by the thick line at the foot of each separate diagram, *a*, *b*, *c*, and *d*. The remaining portions of the diagram are referred to in the paragraph " Effect of Working."

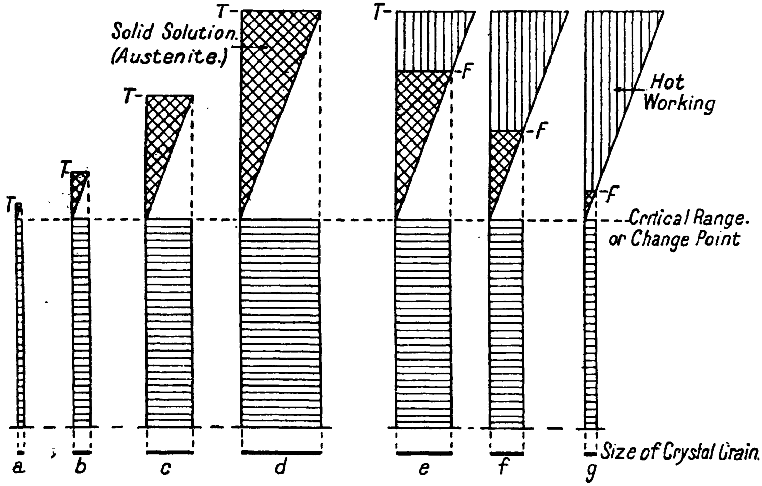


FIG. 78.—Diagram showing effect of High Temperatures on the size of the Crystal Grains. Also the influence of Work (forging) in tending to reduce their size (Sauveur).

This increase in the grain size is also dependent on the length of time the steel is maintained at the high temperature, larger and still larger grains being formed as the time is prolonged.

From the practical standpoint therefore, the result of high temperatures and prolonged heating above the Ac3 range is the production of a coarse crystalline structure, which is extremely weak dynamically, being unable to resist sudden shocks or even to withstand continuous vibration or successions of small impacts.

It is important therefore that the temperature should not be allowed to rise much above the Ac3 range and thus allow the grain size to increase.

At very high temperatures approaching the fusion point of the steel, another trouble is liable to occur, and that is oxidation in the interior of the steel, and the formation of so-called oxide inclusions or films between the crystal grains, which at once render the steel unfit for service. Such steel is generally referred to as " burnt."

Diffusion.—Next in importance to grain size is the equalisation of the masses of the different constituents, or in other words the complete uniformity of their distribution. This depends on diffusion, which can only take place while the steel is in a state of solid solution.

In a low carbon or medium carbon steel, the ferrite above the Ac3 range is completely absorbed by the solid solution, but *although the absorption is complete, it does not follow that the diffusion is complete*, or that the constituents are uniformly distributed. This will be understood more clearly if the solvent action of water on a grain of salt or sugar is considered. Although the salt or sugar is dissolved in the water, it is only the water in the immediate vicinity of the salt or sugar that dissolves it, and not the entire mass of the water. Eventually, of course, the rich solution is weakened, the salt or sugar gradually diffusing through the mass of the liquid until it is uniform in composition.

In steel the diffusion commences as soon as the constituents pearlite, ferrite, or cementite go into solution, *i.e.* the Ac1 range and continues through the different ranges. Thus, given sufficient time, diffusion can be completed before the Ac3 range is reached. In practice, however, the diffusion takes place very slowly below the Ac3 range, and it is generally advisable to heat the steel to above this range, when diffusion takes place more rapidly. Apparently the rate of diffusion increases very rapidly with further increases in temperature, and it may be advisable, in spite of the growing of the grains, actually to heat a steel well above the upper critical range Ac3, in order to facilitate the diffusion, and then, after cooling, again to heat it to just above this range so as to restore the grain size to the small dimensions so desirable in steel.

The importance of diffusion may be realised in the case of rolled bar and forgings, or steel which has been subjected to severe mechanical working—or in those cases where it has been seriously overheated. The structure may then be in the form of bands or streaks running in the direction of rolling or working as shown in Fig. 79. Here the effect of proper treatment is to remove this form of structure and to produce one of greater uniformity—due to diffusion.

Bullens * sums up the slowness of diffusion in the following words : " It seems that the greater the internal stress upon the steel the greater is the amount of intermolecular lag or final release of this stress behind the actual change of constituents. That is, even though a totally new structure may be set up by the annealing heat, there remains for a considerable length of time a tendency for the new structure to return, upon slow cooling, to the stressed condition of the original, even though the constituents themselves may be those born at the new temperature."

Effect of Working.—The hot rolling, forging, and stamping of steel has an important bearing on the grain size in so far that work of this kind

---

* " Steel and its Heat Treatment," by Denison K. Bullens.

tends to break up the grains and to produce a finer structure. But as soon as the working is stopped, the grains will commence growing and their size will depend on the temperature at which the working is stopped, and on the length of time the steel takes to cool down to the critical range.

The temperature at which working is stopped is usually referred to as the "finishing" temperature and, as will be seen, this temperature is very important.

Referring again to Fig. 78, it will be noted that the range over which the steel is being worked is represented by the upper closely shaded portion in *e*, *f*, and *g*. Although the steel has been heated to the initial temperature T in each case, work has been "put" into it until it has cooled to the finishing temperatures F, and in consequence the grain size is only that which can form at these finishing temperatures and during cooling. From this it is clear that by continuing the working until the steel has nearly cooled to the critical range the smallest size of grain will be obtained. Steel, however, at these lower temperatures, just above the critical ranges, is not sufficiently plastic for rolling and forging, etc., and in consequence the finishing temperature will always be a little above this point, and because of this there must always be a range of temperature in which the grains will grow in size. Hence, most forgings, stampings, and rolled bar will be found crystalline and more or less coarse-grained.

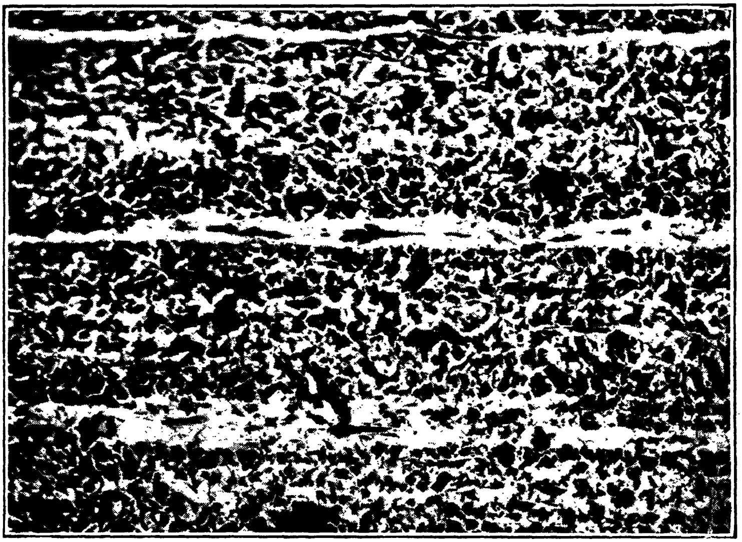


FIG. 79.—Micrograph showing Banded Structure in Rolled Steel, *i.e.* lack of diffusion, the ferrite running in broad bands in the direction of rolling. Magnification 100 diameters, etched with picric acid.

The degree of grain size can, however, be kept within reasonable limits by selecting a temperature to which the steel is initially heated, and which gives sufficient time during the cooling to allow the forging to be completed, before the steel is too cool for working or so hot as to produce a coarse-grained structure.

A further improvement can be effected by working the steel very lightly right down to the upper critical range, and even below it in the case of low and medium carbon steels.

This will produce the maximum fineness of grain and will also have the effect of preventing the free ferrite, which separates from the solid solution, forming into large masses. No further improvement can be effected below the bottom critical range. When the working is continued to temperatures below the critical range, the grain size may be reduced to its minimum, but there will be a tendency to produce distortion of the grains. This distortion will not be serious at temperatures within the vicinity of the critical ranges, but will be quite appreciable at lower temperatures, as is shown in bars which have been rolled or drawn while cold.

The control of the finishing temperature is not easy in the case of large masses of steel, because the interior of the mass must always be hotter than the outside. Hence, the structure at the centre will be coarser. It will be evident, however, that working the whole mass as much as possible before the outside is too cool will have a greater refining effect on the structure than mere heat treatment alone, for without this working, the interior will develop a larger grain size because of its much slower cooling. In fact, when large masses are under consideration, it will be better to refine them by working rather than by heat treatment alone. The rate of cooling in large pieces is so slow that ordinary methods of heat treatment are often of little use.

Cold Working.—The annealing or treatment for correcting the effects produced by cold working, such as rolling, drawing, or press work, is one that must be considered apart from that which governs the grain size in a steel that has been heated above the critical range.

In Chapter VII. reference is made to Beilby's theory of grain deformation that takes place during cold working, and according to this the grains tend to, or actually do, split along their cleavage planes, and slipping takes place with the formation of amorphous material at the slipping surfaces. Thus the grains break up into pieces and these become smaller still as the deformation increases. This breaking up, of course, takes place below the recrystallisation temperature, and the term "cold work" only applies to the working of metals and alloys at temperatures below this point.

The annealing or recrystallisation process after deformation is governed by a series of laws which have been very clearly defined by Zay Jefferies,* and which will be stated later. For the present the behaviour of a piece of deformed metal when heated should be noted. At a certain temperature the distorted grains, which are said to be strain-hardened, break up and form normal-shaped grains which may or may not be smaller than the original grains. If the temperature is raised grain growth occurs, some grains growing at the expense of others, and, in most cases with time, this will continue and what is known as exaggerated grain growth will take place.

The temperature at which the distorted grains assume normal shapes is referred to as the recrystallisation temperature, but this is not a fixed temperature. In most of the common metals the lowest recrystallisation temperature occurs at about 40 per cent. of the melting-point expressed in absolute

---

* Zay Jefferies, D.Sc. Inst. of Metals, Sept. 11, 1918.

temperature. Thus the melting-point of iron is about 1700° C. (abs.), and its lowest recrystallisation temperature is about 750° C. (abs.), or approximately 44 per cent. of its absolute melting temperature. The actual recrystallisation temperature depends on the previous treatment of the metal and also on time. In general this temperature becomes lower—

(1) as the amount of cold work or deformation increases;
(2) as the temperature at which the cold work is conducted is lowered;
(3) as the time of heating at the annealing temperature is increased;
(4) as the original grain size before deformation decreases.

It is necessary, therefore, to determine what the correct annealing temperature is for any given set of conditions. This, however, is not all that has to be considered, because, as stated above, there is the phenomenon of grain growth to take into account. It is clear that if the grains are to increase in size there must be a reduction in their number, and that consequently some grains must grow at the expense of others. This condition at once indicates lack of equilibrium in the internal forces between the different grains or their constituent molecules. That such a condition will often be found in practice is easy to understand, *e.g.* the cold rolling of sheet metal will strain the outer layers more than the inner portion, and as a result some grains will be strained more than others. The more strained grains will possess a lower recrystallisation temperature, and they in consequence will actually attack and absorb those which have been strained to a less degree.

This effect might be termed "strain gradient."

In the same manner, a gradient in temperature will produce grain growth, as many grains will attain their recrystallisation temperature before the others and thus absorb them. Unequal heating will produce this effect.

The above statements show that all the conditions which lead to lack of uniformity in the operations previous to annealing have an important bearing on the results obtained at any given temperature.

The general laws relating to grain growth are summarised as follows, the basis being those expressed by Zay Jefferies in his excellent paper, to which reference has already been made :—

(1) The attacking power of a grain increases directly with its size, *i.e.* a large grain has a greater absorptive power than a small one. Conversely, a small grain has both slight power of attack and slight power of resistance to absorption. Contrast therefore in grain size will favour grain growth.

(2) Velocity of grain growth increases as the temperature increases. This, of course, only applies to temperatures above the recrystallisation temperature.

(3) A grain which has been deformed by cold work (*i.e* below the recrystallisation temperature) does not act as a unit as regards growth, but instead acts as if it had been broken into pieces smaller than the initial grain, and these become still smaller as the degree of deformation increases. They also become smaller as the temperature of deformation is lowered, and also as the size of the initial grain is smaller.

(4) Two small adjacent grains or adjacent pieces of a deformed grain may not in a given time and at a given temperature be able to coalesce to form one larger grain, but may both be absorbed at the same temperature and in the same time by an adjacent grain larger than themselves.

(5) The deforming of a metal by a process such as cold rolling produces different degrees of strain in different parts of the metal. The surfaces in

contact with the rolls receive more deformation than the interior. Even under equal stress conditions a strain gradient can be produced, due to the directional properties of the grains. The orientation of the grains may be such that some may lie in a direction parallel to the direction of the stress, and this may coincide with their direction of least resistance to deformation. Thus, according to the position of each individual grain, so the amount of deformation will vary. This condition, of course, is most marked under slight stress, and becomes less and less pronounced as the stress is increased, and will tend to disappear when the metal is severely deformed.

(6) A strain gradient in the metal produces a recrystallisation gradient, and this under suitable temperature conditions will produce exaggerated grain growth. The term "germinative" temperature is suggested for the temperature at which this exaggerated grain growth takes place. In a piece of metal that has been subjected to strain gradient the germinative temperature will vary from that corresponding to the least strain down to that corresponding to the highest strain. If a piece of steel is heated quickly to, say, 650° C., recrystallisation will commence in a certain zone, and if the steel is maintained at this temperature for some hours the grains at the boundary of the inert region will grow. It is important to realise that this growth will tend to take place more in the direction of the less strained portion than in more severely strained regions.

The region that has not been strained so much will have a higher germinative temperature, and at 650° C. will therefore be inert; but the regions on the opposite side of the germinative range form the growth region, and because of this the grains offer more resistance to absorption than those situated in the inert region.

If the steel has been so severely strained by cold work that the recrystallisation temperature of all parts occurs at approximately the same temperature, then it will not be possible to develop large grains by ordinary furnace heating.

Under these conditions grain growth (or germination) will take place from many centres simultaneously, and each germinant centre or grain will find no inert grains to feed upon, with the result that only normal grain growth can proceed.

(7) If while any marked change in grain size takes place in the metal at a certain temperature or within a given range, a temperature gradient also exists, which maintains one part of the metal above this temperature and other parts below, then a coarse-grained structure may be produced. A temperature gradient is not always sufficient to produce exaggerated grain growth; time becomes an important factor. If the heating up is conducted slowly or is stationary at some certain temperature, then as those grains reach the germinative temperature they will commence to absorb the others that are still inert, *e.g.* a bar of steel that has been subjected to a uniform stress to produce a uniform strain through its cross-section will behave somewhat as follows when heated by a current of electricity: The centre of the bar will be hotter than the surface, and in consequence the grains in the interior of the bar will coalesce more or less rapidly, while those nearer the surface cannot do so owing to their lower temperature. At the boundary of the germinative and the inert regions absorption of the weak and inert grains will take place, and may continue until they have grown to the surface of the bar. If the heating is more rapid then the region in which germination takes place will

be wider and the grains will be about the same size, because they have been produced under substantially the same conditions, but again at the boundary of the inert region grain absorption will tend to take place.

Even then those grains that reach their germinative temperature first will, after attaining a size considerably larger than the others, attack and absorb them, so that, given time, the first germinative grains finally absorb all other grains.

Now, on the other hand, if the bar is raised to a temperature which will permit growth to proceed simultaneously at all parts a fine grain structure will result, even though the temperature gradient may have been so much greater.

(8) The higher the germinative temperature the more quickly will large grains develop, and usually the grains will be larger as the germinative temperature increases. The germinative temperature can be raised artificially by adding non-metallic matter to the steel, such as slag, which tends to obstruct grain growth; but when the higher germinative temperature is reached the growth is much more rapid, and the grains are larger than would be the case at the true germinative temperature.

(9) Initially fine grains or small grain fragments favour exaggerated grain growth at the germinative temperature. This only applies in so far as it does not oppose the conditions set up under (8). If the fine grains are the cause of lowering the germinative temperature, then the development of coarse grains at the germinative temperature may be defeated. If, however, the grains or grain fragments at the germinative temperature are much smaller than the equilibrium grains at that temperature, the formation of coarse-grained structures will be facilitated.

A careful consideration of the above rules reveals the importance of time. If in the first place the steel is heated rapidly to a temperature above the germination temperatures of all portions of the piece (see (7)), the result will be much more favourable than that obtained with slow heating.

Prolongation of the time of soaking at a temperature above the recrystallisation temperature allows those grains that germinate first to grow at the expense of the others, thus producing a coarse-grained structure. The time required for recrystallisation is less as the temperature is increased. If a piece of cold-rolled sheet is heated to a certain high temperature it may recrystallise in ten seconds. At a lower temperature it may require ten minutes, while ten hours may be necessary at a still lower temperature.

The inert grains at a given temperature are only inert for a certain time. Really grain growth becomes a race between the germinant grains and the inert grains. If the inert grains can increase their size by coalescence with one another before the germinant grains can absorb them, they may have won the race. Exaggerated grain growth will be most pronounced under conditions in which the germinant grains possess the greatest excess of growth-velocity above that of the grains they feed upon.

The effects produced by the presence of other constituents in a metal, or by impurities, have not been fully determined; but it would appear that those elements which do not remain in solution tend to obstruct grain growth. In the case of steel the pearlite constituent retards the growth, and therefore the less carbon there is the larger will be the grains. For this reason the question of grain size is particularly important with very low carbon steels, especially in the case of sheet-steel and tin-plate employed for pressings. Slag in steel will act in a similar manner.

Chemical or Ultimate Composition of Steel

The preceding pages have dealt with the proximate composition of steel, showing in what form the carbon exists and the various changes that can be obtained through heating and cooling. Chemical analysis gives little or no information of this character, but in the routine examination of raw steel the determination of the carbon content is unquestionably one of the most valuable of all tests. Knowing the percentage of carbon in a carbon steel, it is possible to specify the heat treatment that will give the desired mechanical strength. Further, assuming that an incorrect steel has been received, the carbon content at once establishes this fact and at the same time definitely settles the question as to whether it could be heat treated to meet the requirements.

The determination of nickel, chromium, or other strong controlling constituents in alloy steels is valuable on account of the fact that micro-examination of such steels gives a very poor idea as to the proportion of these constituents present.

Further, the necessity for specifying the chemical composition of steel for a particular purpose necessitates the analysis of such steels. Also the presence of impurities calls for a thorough analysis or, at any rate, a statement specifying the maximum permissible limits.

Nominally, steel is an alloy of iron and carbon, but commercially it contains small quantities of other elements of which the chief are: (1) Manganese, (2) Phosphorus, (3) Sulphur, (4) Silicon, (5) Slag.

Iron.—Although iron is the main constituent of steel, its properties are so much altered by the carbon present that any knowledge of the behaviour of the pure metal is of little help except when considering very mild steels. It then gives the steel the soft and ductile properties which are normal to it. It is recognised under the microscope as ferrite.

Carbon.—This element exists in all steels and irons, and can only with great difficulty be removed from the iron. A large proportion is derived from the iron (usually pig iron) used for steel making, but the correct amount required in the steel is made up generally by adding it in some form such as carbon-rich iron.

In low and medium carbon steels the carbon always exists as a chemical compound known as iron carbide (Fe_3C), called cementite, which, as explained in the preceding pages, may take up different states known as austenite, martensite, troostite, sorbite, and pearlite, all possessing different properties and conferring these properties on the steel in a degree depending on the amount of carbon present.

In high carbon steels, however, containing more than 0·9 per cent. carbon, some may exist as graphite, especially if the amount of silicon is high, but more usually it forms the compound iron carbide (cementite), a portion of which exists in the free state.

Manganese.—Manganese is added to steel during the making to assist in removing some of the impurities (sulphur), and is, therefore, always found in some proportion in the finished steel.

Manganese readily combines with sulphur, forming manganese sulphide

(MnS), and will, in good steel, take up all the sulphur (up to about 0·05 per cent.). To do this it should not be less than 0·25 per cent. of the total steel. In this respect it fulfils a useful function, reducing the disastrous effect of sulphur in the form of iron sulphide, owing to its greater affinity than iron for sulphur. The manganese not used in this manner tends to combine with carbon forming manganese carbide (MnC_3), and this associates with the iron carbide (cementite) and increases the tensile strength in treated steels. This increase amounts to about 0·75 ton per square inch for each 0·1 per cent. of manganese up to about 2·0 per cent., and appears to be due to a retarding influence on the change from austenite into martensite. It lowers the critical range Ac3, by about 3° C. for each 0·1 per cent. present, and therefore must be taken into account when determining heat treatments, especially with steels containing about 1·0 per cent. Generally speaking manganese makes the steel more sensitive to drastic quenching and may cause cracking to occur, particularly if the carbon content is high. Steel containing 0·9 or 1 per cent. carbon and 1 per cent. manganese is very liable to crack during water quenching, and even if the carbon is much lower there is still some risk, while with 1·5 per cent. manganese it is almost certain to fail. With tool steels the manganese should not be more than 0·4 per cent. Slower cooling can be adopted with safety, but even without quenching there are limits, which may be taken as 1 per cent. carbon and 2 per cent. manganese.

The importance of this cracking difficulty appears when mild steel is case-hardened (see Chapter XIII.). The carbon in the "case" may range from 0·9 to 1·4 per cent. and will, therefore, behave like tool steel and crack during or after quenching in water should the manganese exceed 1 per cent. For this reason case-hardening steel should have a low manganese content, and in America this appears to be limited to about 0·35 or 0·4 per cent., but in England it usually ranges from 0·7 to 0·9 per cent. with the object of increasing the toughness of the core. These high values are, however, risky and will often lead to cracking in intricate parts with sharp angles, corners, etc.

Manganese is added in larger amounts to produce manganese steels, and owing to the gradual lowering of the critical ranges that results it is possible to produce a steel which is austenitic at ordinary temperatures and is therefore always hard. Such steels, however, are discussed under "Alloy Steels," Chapter XII., to which reference should be made.

Phosphorus.—Phosphorus is introduced in the steel from the iron which, in turn, receives it from the charge in the blast furnace. In the "acid" process of steel making the whole of the phosphorus remains in the steel, which fact necessitates employing low phosphorus irons. With the "basic" process, irons and scrap richer in phosphorus can be used, because a large proportion of the phosphorus is removed.

Phosphorus combines with iron, forming the chemical compound phosphide of iron (Fe_3P), which in turn goes into solution in the iron (or ferrite) and remains in solution at ordinary temperature. It is, therefore, not visible under the microscope, although by using Stead's cupric etching reagent it is possible to differentiate between those portions of the solution which are rich in "phosphide" and those that are poor. It does not affect the crystalline form of the ferrite, but has a tendency to increase the size, which tendency is very marked when present in quantities greater than 0·1 per cent. This accounts for the brittleness in steel containing much phosphorus, for, as has been stated already, a coarse-grained structure is more brittle than a fine-grained one. Phosphorus is usually responsible for what is termed "cold-shortness" in steel.

Those portions of the solution rich in phosphide have a tendency to exclude carbon and it is common to find these areas freer from the carbon constituents, a fact which leads to the trouble known as segregation in which the steel separates into large areas, some free from carbon and others rich, and this through the influence of rolling or forging produces strata or bands in the steel running in the direction of rolling or forging, the bands being alternately rich in phosphorus and carbon. This tendency and its effects are shown by Fig. 79.

Good steels should not contain more than 0·05 per cent. phosphorus, but many steels are found to contain up to as much as 0·1 per cent. and are used with good results for most work. In vital parts, however, that are highly stressed, the amount should be kept low owing to the brittleness induced and the consequent low dynamic strength which results.

A large amount of phosphorus improves the machining quality of the steel and it is a common practice to use high phosphorus mild steel for bolts, studs, nuts, and other automatic machine work. The steel is rendered soft and cuts with great ease. In such steels the phosphorus may be found as high as 0·16 per cent.

Sulphur.—The sulphur in steel results from the coal or coke used in the reduction of the iron from its ores. When charcoal is used the iron produced is comparatively free from sulphur, as in the case of Swedish iron, which is produced in this manner.

Sulphur combines with iron forming the chemical compound iron sulphide (FeS), but as manganese is added to steel to purify it and has a greater affinity for sulphur than iron, the compound manganese sulphide (MnS) is formed instead, and this is what is usually found in steel. This compound does not enter into solution and is therefore seen under the microscope as a separate constituent, usually in the form of globules or elongated areas (in rolled or forged steel). This, however, only occurs when the amount is large or when segregation troubles occur (see Fig. 109). In good steel the sulphur should not exceed 0·05 per cent., and as only about twice this amount of manganese is required to combine with it the steel will only contain 0·125 to 0·15 per cent. of manganese sulphide, an amount which has no appreciable effect on the properties of the metal. In such cases it exists at the boundaries of the crystal grains in small particles or streaks, and only breaks the continuity of the metal very slightly.

If the sulphur is "high" or there is insufficient manganese to combine with it, the compound iron sulphide is formed with the excess of sulphur. This compound, like manganese sulphide, is not soluble in the steel. It probably forms an eutectic with iron and is therefore thrown out of the crystal grains, but unlike manganese sulphide it tends to form continuous envelopes or membranes surrounding each grain of pearlite. These membranes are weak and brittle and impart weakness and brittleness to the metal.

Iron sulphide having a low melting point (about 950° C.) probably produces the well-known red-shortness in steels containing much sulphur or too little manganese. At forging or higher temperatures the sulphide (or sulphide eutectic) melts and destroys the cohesion between the grains and cracks develop immediately.

Silicon.—This element enters iron and steel from many sources, such as the furnace linings and the blast-furnace charge. It probably combines with iron forming a compound, silicide of iron (FeSi), which then dissolves in the iron forming a solid solution, in which it remains at ordinary temperatures. It exists in both the free ferrite and that forming pearlite. It has no influence on the form of the crystal grains or apparently on their size, and does not affect the properties of the steel very much. For welding purposes it is advisable to employ only low silicon steel or iron, because the silicon renders welding more difficult.

In high carbon steel it exerts some influence on the carbon, throwing it out of solution as graphite instead of iron carbide (cementite). This, however, only occurs in steel which has been annealed, *i.e.* slowly cooled.

Good steels should not contain more than 0·3 per cent. silicon, but often quantities as high as 0·5 per cent. are found.

Slag.—In good steels, slag should be entirely absent and is so except in the case of mild steels or mild case-hardening steels, when it may be present in small amount without risk.

The composition of slag is complex, depending on the earthy matters associated with the original ore and on the fluxes used to reduce this matter, and also on the nature of the furnace linings in which, first, the iron is produced and then, second, the conversion of iron into steel takes place. Its composition, however, is of small importance to the engineer, and therefore the general statement that slag is a mixture of phosphates and silicates of both iron and manganese is sufficiently accurate for the present purpose. It is more important, however, to know the form this impurity assumes. It is insoluble in the steel and can therefore be seen with the microscope, when it will be found either as irregular-shaped globules or as black streaks running in the direction of rolling or forging (see Figs. 105 to 107). If present in large amount this streaky formation will impart what appears to be a fibrous structure and fracture to the material. Wrought iron (puddled bar, etc.) is an example of this formation.

The presence of slag in case-hardening steel is a source of danger in so far as it causes the high carbon " case " to crack or peel off. If a slag streak (commonly referred to as a slag inclusion) runs to the outer surface of the steel a flaw is formed at once and the metal will peel or break away at this point.

Slag inclusions will often have the effect of giving a higher impact strength, this being due to the fact that they break the continuity of the metal (across the direction of rolling), and therefore the crack which starts from the surface, stops as soon as it runs into the slag inclusion and must either travel up the slag or recommence a crack on the other side of the streak, and as is well known, it is more difficult to start a crack than to continue one. This effect is shown by Fig. 80, from which it will be realised that breaking a bar across the streaks or seams is more difficult than if it were entirely homogeneous, and further, that to break it along the direction of the streaks or seams will be less difficult than either of the other cases.

Slag appears to have the property of collecting the free ferrite around it and, in consequence, the area surrounding a slag inclusion is usually free from carbon.* This, of course, produces lamination during rolling and then heightens the effect of the fibrous structure.

---

* This in many cases is probably due to the presence of phosphorus (in solution in the ferrite) which throws carbon out of solution. Slag and phosphorus are often associated.

Gases.—The gases which are liberated in cast ingots of steel during cooling produce blowholes and cavities which may extend to some considerable depth in the centre of the ingot (the last portion to cool). The upper portion of the ingot should be cut off to remove this spongy mass, which also contains a large proportion of the impurities such as sulphur and phosphorus. It sometimes happens, however, that a sufficient amount is not cut away, and in consequence the ingot is rolled down while still containing blowholes or "pipes." These are closed up during the rolling and in many cases the sides are welded together, but in others the cavities may contain a little iron rich in phosphides and sulphides, or the inside surface may be coated with oxides, either of iron or manganese, and in consequence the welding cannot take place. This results in internal flaws which, in the rolled billet or bar, may run for considerable lengths and cause disaster in parts stamped or machined from the material, because of the splitting or shearing apart along the flaw.

When the cavities contain phosphides and sulphides the action of rolling draws these impurities into streaks or bands known as ghost lines, which as a rule are fairly free from carbon. These bands are naturally lines of weakness and may cause considerable trouble in machining and in the strength of the finished part.

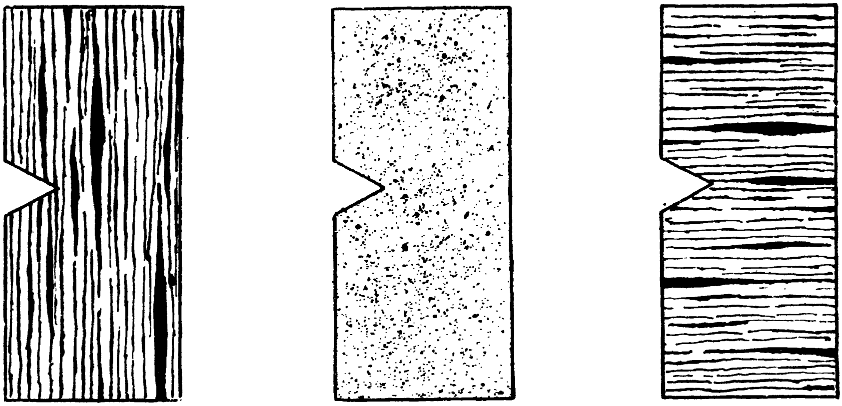


FIG. 80.—Effect of Seams or Bands on resistance to Fracture. A crack will proceed more readily along a seam than across.

Summary.—From the foregoing paragraphs it will be seen that a good steel should contain approximately :—

1. Carbon, 0·05 to 1·5 per cent., according to requirements.
2. Manganese, not more than 0·4 per cent. for water quenching high-carbon steels (1 per cent. and above) ; not more than 0·75 per cent. for mild case-hardening steels ; not more than 0·5 per cent. for alloy case-hardening steels.
3. Phosphorus, not more than 0·05 per cent., except when machining qualities are most important, when 0·1 per cent. is the maximum.
4. Sulphur, not more than 0·05 per cent.
5. Silicon, not more than 0·3 per cent.

The trouble known as segregation is mainly associated with phosphorus, sulphur, and silicon, and accompanies the piping or blowholes formed in the original ingot. These, as has been explained already, may contain phosphides and sulphides which in the rolled material form bands or lines and which, as a rule, are weak in carbon. Segregation is partly caused also by the fact that during the solidification of the steel the crystals that form first are nearly pure ferrite, and as freezing proceeds the successive additions are less and less pure, the carbon, phosphorus and sulphur becoming more and more concentrated in the still liquid portions. Thus the last portions to solidify are those containing most of these elements. This banded structure should always be looked out for, particularly in bar material. Slag, although helpful in some cases, is a source of trouble in many others, so also are internal flaws due to blowholes. All banded or laminated steels are risky for case-hardened parts owing to the tendency for the case to peel off.

Alloy Steels.

The alloy steels in general use may be considered as carbon steels to which certain proportions of the "alloy" metal have been added. It is, therefore, only necessary to take the carbon steel as a base and then to consider the effects produced by the addition of the "alloy." These so-called "alloys" may be any of the following metals and, because of their addition, the steel is named after them ; thus the addition of nickel produces "nickel steel."

Metals added to form alloy steels :—

Metals	Properties
Nickel Silicon	Soluble in iron (or ferrite).
Chromium Vanadium Manganese	Forming compounds with carbon and also partly soluble iron (ferrite).

Other elements, such as tungsten, molybdenum, titanium, are added to steel, but owing to their high cost are mainly confined to tool steels.

The above list of alloys is divided into two groups : those which are soluble in ferrite, and those which form compounds (*i.e.* carbides) with the carbon. This big distinction will, as would be surmised, lead to the expectation of very different effects on the steel ; the soluble element changing the characteristics of the ferrite areas, and the carbide-forming element the nature of the "carbon" areas, with also a possible change in the ferrite.

The principal effect of these added elements is the lowering of the position of the critical ranges, which effect increases with the amount added. This effect may be so great that even the change from austenite into martensite can only take place at very low temperatures, sometimes below the ordinary atmospheric temperature. The position of the change is also affected by the initial temperature from which the steel is allowed to cool, the higher temperatures usually lowering the change point.

The alloys also have a tendency to oppose changes both on heating and cooling and, as a result, the temperature at which the change takes place on heating may be much higher than the corresponding reversal on cooling. This effect (which is termed "Hysteresis") may be called sluggishness and is a characteristic of these steels. It also accounts for the difficulty or slowness with which diffusion takes place, and, lastly, but very important, the slowness with which the size of the grain alters even at high temperatures. The difference in behaviour between carbon and alloy steels may be likened to that between water and thick cylinder oil at ordinary temperatures.

Nickel.—This element dissolves in the iron or ferrite and is therefore not distinguishable with the microscope. It appears to dissolve in almost any proportion and steels with as much as 25 per cent. nickel are used commercially. Its effect on the ferrite is to increase the tensile strength without reducing the ductility of the steel. Thus the addition of 2·5 to 3·0 per cent. nickel to case-hardening steel of about 0·15 per cent. carbon content will raise the tensile strength of the core from 35 tons to 45 tons per square inch without any serious change in the ductility or the dynamic strength.

Nickel lowers the critical range points much more rapidly than carbon and also retards the change, so that the *Ar* (cooling) points are much lower. For small additions (less than 7 per cent.) the *Ac*1 point (heating) is lowered by about 10° C. for each 1 per cent., while the *Ar*1 (cooling) falls by about 20° C. for each 1 per cent. below those of the corresponding carbon steels. Thus the heat treatment of nickel steel can be carried out at lower temperatures than the corresponding carbon steels.

The carbon saturation value is also affected and instead of requiring 0·85 per cent. carbon to give a wholly pearlitic steel a less amount is now sufficient; a 3 per cent. nickel steel only requiring about 0·75 per cent. carbon. This is important with case-hardening steels, because this lower saturation value is obtained in less time than the higher value of 0·85 in ordinary carbon steel.

High nickel steels, containing 25 per cent. or more nickel, do not undergo any changes during heating or cooling. Their structure is austenitic owing to the great retarding influence of nickel over any changes in structure. Consequently these steels are very tough. They are also non-magnetic.

Nickel increases the difficulties in steel manufacture and in rolling owing to its tendency to increase piping and segregation in the ingot, and the production of a laminated or seamy structure (banded effect).

Silicon.—This element dissolves in the iron, probably as a compound, silicide of iron (FeSi). It has very little influence on the critical ranges, which are about the same as for ordinary carbon steels, but it renders the material more sensitive in heat treatment, which must be carried out with care and accuracy. Silicon steel possesses a low magnetic hysteresis and a high permeability factor, both of which make it useful for electric machinery. Such steels usually do not contain more than 5 per cent. silicon.

Chromium.—Chromium forms a compound with the carbon, and this, in conjunction with the iron carbide, produces what are known as "double carbides," which in the hardened steel are harder than the iron carbide (cementite) itself.

This element strongly opposes any change in the formation or breaking up of the carbides and in consequence the critical ranges are affected; the changes taking place more slowly, causing the *Ac*3 (heating) point to be raised and the (*Ar*1) cooling to be lowered. The *Ac*3 point is raised by about 2° C. for each 0·1 per cent. of chromium. This retarding influence enables an austenitic structure to be obtained by rapid cooling thus producing a hard, tough steel, the hardness being further enhanced by the double carbide formation.

This great hardening characteristic of chromium is of special importance owing to the increased resistance to wear that results. Further, the tendency, with suitable heat treatment, to form a fine-grain structure gives the steel a high degree of toughness without any serious change in its ductility. Thus the addition of chromium instead of more carbon to obtain hardness is much better, for not only is the steel rendered much harder but its brittleness is much less.

Chromium has a serious influence on the grain size during prolonged heating, tending to increase it and to coarsen the structure. In this respect it acts in an entirely opposite manner to nickel. Thus chrome steels which have been carburised or subjected to prolonged heating will require special heat treatment to refine the structure.

Vanadium.—This element enters partly into solution in the ferrite and also partly forms double carbides with the carbon and iron carbide (cementite).

The influence of vanadium is very great; small amounts (less than 0·25 per cent.) producing great improvements in tensile strength, ductility, and also dynamic strength. This is probably due to its influence on the ferrite in which it enters into solution in the same manner as nickel, except that the effects produced are greater.

Larger amounts produce double carbides having the same characteristic hardness as those produced by chromium.

The effect on the critical ranges (on heating) is similar to that produced by chromium, and higher quenching temperatures must be employed in heat treatment.

It is unlike chromium, however, in its effects upon the grain size during prolonged heating, and these steels can be heated without any serious coarsening of the structure.

Manganese.—Manganese, in excess of that required to combine with the sulphur, associates with the cementite, forming a double carbide which exerts its full influence only in hardened steel. Its effect then (up to 2 per cent.) is to raise the tensile strength by about 0·75 ton per square inch for each 0·1 per cent. present.

The retarding influence on the change from austenite to martensite becomes very marked as the manganese content is raised, and with steels containing about 15 per cent. the change does not take place at all, the steel being entirely austenite or hard at ordinary temperatures. The double carbide is then very prominent unless the steel has been quenched in oil or water, and then it remains in solid solution in the austenite. In the former state the steel is weak and possesses very poor ductility, whereas in the latter state it is very tough and ductile.

The effect of manganese on high carbon steel and the tendency to induce brittleness is described on p. 121.

CHAPTER IX

CHEMICAL COMPOSITION AND MICRO-STRUCTURE OF CAST IRON, MALLEABLE IRON CASTINGS, STEEL CASTINGS, NON-FERROUS METALS, AND ALLOYS

Cast Iron

CAST iron as produced by the modern blast-furnace methods, contains, in addition to the all-important carbon, comparatively large percentages of other elements, many of which can be regarded as impurities since they have a detrimental influence on the material.

The principal feature of cast iron is the amount of carbon it contains and the forms in which the latter may exist. When in the uncombined state (free as graphite) it will by reason of its low density occupy a large space, a fact which is confirmed by the micrograph Fig. 81, which represents the structure of very coarse-grained grey iron.

FIG. 81.—Micrograph of Coarse-grained Grey Iron. Magnification 75 diameters; specimen polished only.

The typical composition of a foundry iron may be represented by the following figures :—

Carbon, total	3·5 per cent.
„ combined	0·5 „
„ graphite	3·0 „
Silicon	1·8 „
Sulphur	0·75 „
Phosphorus	1·0 „
Manganese	0·8 „

These figures, however, must by no means be taken as suitable for every purpose for which it is intended to employ cast iron. The following pages will show how advisable it is to select or specify certain compositions to meet the requirements of the work in hand.

Carbon.—The carbon in cast iron is derived from the coke employed in its reduction from the ore, and it is now practically accepted that the "mother" iron in the blast furnace is a saturated solution of carbon in iron. As the iron, in the liquid state, cools a certain proportion of the carbon is thrown out of solution (in the form of the compound iron carbide (Fe_3C), which dissociates immediately into iron and carbon) and is known as "kish," and this comes to the surface. On solidification some of the carbon remains in solution (forming the solid solution known as austenite) while the rest exists as free carbide, which may dissociate partially or wholly, depending on the rate of cooling, and the amount of the other constituents present. During the further cooling, the carbon as carbide continues to be thrown out (from the solid solution), and as before, this will remain as carbide, or will dissociate, according to the conditions of cooling and composition.

Then at about 700° C. the solid solution (austenite) changes and becomes a mixture of carbide and free iron. The carbide, again, may dissociate, or if not, will be found in the iron as pearlite. If it dissociates the result is soft, grey pig-iron, containing practically all the carbon in the form of graphite.

The carbon thrown out of solution remains in the mass in the form of graphite, usually as thin curly plates. These are easily recognised in the micrograph (Fig. 81, also Fig. 67). Incidentally owing to the graphite being more bulky than the carbide, it is evident that its formation will set up an internal stress which must resist further liberation of the carbon. That the carbon is liberated, according to the argument of H. M. Howe, is due to the greater stability of the graphitic state as compared with the combined state. The force tending to produce the graphitic state is clearly able to overcome the pressure it creates, but there is a stage when the internal stress may be sufficient to balance this force and as a result the carbon is retained in the form of carbide. In such a case the fracture of the iron may exhibit dark patches of what is apparently grey iron interspersed with white iron.

Now it is of the utmost importance to know what state the carbon is in, or rather, what proportion of it is in the combined state (cementite). Other factors remaining constant, it can be assumed that as the proportion of combined carbon is increased, so is the maximum tensile stress increased. In practice, however, the other constituents such as silicon, sulphur, and manganese very largely control the proportion of combined carbon, as will be shown later.

Also, the casting temperature and the rate of cooling are factors which influence the state of the carbon. In fact, the physical properties of cast iron are very sensitive to the manner in which the material is produced.

The more quickly the material is cooled the more carbon is retained in the combined form which, being extremely hard, renders the material hard. Thus it is possible to retain all the carbon in the combined state, producing what is known as white iron; a very hard material. This has an important bearing on test bars which may, or may not, be cast with the main casting. When cast separately such bars will nearly always be found stronger than the material of the main and much larger casting. It should, wherever practicable, be made a strict practice to cast the test bar with the main casting *as part of it.*

The temperature of casting, and the rate of cooling, also influence the character of the graphitic carbon; slow cooling producing coarser graphitic plates than rapid cooling and consequently weakening the material.

Silicon.—The presence of silicon in cast iron affects the solubility of the carbon, reducing it and causing the carbon to change from the combined state to the graphitic state. It also has the effect of slightly raising the melting temperature owing to the reduction of the total carbon. From a series of test bars T. Turner found, under the conditions in which they were prepared, that the maximum tensile strength was obtained with 1·96 per cent. of silicon, the combined carbon being 0·56 per cent. A composition, however, of about 1 per cent. silicon and approximately 2 per cent. combined carbon gave the best crushing strength.

The silicon content should be controlled by (1) the size of the casting, (2) the rate of cooling, and (3) the casting temperature. The size of the casting generally determines the rate of cooling, and in the case of a large one the cooling may be so slow that the combined carbon is almost nil, hence it is necessary to select irons containing suitable amounts of silicon for the work in hand. For large or slowly-cooled castings the silicon content should be lower than that used for light or quickly-cooled castings. The casting temperature if raised counteracts to some extent the effects of silicon, for with higher temperatures the combined carbon is higher for a given silicon content.

Although, as a general rule, the percentage of silicon controls the quality of the iron, it must be borne in mind that its influence is always conditional. Still, as a guide, the following figures given by McWilliam and Longmuir * can be adopted as representing safe practice :—

Type of Casting.	Silicon per cent.
Chilled grey iron cylinders	0·75 to 1·00
High-pressure cylinders	1·30
General machinery	1·50
Soft iron castings	2·50
Stove grates, etc.	2·5 to 3·0
Hollow ware	3·0 to 3·5

The remelting of cast iron tends to reduce the silicon content and hence increases the hardness of the metal.

Phosphorus.—This element combines with the iron forming iron phosphide (Fe_3P), which tends to dissolve in the remaining iron as a solid solution. If the

---

* "General Foundry Practice."

iron was free from carbon the amount of phosphorus dissolved in this way would be about 1·7 per cent.,* but the action of carbon, which also tends to go into solution (as iron carbide), is to oppose this, and as a result the phosphide is partly thrown out and exists as a separate constituent. The phosphide reacts

Fig. 82.—Micrograph of Cast Iron showing Flake of Graphite (large dark mass on left side), Pearlite Areas (parallel bands, both coarse and fine), Phosphide Area (lower portion towards right of photograph), nearly white with irregular masses of Iron Phosphide, Sulphur (as manganese sulphide) as dark spots in different places. Magnification, 450 diameters; etched with picric acid.

---

* Stead, *Journal Iron and Steel Inst.*, vol. 2, 1908.

in a like manner and throws the carbide out while the iron is still molten and, as this immediately dissociates into carbon and iron, the carbon is lost. Thus in high phosphoric irons the total carbon content is usually lower than in those containing only small amounts of phosphorus. Beyond this action the phosphorus does not appear to affect the condition of the carbon in ordinary pig-irons.

In most cast irons, therefore, the phosphorus exists partly in solution and partly as a separate constituent (in both cases as phosphide of iron). In the former case it influences the size of the ferrite grains tending to make them larger, while in the latter case it surrounds the crystal grains or exists as separate areas depending on the silicon content of the iron. In either case it weakens the iron, making it more brittle, the large-grain structure always being weaker and the phosphide itself being very weak.

The structure of these phosphide areas is somewhat laminated like pearlite owing to it forming an eutectic mixture with iron. This can be seen in Fig. 82. The action of silicon in breaking down the iron carbide causes these phosphide areas to be fairly free from carbon, while in low silicon irons (white irons), this influence being weaker, the phosphide is often found closely associated with iron carbide (cementite).

Phosphorus lowers the melting point of cast iron and enables very delicate castings to be produced; such castings being as a rule sharp and clean.

Sulphur.—The influence of sulphur on the properties of cast iron is somewhat obscure. It appears to assist in the formation of, or to resist the breaking down of, the iron carbide, and thus produces hard iron. When manganese is present the sulphur combines with it forming manganese sulphide (MnS) and this hardening effect disappears.

As in the case of steel the manganese sulphide is insoluble in the iron and is therefore found as a separate constituent, usually in the form of globules (see Fig. 82). Up to 0·1 per cent. it exerts no serious influence on the iron, although it is advisable to keep the amount down to about 0·05 per cent.

If little or no manganese is present the sulphur combines with the iron forming iron sulphide (FeS), a very brittle constituent.

Manganese.—As explained already, the addition of manganese to cast iron results in the formation of manganese sulphide with any sulphur present, and this compound, being insoluble, exists as a separate constituent. This compound appears to have little influence on the properties of the iron unless both sulphur and manganese are present in large amounts, an unusual state of affairs in modern cast iron.

If manganese is added in large amount a proportion of it forms a double carbide of iron and manganese, and the material is rendered harder in consequence.

Malleable Cast Iron

The composition and structure of malleable cast iron depends on the process of malleablising adopted. The processes in use are (1) the Reaumur or European method, and (2) the Blackheart method.

The method that has been employed is readily determined by the nature of the fracture, which is glistening white in the case of the Reaumur method, and grey (or black) if the process is Blackheart. This great difference in the appearance of the fracture is entirely due to the amount of carbon present, and it follows, therefore, that the amount of this element and the form it assumes are of principal importance.

Carbon.—Ordinary grey cast iron as used for foundry purposes is unsuitable for the manufacture of malleable castings because of the form in which the carbon exists.

In such iron a large proportion of the carbon is graphitic and, as shown by Fig. 81, the graphite exists in curly flakes which reduce the strength and account for the brittleness of the metal. White iron, containing the carbon entirely in the combined form, is extremely hard and brittle, but on heating this the iron carbide commences to dissociate and at certain temperatures the carbon is thrown out as graphite. At 1,100° C. the graphite thrown out is in what is termed its primary form, which is the curly, flaky graphite of ordinary grey iron. White iron treated in this manner is no better than ordinary foundry iron.

If, however, white iron is subjected to prolonged heating at temperatures between 700° C. and 1,000° C. the carbon, although it dissociates from the combined form (iron carbide), does not assume the curly flaky form produced at higher temperatures. Instead it takes up the form of secondary or fine-grained graphite which is often referred to as "annealing carbon." This particular form has nothing like the weakening effect on iron that the primary or flaky form has, and its production, therefore, is of considerable importance.

The amount of annealing carbon present depends, apart from the composition of the iron, on the temperature to which the iron is heated and on the duration of the heating. Low temperatures of 750° to 800° C. change the carbon into the required form, but beyond a slight surface decarburisation the carbon content is much the same as in the original casting. Higher temperatures, however, 950 to 1,000° C., not only convert the carbon but also remove the bulk of it, leaving the iron almost carbon free.* Thus the difference in the two processes is explained here; low temperatures produce blackheart iron and high temperatures whiteheart iron (*i.e.* Reaumur or European process). The dominating factor, however, is the sulphur content, which must be very low for blackheart iron, otherwise the annealing is commercially impossible at the lower temperatures.

The time required to effect this change and to remove the carbon (in whiteheart iron) is considerable and depends on many factors, as will be seen later. Clearly the removal of the carbon, which is effected by oxidation, must be slow even though the temperature is high. Usually the heating, or annealing operation as it is called, occupies several days and sometimes weeks, and is therefore an expensive one. Much depends on the presence of other constituents and on the section of the castings.

The structure of a blackheart casting is shown by Figs. 83 and 84, which show the material as polished and also after etching. The shape of the nodules of annealing carbon will be noticed and, if compared with the usual flaky graphite of ordinary cast iron, the reason for the increased strength and ductility of the metal will become apparent.

---

* In this country most foundries produce whiteheart iron, but in many cases it is not the true type, because a certain amount of carbon still remains in the casting, some as graphite and the remainder in the combined state.

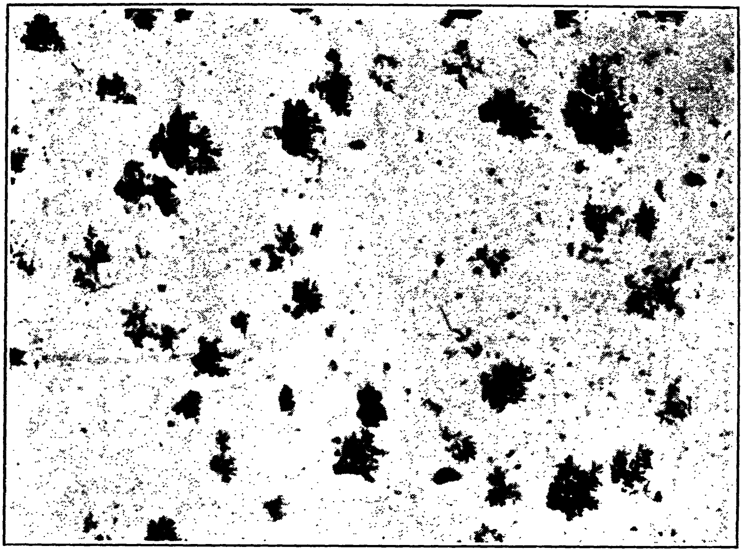


FIG. 83.—Micrograph of " Blackheart " Malleable Iron, showing annealing Carbon Magnification 150 diameters ; specimen polished only.

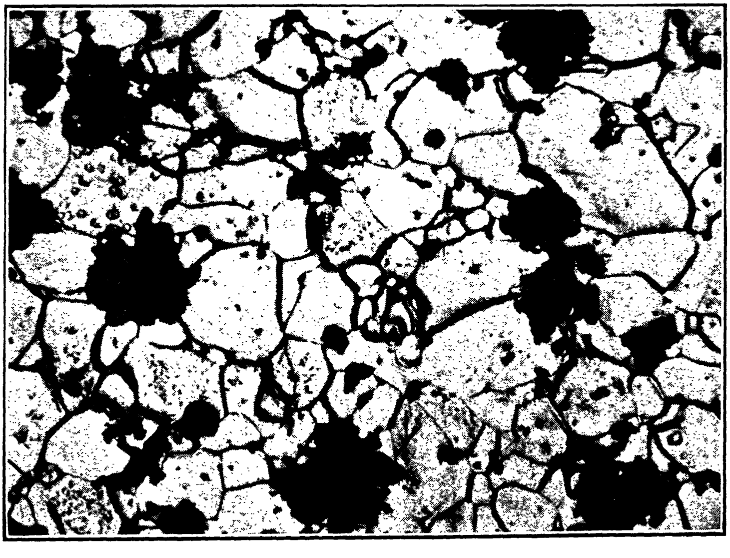


FIG. 84.—Micrograph of " Blackheart " Malleable Iron, showing annealing Carbon and also grains of Ferrite. Magnification 300 diameters ; etched rather deeply with picric acid.

Silicon.—Silicon unites with iron forming iron silicide (FeSi), which goes into solid solution, and as carbon is less soluble in this it is thrown out as graphite in amounts increasing as the silicon content is increased. Thus this element assists the annealing operation in that it tends to change the combined carbon into annealing carbon. The amount, however, must be watched since in the making of the original casting it is desirable that no flaky graphite should be formed; the iron should be as white as possible and silicon defeats this. Thus it is usual to limit the amount of this element to 0·5 to 1·10 per cent. or an average value of about 0·75 per cent. A certain amount of silicon is necessary to reduce porosity of the castings.

Sulphur.—This element tends to prevent or delay the separation of the carbon into graphite and therefore retards the annealing operation. Iron containing much sulphur must be annealed at a high temperature to effect the separation of graphite. Thus for the low-temperature, or blackheart, process the proportion of sulphur must be low, whereas for the whiteheart method higher percentages of sulphur are permissible, in which case it is usual to increase the silicon content to counteract the retarding influence.

The iron used for the blackheart process should not contain more than 0·15 per cent. sulphur, but with the whiteheart process the iron may contain up to 0·35 per cent.

Manganese.—Manganese delays the annealing process because it tends to keep the carbon in solid solution. Small amounts up to 0·4 per cent., however, assist the separation, probably because of the chemical union of the manganese and the sulphur (forming manganese sulphide). The manganese content should not exceed 0·5 per cent. in good quality castings.

Phosphorus.—The amount of phosphorus allowable depends on the process adopted for annealing. Generally for the blackheart method the phosphorus may be higher than in the case of the whiteheart process. There is still some uncertainty as to the behaviour of phosphorus, but Stead has shown that phosphorus, which combines with iron as iron phosphide (Fe_3P), forms an eutectic consisting of iron phosphide and iron which melts at about 980° C. This tends to segregate, forming areas of weak and brittle material. This, in practice, appears to take place at a little over 900° C., and this temperature, therefore, is part of a critical range affecting the condition of the phosphorus.

In the blackheart process the annealing temperature is always lower than 900° C., hence the effect of phosphorus is not so serious, in fact it may be as high as 0·25 per cent. For whiteheart castings, however, it should be kept lower and not exceed a value of 0·15 per cent. It increases the grain size and the tendency to be brittle, while it also reduces the tensile strength, elongation, reduction, the bending angle, and deflection under the bend test.

Steel Castings *

Steel castings may be regarded as castings made from mild steel, since the best castings contain only a low percentage of carbon, less than 0·3 per cent.

---

[*] These must not be confused with ordinary cast steel such as tool steel, or those steels that are prepared in crucibles. All steel, of course, is cast, but this section refers only to those castings which eventually form part of a machine, and are cast in moulds to the finished shape.

They differ considerably, therefore, from iron castings in that the carbon content is much less and, further, that the metal must be much freer from impurities like sulphur and phosphorus.

The low percentage of carbon means that the metal has a high melting point and that steel castings must be made at much higher temperatures than iron castings. This fact accounts for the difficulty experienced in obtaining sound castings, especially when the section of the part is considerable, or one portion is much thicker than another which adjoins it.

The employment of the electric furnace for melting the metal enables better material to be produced, since its composition can be kept under better control. The contraction of the metal is considerable, and this again renders the production of castings of varying section difficult, especially when the change of section is abrupt.

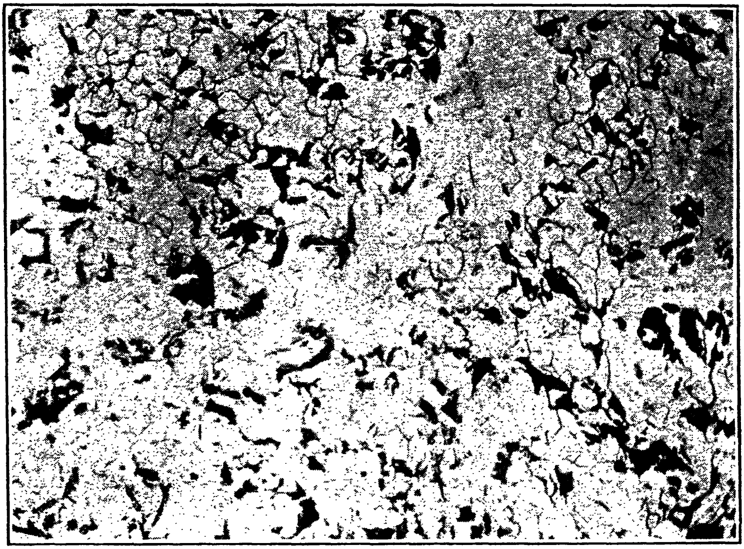


FIG. 85.—Micrograph of Steel Casting improperly annealed, showing free Graphite. Magnification 150 diameters; specimen polished only.

The castings should not be used in the raw state just as they come from the moulds; they should be annealed to break down the coarse crystalline structure and to diffuse the carbon constituent more uniformly. This is important, but is often neglected or not carried out well enough by the steel founders, with the result that hard, brittle castings are supplied.

Carbon.—The amount of carbon should not exceed 0·3 per cent., while for most purposes where ductility and a high dynamic strength are required the percentage should be about 0·2. In a good casting the carbon should be in the pearlitic state and the micro-structure should resemble ordinary mild steel. It sometimes happens, however, that during the annealing process, especially when the silicon content is high, some of the carbon is thrown out in the free state as graphite. An example of this is shown by Fig. 85

while the pearlite constituent is readily recognised in Fig. 86, which shows the same material at a magnification of 600 diameters. The proportion of carbon in this steel was 0·25 per cent.

A low carbon steel casting is represented by the micrograph Fig. 87. The carbon content of this is 0·19 per cent., the dark portions representing the carbon areas which, if magnified, would show up as pearlite.

There is a tendency to supply castings having a higher carbon content than 0·3 per cent. owing no doubt to the greater ease in casting such metal, but these are not desirable owing to the reduced ductility and dynamic strength.

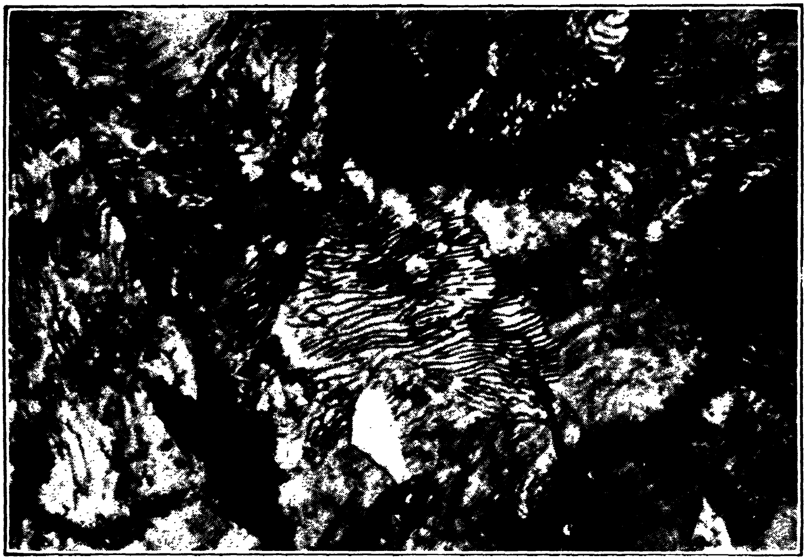


Fig. 86.—Micrograph of same Steel Casting at a magnification of 600 diameters, showing Pearlitic Structure (laminated in centre); etched with picric acid.

The micrograph of a steel casting containing 0·42 per cent. carbon is shown by Fig. 88.

Sulphur and Phosphorus.—In ordinary steel it is necessary to keep the proportion of these impurities down, but in steel castings it is even more important. The soundness of the castings and the dynamic strength are affected very considerably by these elements and neither should exceed 0·03 per cent.

Manganese.—This is added to nullify the effect of the sulphur, since it combines with it to form manganese sulphide (MnS). Any further amount is harmful since it tends to develop brittleness, and it should not exceed 0·5 per cent.

Silicon.—Silicon combines with iron forming silicide of iron, which goes into solid solution in the metal. It promotes soundness in the castings by removing the occluded gases, and is usually found in quantities up to 0·4 per cent. The tendency of this element to throw the carbon out as graphite has been referred to already.

Slag.—The presence of slag in castings is harmful and should be watched

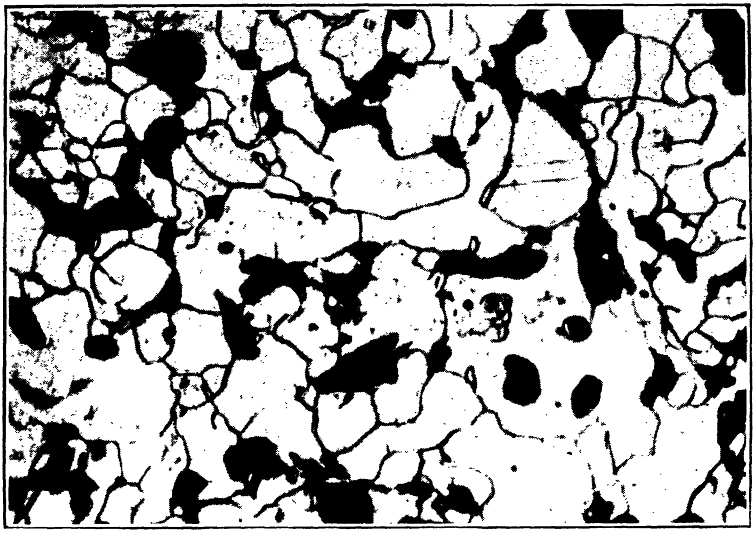


Fig. 87.—Micrograph of a Low Carbon Steel Casting, showing Carbon Areas (dark patches) and Ferrite Grains (white). Magnification 300 diameters; etched with picric acid.

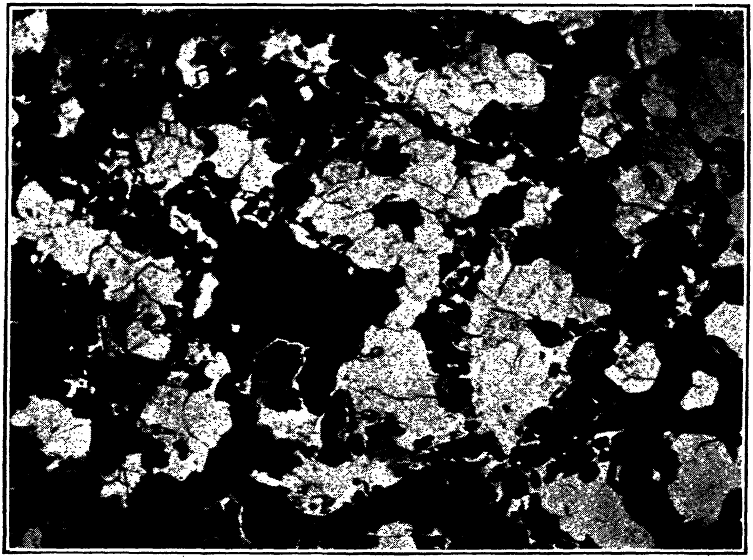


Fig. 88.—Micrograph of High Carbon (0·42 per cent.) Steel Casting, Carbon Areas dark, Ferrite white. Magnification 300 diameters; etched with picric acid.

for because of the weakness and brittleness that result. The following micrograph, Fig. 89, shows the form in which the slag appears.

FIG. 89.—Micrograph showing Slag in Steel Casting (Slag dark). Magnification 150 diameters; specimen polished only.

Non-ferrous Metals

ALUMINIUM

The principal impurities in commercial aluminium are copper, iron, and silicon, and a good quality metal will analyse as follows :—

Aluminium	99·2 per cent.
Copper	0·2 ,,
Iron	0·3 ,,
Silicon	0·3 ,,

Some samples of aluminium contain as much as 99·6 per cent. pure metal, while lower grades contain only 98 per cent.

The copper forms a solid solution with aluminium and cannot, therefore, be recognised under the microscope; its effect on the strength of the metal is negligible.

Iron combines with aluminium forming the compound Al_3Fe, which is practically insoluble in aluminium at ordinary temperatures and is thrown out to the grain boundaries. Silicon appears to exist in solid solution (but only to a slight extent) and as free crystals.

Most pure aluminium is used for rolling or drawing into wire, rods, sheet, and bars, etc., hence it is in this state that the metal is generally met with. The metal used for alloys is usually richer in copper.

The metal as cast assumes a crystalline structure, but the effect of cold work is to break this down into what appears to be an amorphous state, but is really a laminated structure of flattened crystal grains. This new structure can be changed again into an obviously crystalline one by the process of annealing, although the procedure is a slow one.

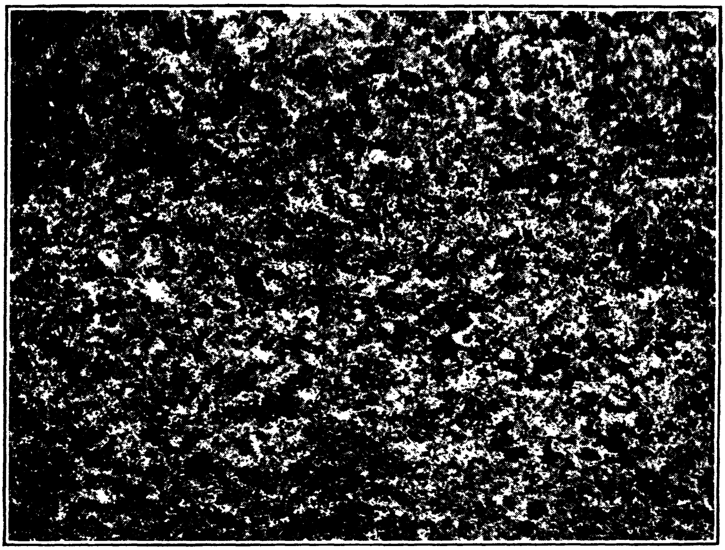


FIG. 90.—Micrograph of Drawn Aluminium Rod. Transverse section. Magnification 150 diameters; etched with caustic soda.

COPPER

The principal impurities in commercial copper are bismuth, arsenic, sulphur, oxide of copper, lead, iron, and antimony.

A sample of drawn copper tubing or rolled sheet will probably have an analysis as follows :—

Copper	99·5 to 99·8	per cent.
Bismuth	0·000 to 0·01	,,
Arsenic	0·005 to 0·07	,,
Sulphur	0·002 to 0·005	,,
Oxide of copper	0·050 to 0·2	,,
Lead	0·005 to 0·05	,,
Iron	0·001 to 0·004	,,
Antimony	0·000 to 0·005	,,

The impurities are small in amount but their effect is often very marked. Other elements are found such as nickel, silver, tin, and sometimes selenium and tellurium, but these are rarely found in the commercial material.

Bismuth.—This element has a most injurious effect on the properties of copper. When present in amounts up to 0·05 per cent. it makes copper quite brittle, while it has been found that with over 0·0005 per cent. copper cannot be drawn into wire. Arsenic and antimony, which are usually found in copper, have a neutralising effect on bismuth and in consequence some samples of copper may contain a fair percentage of bismuth without being brittle, but this is due to this counteracting influence of arsenic and antimony.

Bismuth forms exceedingly fine membranes of metallic bismuth round the crystal grains of the copper, and it is this formation that accounts for the brittle character of the copper.

Arsenic.—The effects of this element on copper are important as will be seen from the following table :—

INFLUENCE OF ARSENIC ON STRENGTH OF COPPER.*

Arsenic per cent.	Elastic limit.	Tensile strength.	Elongation per cent.
0·00	6·25	11·9	25·0
0·24	9·15	15·1	27·5
0·53	8·47	16·4	29·5
0·75	7·84	16·3	21·0
0·94	8·11	16·1	25·0
1·37	8·99	16·8	28·0
1·80	10·27	15·9	20·0

The mechanical properties of copper are not affected seriously until the amount of arsenic exceeds 0·8 per cent., and even at this figure copper can be drawn into very fine wire. If, however, oxide of copper is present in any large amount the metal becomes "cold short" or brittle. For practical purposes the limit for arsenic should be set at 0·6 per cent. Arsenic alone will cause "red shortness" if it exceeds 2 per cent., but this metal will roll if carefully handled.

Arsenic in these amounts forms a solid solution with the copper, and therefore is indistinguishable under the microscope.

Sulphur.—This element is found as cuprous sulphide (Cu_2S). The effect on copper is to reduce its malleability; 0·5 per cent. sulphur making the metal quite brittle. The limit for good metal is 0·01 per cent., but with 0·25 per cent. copper is still fairly malleable, but much smaller amounts are often a source of unsoundness.

Oxygen or Oxide.—Oxygen does not disolve in copper but takes up the form of copper oxide (Cu_2O). This oxide forms an eutectic with copper which is distinguishable under the microscope (in commercial rolled copper as pale blue globules). With amounts below 0·45 per cent. the mechanical strength of the copper remains unaffected, but above this the tensile strength increases slightly, and the malleability diminishes when 0·9 per cent. Cu_2O is reached.

The hot forging properties are adversely affected when the oxide exceeds 3·45 per cent., this representing the composition of the eutectic alloy.

Lead.—This metal does not alloy with copper except in a very minute quantity, when it takes up the form of a eutectic. When present it is usually found in globules or at the crystal boundaries. Its effect on the properties of copper depends to some extent on the amount of copper oxide (Cu_2O) present

---

* Lewis, *J. Soc. Chem. Ind.*, 1901, xx. 254.

since it has the power of reducing the oxide. Thus with much oxide present the amount of lead can be high, but if the oxide is low the copper will be red short and brittle. For most purposes the amount of lead should not exceed 0·1 per cent.

Iron.—Copper always contains iron, which has a tendency to make it hard and brittle. Iron in small amounts forms a solid solution and is not recognisable under the microscope. The limit for good copper should be about 0·01 per cent.

Antimony.—The effect of antimony on copper is somewhat similar to arsenic. It forms a solid solution when present in small amounts. The limit for good metal is usually taken as 0·05 per cent.; above this the material does not roll well.

Nickel.—The effect of this metal in small quantities is not pronounced; up to 0·3 per cent. nickel has no effect, but above this the copper becomes harder and has a higher tensile strength. This metal forms a solid solution with copper.

Non-Ferrous Alloys

ALUMINIUM ALLOYS

The tremendous output of aluminium during the last few years and the demand for its alloys in connection with the aircraft and automobile industries have settled many doubts as to the efficacy of these alloys, and they are being used now more freely and with greater confidence.

The principal commercial alloys of aluminium are dealt with in Chapter XV. The forms which the added metals assume in these alloys are only briefly described here.

Generally aluminium combines with ordinary metals forming compounds which are only partially soluble or are insoluble in the metal itself. Thus such alloys during cooling form grains of the almost pure metal itself and the compounds are often found at the boundaries. This form of structure (see Fig. 91) is usually poor or is only useful for certain purposes. Zinc is the principal exception and forms a solid solution with aluminium, and the alloys so produced are some of the most valuable in use.

Copper.—This metal forms a compound with aluminium ($CuAl_2$) which is partially soluble in aluminium. The amount which is capable of being dissolved without annealing is about 3 per cent. of copper. That which does not dissolve forms a eutectic with aluminium, which contains about 32 per cent. of copper and melts at 545° C.

Alloys of aluminium with less than 3 per cent. of copper will not show much of the latter constituent under the microscope owing to it being in solid solution. Above this amount, however, the eutectic which forms becomes visible, as will be seen in Fig. 91, which is the micrograph of an alloy containing approximately 11·5 per cent. copper, used for an aero-engine cylinder.

The addition of copper to aluminium increases its tensile strength and improves its machining qualities. Above 6 per cent. the alloys can be used for die castings, a fact which renders them of great value.

Zinc.—This metal in quantities less than 40 per cent. forms a solid solution with aluminium. Zinc forms a compound with aluminium (Al_2Zn_3) which, however, decomposes at 256° C.

Zinc increases the tensile strength of aluminium but renders the material more sensitive to temperature rise, the alloys becoming much weaker as the temperature increases. There is a tendency for the alloys to "tear" or "drag" during machining, and it is usual to add about 3 per cent. of copper to reduce this defect. The structure of such an alloy is shown in Fig. 94, which is the micrograph of an alloy containing about 12·5 per cent. of zinc and approximately 2·0 per cent. copper.

Magnesium.—This element combines with aluminium forming a compound (Al_3Mg_4) which forms a eutectic with aluminium containing 35 per cent. magnesium and melting at 465° C. This compound is also partially soluble in aluminium to the extent of about 10 per cent. magnesium. In small amounts it has a very marked effect on the strength of aluminium, increasing it very considerably. This effect is no doubt due in great measure to its powerful de-oxidising power and the consequent removal of oxide from the alloy.

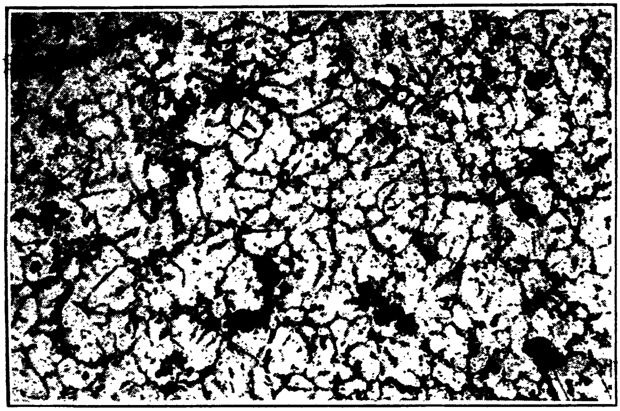


Fig. 91.—Micrograph of Aluminium-copper Alloy (copper 11·5 per cent.), showing Copper-aluminium Eutectic at the Crystal Boundaries (dark). Magnification 75 diams.; etched with caustic soda.

Manganese.—This metal appears to form a compound with aluminium which in turn forms a eutectic containing about 3 to 4 per cent. manganese, melting at 650° C. This compound is insoluble in aluminium. The alloy duralumin is dependent principally on magnesium and manganese for its high tensile properties.* The structure of this alloy is shown by Figs. 92 and 93, which are micrographs of bars having the following compositions :—

Analysis of Duralumin Bars.

	Fig. 92.	Fig. 93.
Copper	4·90	5·66
Magnesium	0·33	0·32
Manganese	0·58	0·54
Aluminium (diff.)	93·39	92·61
Iron	0·5	0·55
Silicon	0·3	0·32
Tin	Nil	Nil
Lead	Nil	Nil
Zinc	Nil	Nil

---

* This, however, is doubted by Rosenhain.

FIG. 92.—Micrograph of Duralumin alloy. Magnification 150 diameters; etched with caustic soda.

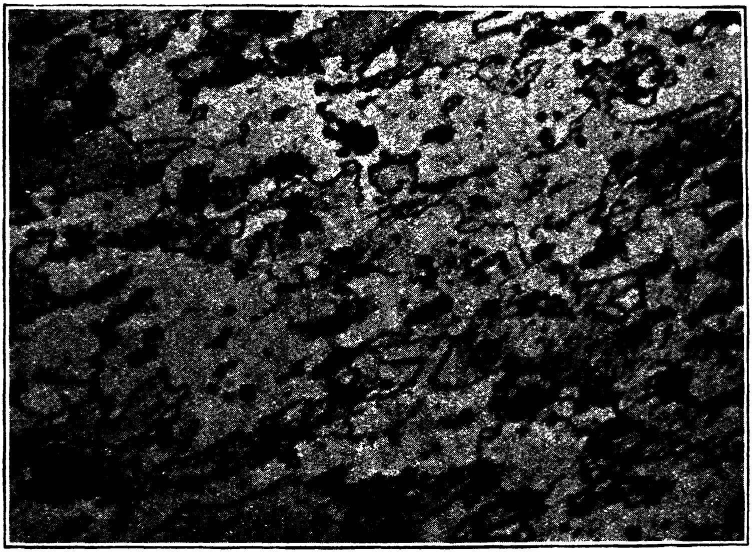


FIG. 93.—Micrograph of Duralumin alloy. Magnification 150 diameters; etched with caustic soda.

Iron.—This element occurs as an impurity and should therefore exist in small amounts only. It is usual to specify 1 per cent. as a maximum. Iron forms a compound with aluminium (Al_3Fe) which is practically insoluble at ordinary temperatures.

Silicon.—This element also occurs as an impurity and is usually limited to a maximum of 1 per cent. Silicon is slightly soluble in aluminium (about 0·5 per cent.) and it also forms a simple eutectic.

Nickel.—Nickel combines with aluminium, forming a compound (Al_3Ni) which forms a eutectic with aluminium, containing 7 per cent. nickel, melting at 630° C. This compound is not soluble in aluminium. The addition of nickel does not increase the strength of the material much, although chill castings are promising.

Tin.—This metal forms a compound with aluminium which appears to have a serious weakening effect on the metal and renders hot working almost impossible. Alloys containing tin can only be rolled cold.

Lead.—This metal should be regarded as an impurity and limited to about 0·1 per cent.

Casting Temperatures.—Aluminium alloys are much influenced by the temperature of pouring (see also Chapter XV.), and should be poured at the lowest possible temperature consistent with filling the mould completely. Aluminium has a high specific heat, and as a result the mould is heated very considerably and the casting cools slowly, producing a coarse-grained strucure. Thus large castings, especially if the section is great, will possess a coarser structure than smaller ones. As an example of this, two micrographs are shown in Figs. 94 and 95, the first being that of a large aluminium alloy rankcase, and the second that of a test bar cast from the same alloy. The rain size of the casting is larger and coarser than that of the test bar. It s, however, becoming standard practice to cast aluminium alloy test bars

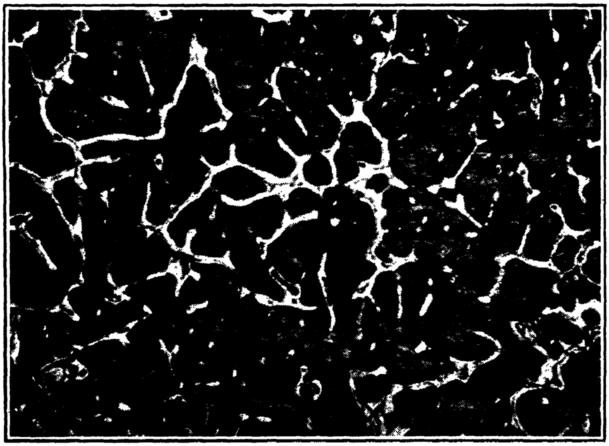


FIG. 94.—Micrograph of Copper-zinc-aluminium Alloy, part of Crankcase, showing large grain structure as compared with test bar (Fig. 95). Magnification 75 diameters; etched with caustic soda.

in a special chill mould, and to judge the metal on the results obtained from these test bars. This method has the advantage of being consistent so far as size and rate of cooling are concerned.

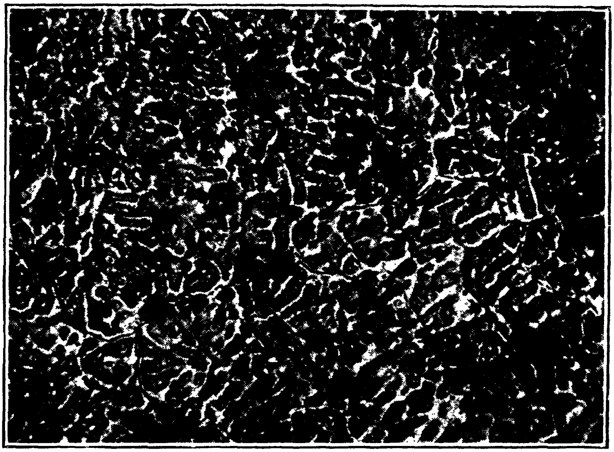


FIG. 95.—Micrograph of same Alloy as Fig. 94, but cut from test bar, showing smaller grain size due to more rapid cooling. Magnification 75 diameters; etched with caustic soda.

COPPER ALLOYS

The great variety of copper alloys and the numerous impurities they are likely to contain, make it difficult to foretell the influence of many component constituents when added to form any of these alloys. The combinations possible with so many elements will provide material for research for some considerable time to come ; the subject is so vast that in spite of the immense amount of investigational work carried out, there still remain many points about which there is little known.

It may be assumed, however, that an alloy which is simple in character (*i.e.* contains only a few components) and which gives the desired physical properties is always better than one which is more complex (*i.e.* contains more components) and which gives the same or only slightly better results. Obviously it is easier to control and manufacture a simple alloy than one which is more complex. The tendency of so many non-ferrous alloy manufacturers to purchase scrap metal (turnings, etc.), and to produce " new metal " from this material results in many " doctored " alloys being put on the market. While such material may fulfil the mechanical tests specified, it is often found that succeeding consignments will vary considerably both as to composition and test results and will often be found to give trouble in the shop in regard to machining. For example, the two halves of a bearing cast at different times and consequently from different " metal " may be found to machine quite differently, one taking the cut of the reamer quite well while the other half tears badly and has a rough finish. Another important case is that dealing with the wearing qualities of an alloy, where the test results may be quite satisfactory but the wearing quality very poor. As an actual instance the following particulars of two phosphor-bronze bushes will be of interest. These two bushes formed the bearings for a hardened knuckle pin in an aero-engine and were subjected to identical conditions as regards load, speed of rotation, and lubrication. Both had been made from material accepted by the Government inspectors who witnessed the mechanical tests at the makers' works, and the test results were good. Yet after giving the engine only a short run on the test bed it was discovered that one of the bushes "scored" very badly while the other remained unaffected. When examined it was noticed that the colour of the metal of the two bushes was different, and on analysis they were found to have the following composition :—

	Scored bush.	Good bush.
Copper	82·42 per cent.	87·10 per cent.
Tin	8·15 "	10·45 "
Phosphorus	0·21 "	0·59 "
Lead	2·39 "	0·65 "
Nickel	0·03 "	trace
Iron	0·63 "	trace
Zinc	6·17 "	1·21 "

The presence of so much zinc in the defective bush is undoubtedly the cause of its failure, and on examining material lying in stock it was found that that which had been supplied by one firm had substantially the same composition as the scored bush while that from another maker agreed with the good bush. Thus the tests for tensile strength, etc., failed entirely to discover and prevent what amounted to a very serious situation.

Chief Constituents of Copper Alloys.—The principal commercial alloys are divided into groups under the following well-known names :—

1. Bronzes ..	Plain Bronze Phosphor Bronze Manganese Bronze* Aluminium Bronze Gunmetal
2. Brasses ...	Cast Brass Low Brass (Muntz Metal) High Brass Special Brasses
3. Special Alloys	Cupro-nickel German Silver (Nickel Silver)

There are in addition many more alloys having many different trade names, but it would be impossible in the space of this book to deal with them. They all come, practically speaking, under one of the above headings and can be dealt with accordingly. The base of all these alloys is copper, which is never less than 50 per cent. of the total. This metal when associated with tin alone forms the basis of the bronze alloys, and when alloyed with zinc alone produces the brasses. Thus the distinctive feature of a bronze alloy is the presence of tin and of a brass alloy the presence of zinc.

The approximate compositions of some of the bronzes and brasses are given in the following tables. These figures, however, must only be accepted for the

---

* Should be classed as a brass.

purpose of fixing in one's mind the general character of the compositions, *i.e.* as a base on which to build up further information regarding the many variations found in practice. A more complete table is given in Chapter XV, containing data as to impurities and also the test results likely to be obtained.

BRONZES.

Description.	Copper.	Tin.	Zinc.	Phosphorus.	Principal uses, etc.
	Per cent.	Per cent.	Per cent.	Per cent.	
Plain Bronze ..	80	20	—	trace	Dies, bells, bearings.
Plain Bronze ..	90	10	—	trace	Pumps, collars, bearings.
Phosphor Bronze	91	9	—	0·5	Gears, worm wheels, etc.
Phosphor Bronze	88	11	—	1·0	Hard bearing metal.
Gunmetal ..	88	10	2	—	Admiralty gunmetal.
Aluminium Bronze	92	—	—	—	8 per cent. aluminium.

BRASSES

Cast Brass ..	66	—	34	—	All classes of castings.
Low Brass ..	60	—	40	—	Yellow brass—hot rolled (Muntz metal).
High Brass ..	70	—	30	—	For tubing—rods and wire (draws well).
Manganese Brass	56	1	41	—	0·5 per cent. manganese, 1 per cent. iron, 0·5 aluminium, for Propellers and all strong castings.

SPECIAL COPPER ALLOYS.

Description.	Copper.	Nickel.	Zinc.		
	Per cent.	Per cent.	Per cent.		
Cupro-nickel ..	60	40	—	—	Constantan-Electrical resistance wire.
,, ,, ..	80	20	—	—	Similar to bullet envelope metal.
,, ,, ..	98	2	—	—	Tubing—rods and wire.
German Silver ..	50	20	30	—	Now known as nickel silver.

These tables do not include the various impurities associated with such alloys; these will be dealt with later. For the present the behaviour and influence of the main constituents will be explained.

Tin.—Apart from copper, tin is the principal constituent in bronze and gunmetal. Theoretically, tin is dissolved in copper to the extent of about 13 per cent. the solid solution being given the name "Alpha" constituent, but in actual practice a less amount is dissolved. This is brought about by the fact that an alloy of 10 per cent. tin when cooling normally freezes too rapidly to attain to homogeneous equilibrium. This same alloy, however, if cooled very slowly, would consist entirely of the alpha phase (solid solution). In practice, the first portions to solidify are richer in copper than the average composition of the mass, and the successive portions freezing contain increasing proportions of tin; thus at the moment of final solidification the portions that are liquid last are so rich in tin as to solidify as a separate constituent (or phase) known as the "beta" phase. At about 500° C. a transformation occurs (in the solid state) whereby this beta phase decomposes into two phases: one being the alpha constituent (of similar composition and properties to the primary alpha crystals), and the other being known as the "delta" constituent (or phase), corresponding approximately to the compound Cu_4Sn in composition, and possessing greater hardness even than that of the beta phase.

The constituent resulting from the decomposition of the beta phase is thus duplex, of reticular form, and is known as the alpha and delta eutectoid. The alpha phase appears (under the microscope) as a bronze-yellow constituent and the delta phase is white with a tinge of blue.

By heating the alloy for a short time above 500° C., the alpha and delta crystals of the eutectoid mutually dissolve one another to form again the beta phase and, if the time of heating be sufficiently prolonged, these beta phase crystals are entirely dissolved by the primary alpha crystals, of which the alloy henceforth solely consists, whether cooled quickly or slowly.

The temperature best suited to effect this change of structure is 700° C., and for most castings a period of half an hour at that temperature will be sufficient. An increase of temperature involves the risk of coarsening the grain (with accompanying weakness) or even of incipient fusion.

From the above it will be seen that with alloys containing 10 per cent. of tin the casting will consist of two constituents: the solid solution which is tough and the delta constituent which is hard and brittle. On heat treating this alloy, however, the latter constituent can be made to disappear and the alloy then consists wholly of a solid solution. Both states of the alloy are of service, the first with its hard constituent being most suitable for bearings or other frictional parts, while the second or heat-treated state is better for pressure work such as hydraulic fittings, etc., since it is less porous and is the stronger. The heat treatment of this alloy is dealt with more fully in Chapter X.

Tin does not increase the strength of copper by a large amount, but it facilitates the production of castings and forms an alloy which is more machinable than copper. When added in amounts less than 6 per cent. an alloy (bronze) is found which is malleable and can be rolled and drawn cold into sheet or wire. Above this amount the alloy cannot be rolled with ease, while at 9 per cent. the formation of the delta constituent entirely prevents working except at dull red heats (700° C.), when it can be rolled or forged. If heat treated as explained above, a certain amount of work can be put into it.

When an alloy having a combination of strength, elasticity, toughness, and ability to withstand shock is required the proportion of tin should be between 8 and 11 per cent. Larger amounts are used for alloys like bell metal, containing from 15 to 25 per cent. tin.

The microstructure of an 8 per cent. tin alloy is shown in Fig. 96.

Phosphorus.—Phosphorus is added to bronzes and similar alloys with the object (1) of reducing any oxides which may be present in the molten metal, and (2) of producing an alloy containing a definite proportion of phosphorus.

In the first case only sufficient phosphorus is added in the form phosphor-copper (or phosphor-tin) to effect the reduction of the oxides. The reaction results in the formation of oxide of phosphorus which, owing to its acid character, combines with the remainder of the oxides and passes into the slag in the form of phosphates. If the amount added is in excess of what is required for reduction purposes the final alloy will contain a little phosphorus, but such an alloy, even though it may be called phosphor bronze, must not be confounded with those alloys containing phosphorus in quantities of 0·2 to 2 per cent. The effect of those larger amounts will be dealt with later.

This purifying action of phosphorus renders the alloy much more fluid and produces castings which are free from pinholes, and are much tougher than those of ordinary bronze. It is doubtful whether any bronzes are produced now without the use of phosphorus as a reducing agent for removing the dissolved oxides.

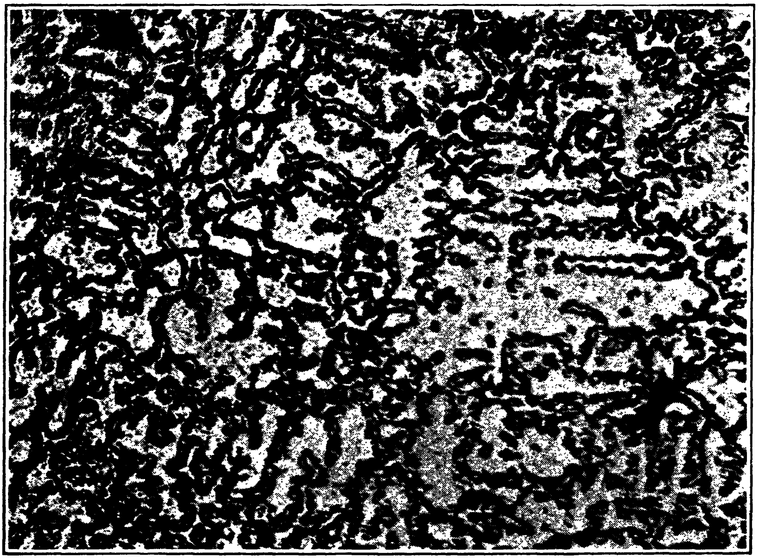


FIG. 96.—Micrograph of Phosphor Bronze (Cu 91·68, Sn 7·99, P 0·05), showing the Alpha Solid Solution and the Eutectoid. Magnification 150 diameters; etched with ferric chloride.

When phosphorus is added in such quantities as to remain in the alloy as a definite constituent it will be found to have combined with the copper, forming phosphide of copper (Cu_3P), which is slightly soluble in copper but which usually separates out as a eutectic with copper. When tin is present in amounts sufficient to form a separate phase (known as the delta phase and approximating to the composition Cu_4Sn) the latter is associated with the phosphide and with some copper-rich alpha solid solution as a "triple" eutectic. The two compounds having nearly the same colour are difficult to distinguish from each other, although the phosphide has a slightly deeper cast of blue. This triple conglomerate is shown in Fig. 97, which is a micrograph of a phosphor bronze containing 88·4 per cent. copper, 10·7 per cent. tin, and 0·9 per cent. phosphorus.

Phosphide of copper is a very hard and brittle compound, nearly as hard as hardened tool steel, while the eutectic formed, although softer, is still very hard. Thus an alloy containing much of this constituent will be hard but will not be ductile, which explains why many phosphor bronzes containing over 0·2 per cent. of phosphorus cannot be rolled or drawn. When tin is present to the extent of over 8 per cent. the compound Cu_4Sn formed also prevents rolling and drawing.

The hardness of phosphide of copper is a valuable property in so far as it makes these alloys very useful for bearings. Its presence as small hard particles supported by the softer tin-copper solid solution forms a structure of the right character for bearing surfaces. Its extreme hardness, however, renders it unsuitable for mild steel shafts, etc., owing to the tendency to score them, but for hardened steel frictional surfaces it is particularly good.

FIG. 97.—Micrograph of Phosphor Bronze. Magnification 150 diameters.

The strength of a bronze (tin-copper alloy) is increased by slight additions of phosphorus owing to its deoxidising action and consequent purifying of the alloy, but as the percentage of phosphorus is raised the strength and ductility fall off. With 1 per cent. phosphorus the elongation on 2 inches is only about 2 per cent. Thus its use as a bearing metal is not demonstrated by tensile tests, its real value in that direction being dependent on the presence of the hard particles already mentioned.

Lead.—This metal is practically insoluble in copper and bronze and nearly always separates out in globules or as a network surrounding the primary crystals. It has therefore a very serious effect on the strength of copper, producing brittleness.

In a good bronze the amount of lead should not exceed 0·15 per cent. When, however, strength is not of great importance a larger amount is permissible or even desirable since it improves the machining quality of the alloy. For bearings lead is purposely added in large amount as it increases the plasticity of the bronze. A well-known brand contains about 4 per cent. and there are special bearing bronzes containing as much as 30 per cent. lead. The lead does not remain in solid solution, but appears in the form of very small globules, and if the proportion is high it tends to segregate or even separate out into a separate layer. This defect is overcome to some extent by chill casting.

Since lead melts at 327° C. it is clear that any alloy containing a marked amount will be useless at high temperatures.

In a high-grade brass the lead should not exceed 0·10 per cent., but where ease of machining is the greatest consideration amounts up to 2·0 per cent. are permissible. The lead being in a free state enables the turnings to break off readily along the lines of weakness caused by its presence. It would also appear that the lead acts as a lubricant, thus permitting higher machining speeds, and producing a better finish.

Nickel is sometimes added to prevent segregation of the lead should this be present in large amount. Apparently it assists in the formation of more complete network, which retains the lead, as it were, in a number of closed compartments.

Zinc.—This metal behaves in a variety of ways when alloyed with copper and the alloys are very complex, depending on the proportion of zinc present. Over the range of alloys used commercially, however, the behaviour is comparatively simple, and it is only these that will be considered here.

The copper-zinc alloys are those chiefly known as brass, and their proportions usually come within the limits of 30 to 63 per cent. of zinc. Up to about 37 per cent. the zinc goes into solid solution in the copper, probably as a compound, but above this another solid solution is also formed. Thus, at ordinary temperatures, brasses with less than 37 per cent. zinc are one uniform constituent, but with more zinc they consist of two constituents. The first can be rolled cold and drawn, but the second can be rolled hot with ease. Hot working is possible with the first, if very pure.

The structure of a rolled bar of brass containing 57·6 per cent. copper, 39·8 per cent. zinc, and 2·5 per cent. lead is shown by Fig. 98. The two constituents are clearly distinct.

Zinc raises the tensile strength from 14 tons per square inch for pure copper, to about 30 tons per square inch for an alloy containing 45 per cent. zinc, after which further additions cause a rapid fall until at 50 per cent. it is practically nothing. The ductility, as shown by the elongation, increases from 32 per cent. for copper to a maximum of 56 per cent. at about 30 per cent. zinc, 70 per cent. copper, and then falls off to almost nothing at 50 per cent. zinc.

Zinc is often added to tin-copper alloys with the object of producing a more fluid metal. It acts as a deoxidiser, zinc oxide being formed and coming to the surface. Up to about 2 per cent. zinc does not affect the mechanical strength of the alloy, but above this it weakens the metal and reduces its ductility. In small amounts the zinc appears to be dissolved in the tin-copper solid solution.

Castings containing zinc are usually freer from pinholes and other defects of this kind.

Iron.—Small amounts of iron in bronze or brass increase its strength and hardness. It appears to combine with the zinc or dissolve in it and takes up the form of small globules which are bluish in colour. A brass known as Delta metal generally contains iron up to about 2 per cent., but also has small proportions of aluminium and manganese present. The aluminium is probably added to overcome the sluggishness of the metal during pouring, brought about by the addition of iron.

Manganese.—This element is often added to copper-zinc alloys (brass) to form what are known as manganese bronzes, although they are, strictly speaking, brasses. The analysis of some of these special bronzes often reveals little or no manganese whatever, but this is explained by the fact that manganese acts as a deoxidiser like phosphorus and has therefore been more or less completely used up in purifying the metal.

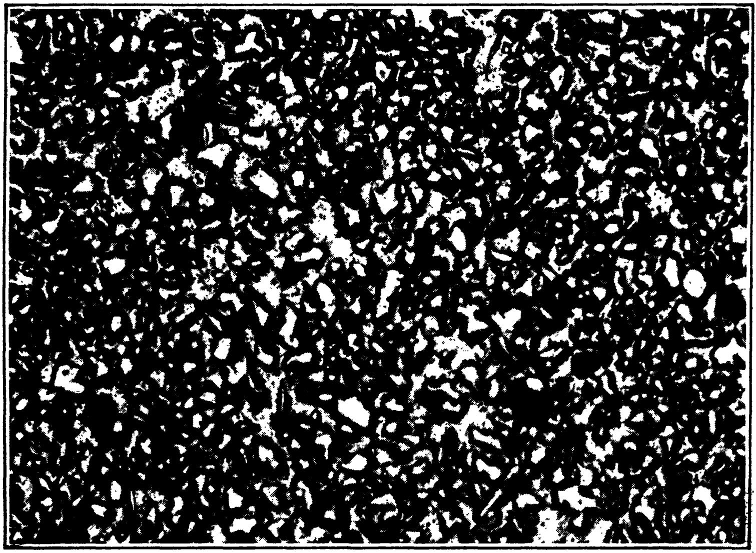


FIG. 98.—Micrograph of Rolled Brass Bar (Cu 57·6, Zn 39·8, Pb 2·5), showing Alpha and Beta constituents. Magnification 150 diameters; etched with ferric chloride.

Manganese goes into solution and is not seen under the microscope, but as most manganese bronzes contain iron and aluminium as well, their structure is somewhat different to ordinary brasses. Figs. 99 and 100 are micrographs of a manganese bronze rolled bar and a hot stamping respectively. The bar is a typical structure, but the structure of the stamping is bad from the machining point of view and in actual practice "dragged" badly.

Manganese increases the tensile strength of the alloy, so also does the iron which usually accompanies it. Aluminium is added to facilitate the pouring and the production of sound castings. Usually the amount of manganese varies between 0 and 2 per cent.

Aluminium.—This metal is added to copper to form a series of alloys known as "aluminium bronzes." These may contain up to 11 per cent. of aluminium. Over this range the constitution of the alloys is comparatively simple: up to about 7·4 per cent. the aluminium goes into solid solution and

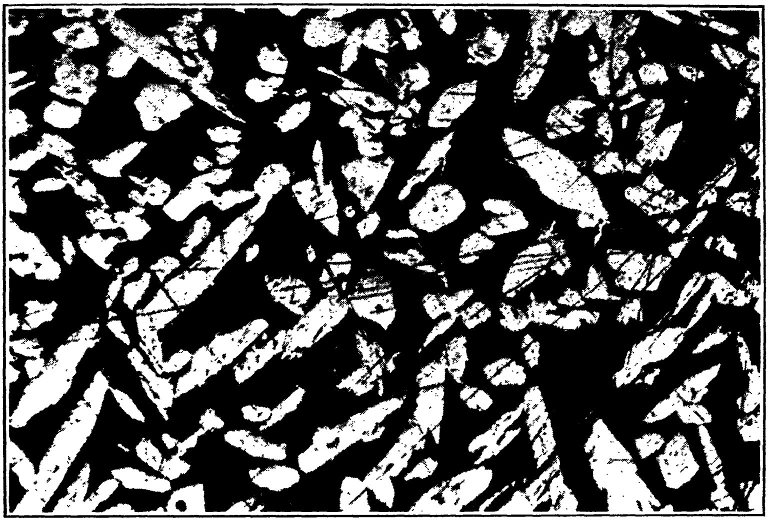


Fig. 99.—Micrograph of Normal Manganese Bronze Bar. Magnification 150 diameters; etched with ferric chloride.

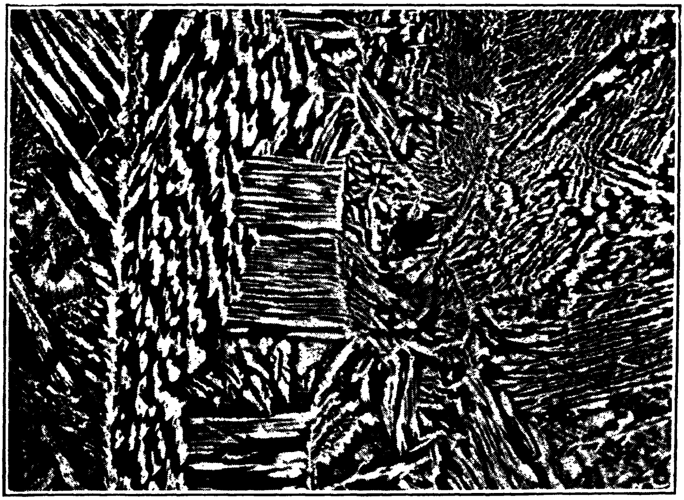


Fig. 100.—Micrograph of Manganese Bronze Hot Stamping. Metal difficult to machine —tears badly. Magnification 75 diameters; etched with ferric chloride.

the metal is homogeneous, while above this, and up to about 10 per cent. a second constituent appears which is dark coloured.

Aluminium increases the tensile strength and especially the ductility, but when the proportion exceeds 7·4 per cent. the latter falls off considerably while the tensile strength increases more rapidly.

The effect of heat treatment on those alloys containing less than 7·4 per cent. aluminium is very slight, and their strength is not altered much by annealing or by quenching in water. The higher alloys, containing over 7·4 per cent. aluminium are, however, much affected and the dark hard constituent referred to above gradually changes, its structure disappearing. It appears to be in an unstable state until subjected to prolonged annealing. These alloys when quenched have a much higher tensile strength. The heat treatment of these alloys is dealt with more fully in Chapter X.

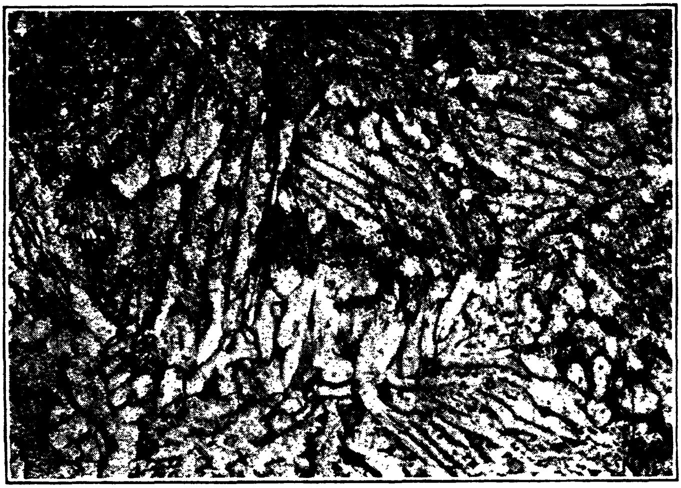


FIG. 101.—Micrograph of Aluminium Bronze (Cu 91·75 per cent., Al 8·05 per cent.). Magnification 75 diameters; etched with chromic acid.

Aluminium is sometimes found in ordinary bronzes and brasses. When present in small proportions it increases the tensile strength, but it causes a serious falling off in the ductility and should not exceed about 2·0 per cent.

Nickel.—This metal forms some useful alloys with copper. The metals appear to be soluble in each other, and the structure of the alloys produced is quite simple. During cooling, especially if rapid, the portions which crystallise first are richest in nickel and the succeeding portions are poorer. Thus the crystal grains may be richer at the centre than at their boundaries.

Defects and Faults in Materials as revealed by the Microscope

A few examples of the more common defects or faults found in commercial materials are collected and described in the following pages. Many other faults are found in practice, and occasional reference is made to these in subsequent chapters.

Steel.—The rolling or cogging down of an ingot of steel has the effect of elongating the separate dendrites or crystals, with the result that a laminated or banded structure is obtained. This is illustrated by Fig. 133, Chapter X, where the effect of cogging down is shown at three separate stages. A typical case of this laminated structure is shown in Fig. 102.

Another case, but where the material is a 4 per cent. nickel steel, and where the specimen is etched with Stead's cupric reagent, is shown by Fig. 103. The structure is very laminated.

This form of structure can be rectified by suitable heat treatment and is generally not dangerous. Fig. 104 shows the effect of heat treatment on the nickel steel just referred to. The laminations are not entirely removed, but no doubt a further heating would produce a uniform structure throughout the mass.

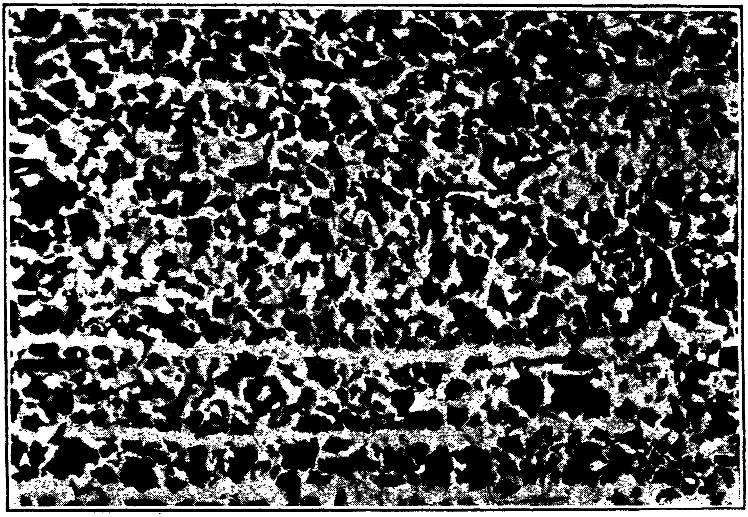


FIG. 102.—Micrograph showing Banded Structure due to Segregation or Coarse Crystal Growth in original Ingot, and the effect of Rolling. Steel 0·4 per cent. carbon. This is a common structure for billet steel. Magnification 150 diameters; etched with picric acid.

This ordinary banded structure must not be confounded with the more serious form, consisting of seams or streaks of impurities such as slag, sulphides, phosphorus-rich iron, oxide inclusions, etc. Such defects are generally due to the cavities which form in the cast ingot during solidification. These nearly always exist in the centre or axis of the ingot because this portion is the last to cool and contain most of the impurities like slag, phosphorus, sulphur and sometimes oxides of manganese and iron. The size and shape of the ingot mould has a lot to do with the presence of these cavities, and their position in the ingot. Also there is no question that the temperatures of the steel during making and during the actual pouring or teeming have a considerable influence on the soundness of the material.

In the subsequent processes of cogging down and rolling of the ingot a

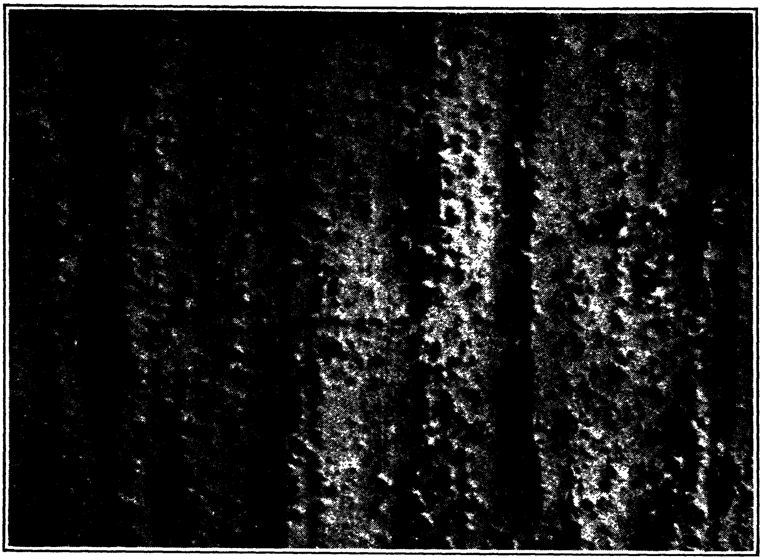


FIG. 103.—Micrograph of 4 per cent. Nickel Steel etched with Stead's Cupric Reagent, showing badly Laminated or Banded Structure. This steel in the hardened state would break away in flakes. Magnification 150 diameters.

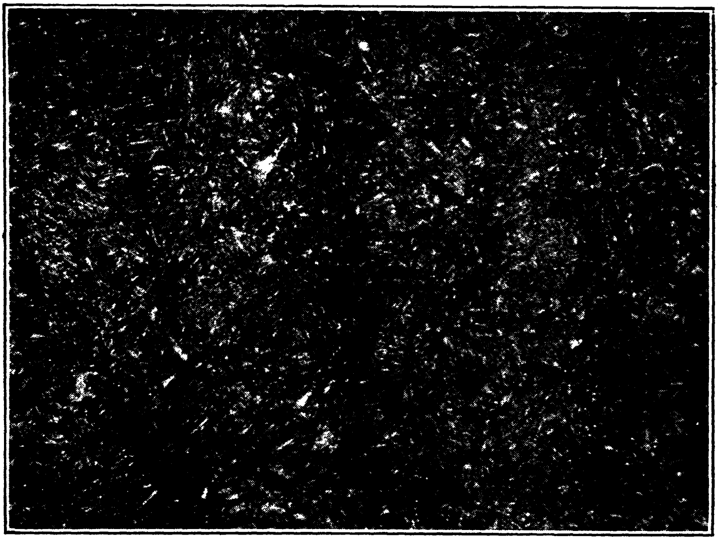


FIG. 104.—Micrograph of the same Steel as Fig. 103, but heat treated to reduce Banded Structure, which, as will be seen, is not completely eliminated. Magnification 150 diameters; etched with picric acid.

number of the cavities are welded up, but where slag or other impurities are present this cannot happen, and, in consequence, these are drawn out with the

Fig. 105.—Micrograph showing Slag Streaks (black ragged lines) in Mild Case-hardening Steel. Magnification 200 diameters; etched with picric acid

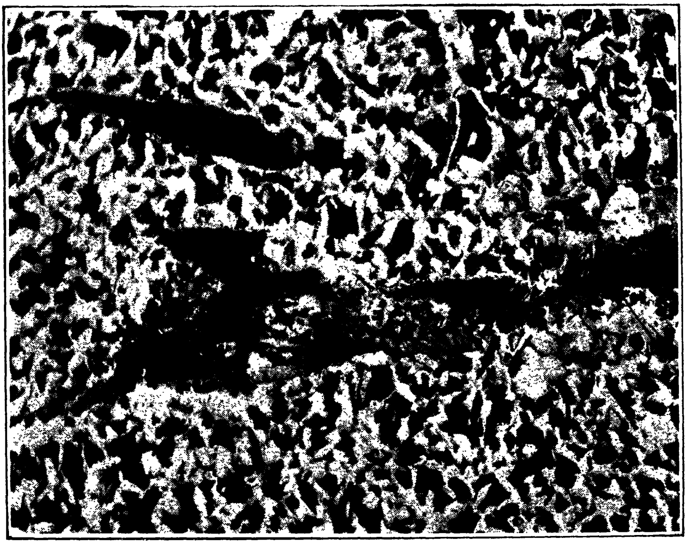


Fig. 106.—Micrograph showing cross-section of Slag Streaks in a Medium Carbon Steel Forging. Magnification 150 diameters; etched with picric acid (slag black, carbon black, ferrite white).

metal into streaks or seams which break the continuity (transversely) of the material. Examples of such streaks or "inclusions" are shown in Figs. 105, 106, 107, 108, and 109. Of these the first four show the presence of slag which is seen as a black-looking streak with ragged edges. Fig. 109 shows inclusions of manganese sulphide running right across the centre. The presence of slag in small amounts is of little danger, but when present in amounts as represented by Fig. 105 or Fig. 106, the steel should be condemned for reliable work.

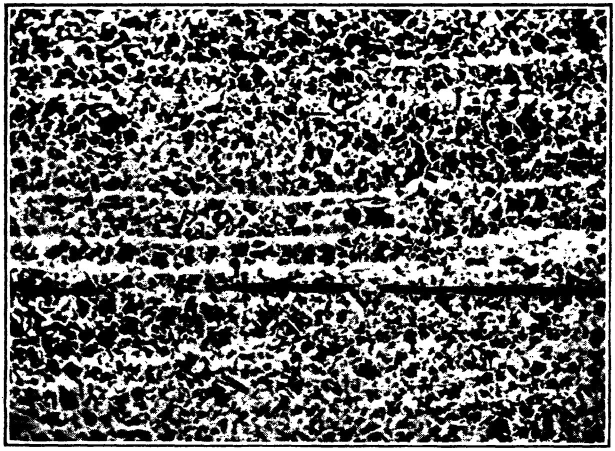


Fig. 107.—Micrograph showing Slag Streaks and Banded Structure in Medium Carbon Steel (0·4 per cent. carbon) Billet. Magnification 75 diameters; etched with picric acid.

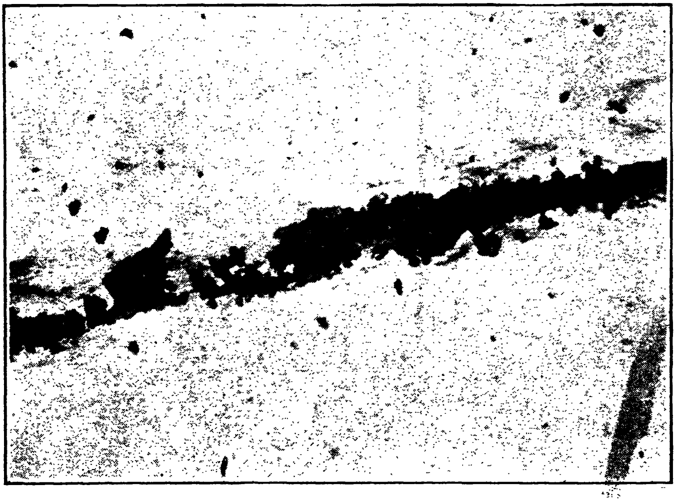


Fig. 108.—Micrograph showing Slag Streak in Alloy Steel (C 0·33, Ni 3·63, Cr 0·97). This accounted for the presence of cracks in heat-treated bars, 15 per cent. being defective in this manner. Magnification 75 diameters; specimen polished only.

Phosphorus is associated with many segregation troubles and is responsible for persistent banding or lamination. It exists in zones or bands dissolved in

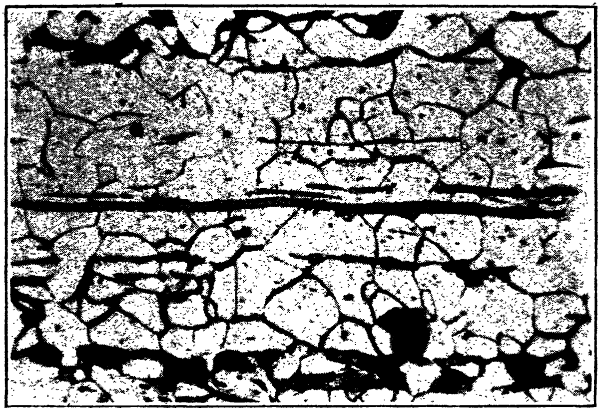


FIG. 109.—Micrograph showing Streaks of Manganese Sulphide (grey) and also Slag (dark ragged streaks) in mild Case-hardening Steel. Magnification 200 diameters; etched with picric acid.

FIG. 110.—Micrograph showing Crack in Medium Carbon Steel Bar. View of cross section with edge of bar showing (top). Note the deficiency of carbon areas in the vicinity of the crack. Magnification 50 diameters; etched with picric acid.

the iron, and as these bands are often freer from carbon than the rest of the material they can be picked out as white bands (sometimes called "ghost lines"). In many cases the cracks found in bar steel are due to a segregation defect of this kind. Figs. 110 and 111 are examples of a crack found in a bar of medium carbon (0·4 per cent.) steel 1¼ inches diameter.

Fig. 110 shows the cross section of the bar near the surface, the actual edge of the bar being shown. The path of the crack towards the interior is quite clear. The path of the crack along the bar is shown by Fig. 111, which is a section taken parallel to the axis of the bar, and about 2 mm. below the surface. In both cases the comparative absence of carbon areas round about the crack will be noticed.

FIG. 111.—Same as Fig. 110, but showing Crack running along the Bar. View about 2 mm. below surface of bar. Note the deficiency of carbon areas in the vicinity of the crack—probably due to phosphorus segregation.

Such a zone or band by reason of the absence of carbon must be weaker than the remainder of the material, and, during the rolling and reheating, any tendency to crack will naturally take effect in this band, particularly if there is much phosphorus present.

Another possible explanation for cracks of this kind is the rolling in of fins of metal during the manufacture of the bar. These fins are decarburised during heating prior to rolling, thus accounting for the lack of carbon in the vicinity of the crack. Spongy ingots are another possible source of trouble.

Overheating is a common source of trouble and usually occurs in the drop stamping or forging shops.

Examples of overheated steel are shown in Figs. 112, 113, 114, 115, 116, 117, and 118.

When the steel is actually " burnt " it is worthless and no method of heat

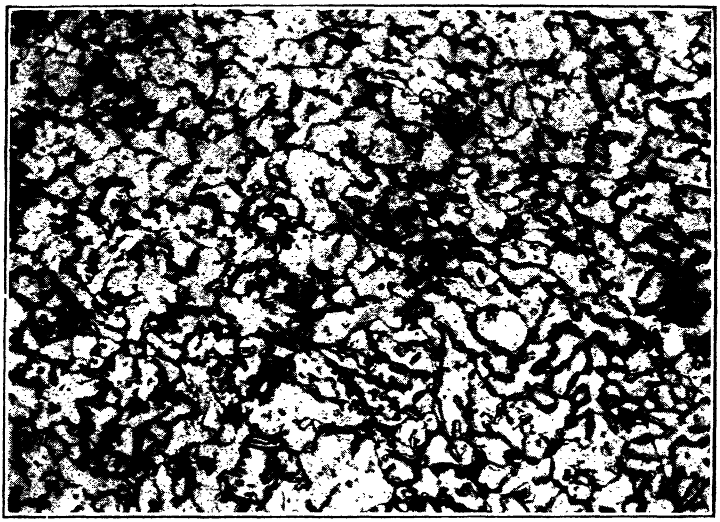


FIG. 112.—Micrograph of a Mild Steel Stamping. The metal has been heated to so high a temperature that it is actually burnt. Note the peculiar formation of the grain boundaries. Magnification 150 diameters; etched with picric acid.

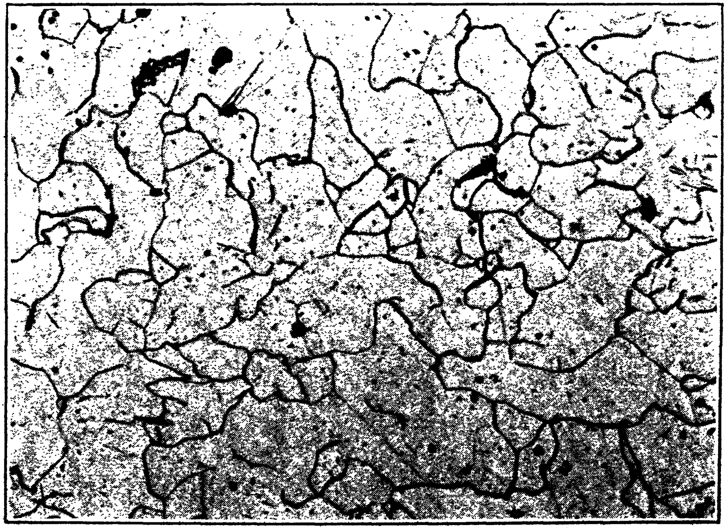


FIG. 113.—Same as Fig. 112, but a view close to the surface of the stamping showing how completely the metal has been decarburised (no carbon areas being visible). Again note the double boundary lines of the grains—due, presumably to oxidation. Magnification 150 diameters; etched with picric acid.

treatment will restore it. Such burnt steel is shown by Figs. 112, 113, 114, and

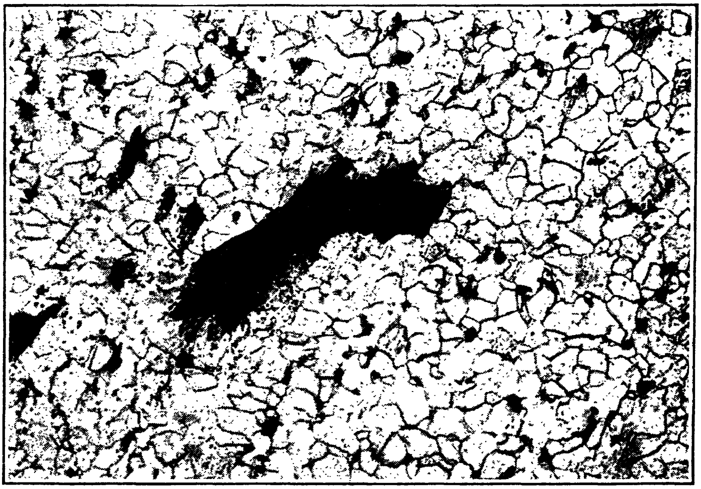


FIG. 114.—Micrograph of a Mild Steel Stamping which has been "Burnt," showing serious oxidation in the interior of the metal. Note the oxide inclusions (black patches, one large one in centre), and the thickness of the grain boundaries. Magnification 150 diameters; etched with picric acid.

FIG. 115.—Micrograph of Medium Carbon Steel which has been seriously overheated and partially "Burnt." Note the formation of the grain boundaries (white) and the black line or dots running along their centres, also the coarse broken-up formation of the grains themselves. Magnification 75 diameters; etched with picric acid.

115. Steel which has been simply overheated can be recovered by heat treatment, although this may have to be a very prolonged operation. A stamping made from medium carbon steel at a temperature about 1,350° C. had the structure shown by Fig. 116, but by heat treatment the structure was considerably refined as is shown by Fig. 117. This, although much finer, is not yet first

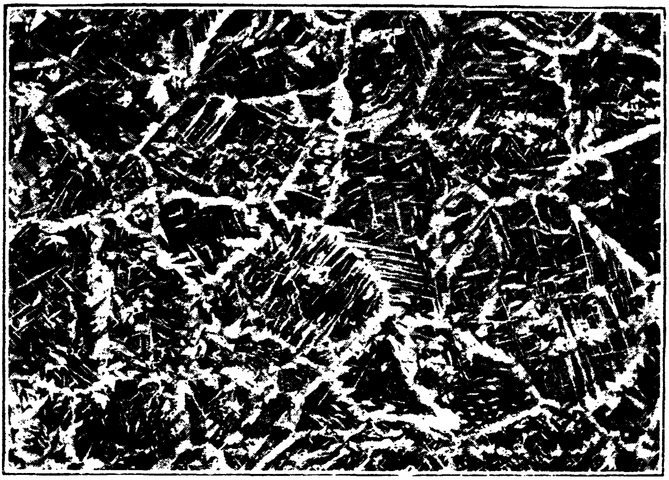


Fig. 116.—Micrograph showing Structure of Overheated Medium Carbon Steel Stamping. Note the coarseness of the grain boundaries and the spine growth or cleavage lines in the grains. This stamping was forged at 1360° C., and finished at about 1100° C. Magnification 75 diameters; etched with picric acid.

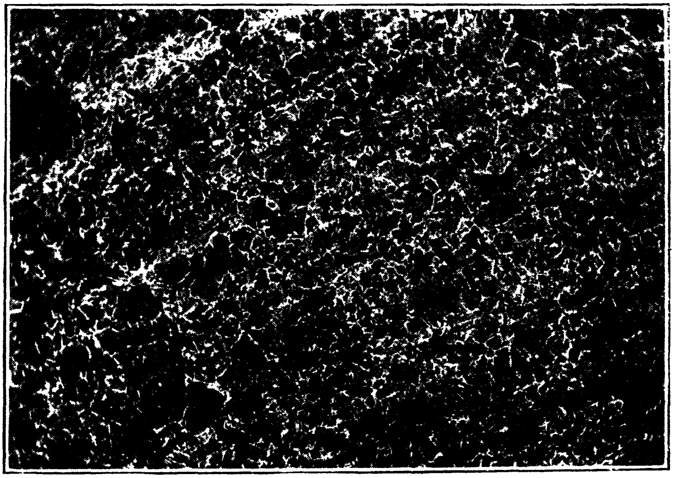


Fig. 117.—Micrograph of same stamping as Fig. 116, but showing the Effect of Heat Treatment. Note the refinement of the grain structure, also that diffusion is not complete. This structure is still capable of further refinement. Magnification 75 diameters; etched with picric acid.

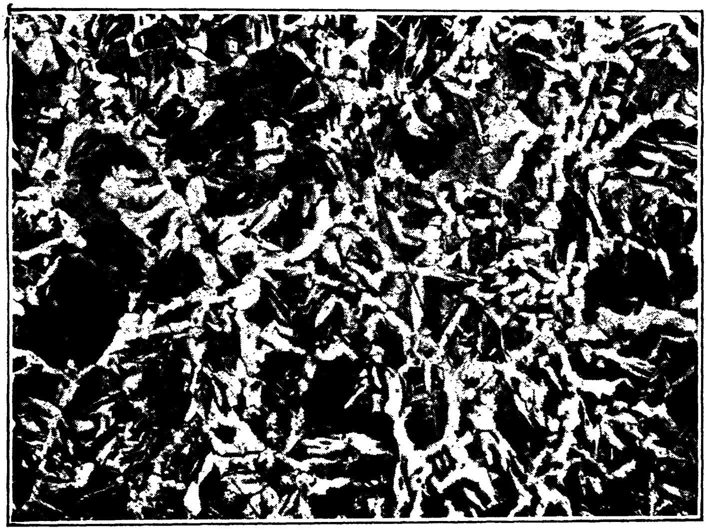


Fig. 118.—Micrograph showing Structure of Overheated Nickel Chrome Steel. Note the lack of uniformity and how difficult diffusion will be when a restoring treatment is applied. Cut from a gear wheel stamping forged at too high a temperature. Magnification 150 diameters; etched with picric acid.

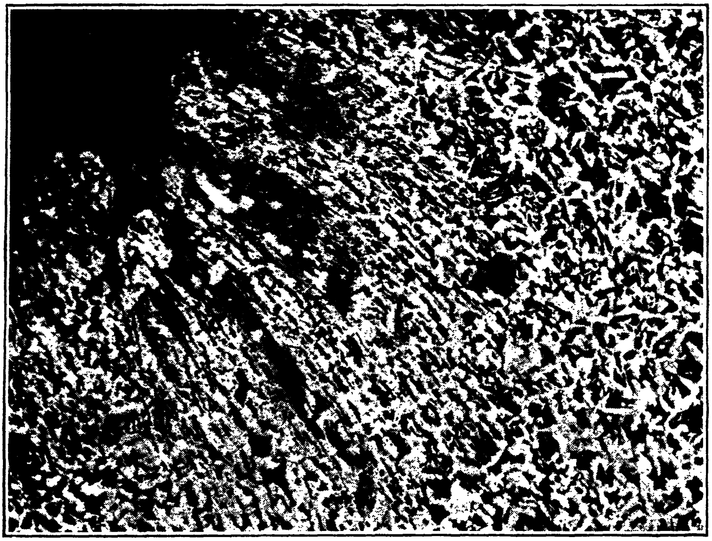


Fig. 119.—Micrograph showing Structure of "Cold-worked" Medium Carbon Steel. View taken at radius of middle web in "H" section connecting rod stamped at too low temperature. Note the distorted form of the grains. Magnification 150 diameters; etched with picric acid.

class. Overheating in the case of alloy steels is very serious because of the extreme difficulty in restoring their structure. An example of overheated nickel chrome steel is shown by Fig. 118.

Cold working also occurs sometimes and as an example Fig. 119 is given. This shows the metal situated at the inside radius of an "H" section connecting rod. The thin section of the rod and the ease with which it cooled is responsible for the punishment the metal has received.

Malleable Iron.—An example of a poor malleable iron casting is shown in Fig. 120. This structure indicates that the casting as originally cast was not white iron but contained graphite flakes like grey iron. This is due to the presence of too much silicon.

FIG. 120.—Micrograph showing Structure of Brittle Malleable Iron Casting (Blackheart). Note graphite flakes, showing that original casting must have been partly grey instead of completely white (*i.e.* all carbon in the combined form). Other portions of same casting were free from graphite flakes, while some parts had a few flakes here and there, showing that casting was more or less mottled. Silicon = 1·1 per cent.; section of metal ¼ inch. Magnification 150 diameters; specimen polished only.

Heat Treatment.—Most cracks seem to develop during heat treatment (although this usually is not at fault). An example of a crack running inside the metal parallel to the surface is shown by Fig. 121, which is a micrograph of a piece of case-hardened nickel steel. The crack exists in the zone between the "case" and the core, namely, where the percentage of carbon falls off to about that of the core itself. In this particular instance the part had been carburised at a very high temperature, 1,050° C., and in consequence the line of demarcation between the core and case was very sharp. This source of trouble, usually referred to as enfoliation, is more usual with carbon than with nickel steels. The hardening sets up a high tensile stress in the case and as, in this instance, this steel was very full of slag streaks, a crack has developed at the weak point shown in Fig. 122, and running from the surface *viâ* two or three slag streaks, has reached the line of demarcation and a cleavage crack has simply

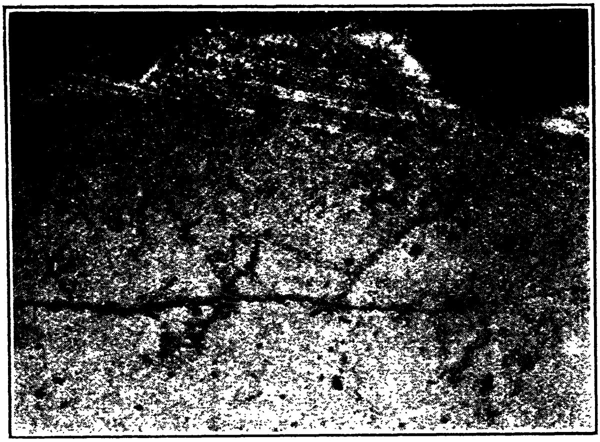


FIG. 121.—Micrograph showing Crack in Case-hardened Nickel Steel. Crack runs parallel to surface in a zone where the high carbon falls off to the low carbon core. The line of demarcation between the core and case is too sharp, due to carburising at too high a temperature. Magnification 150 diameters; etched with picric acid.

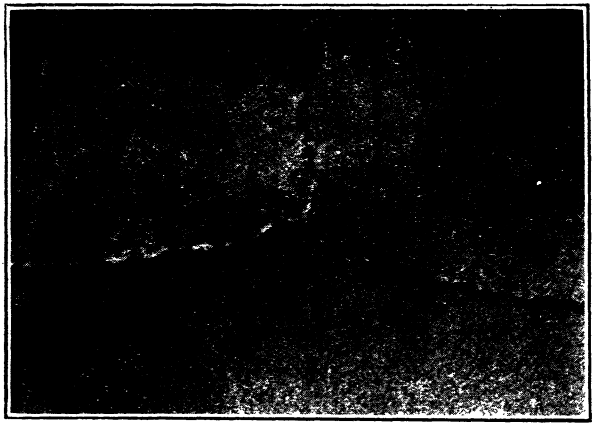


FIG. 122.—Same as Fig. 121, but shows Crack running out to Surface and also how the slag streaks (spots) assist its passage. Magnification 150 diameters; etched with picric acid.

run along this line, and the case has almost peeled off. The manner in which the crack proceeds from slag streak to slag streak (shown in section by round black dots) is shown more clearly in Fig. 123, which is a photograph at a higher magnification (300 diams.) of a portion of the crack shown in Fig. 121.

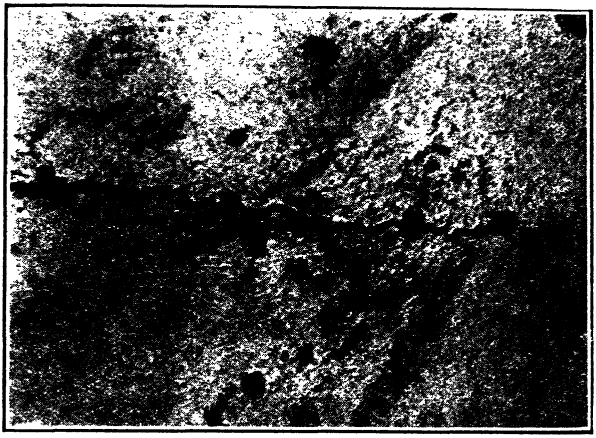


FIG. 123.—Same as Fig. 121, but at a higher magnification showing more clearly how the crack proceeds from slag streak to slag streak (round black dots). Magnification 300 diameters; etched with picric acid.

FIG. 124.—Cracks produced on Surface of Case-hardened Camshaft by Grinding Operation. Phosphorus in case 0·044 per cent. (normal), nickel 2·5 per cent. Magnification 25 diameters; specimen simply polished.

Another source of cracking of the "case" of case-hardened parts is the grinding operation. Such cracks are often very difficult to find at first, but they usually open out and can be seen after a few days. An example of grinding cracks is shown in Fig. 124.

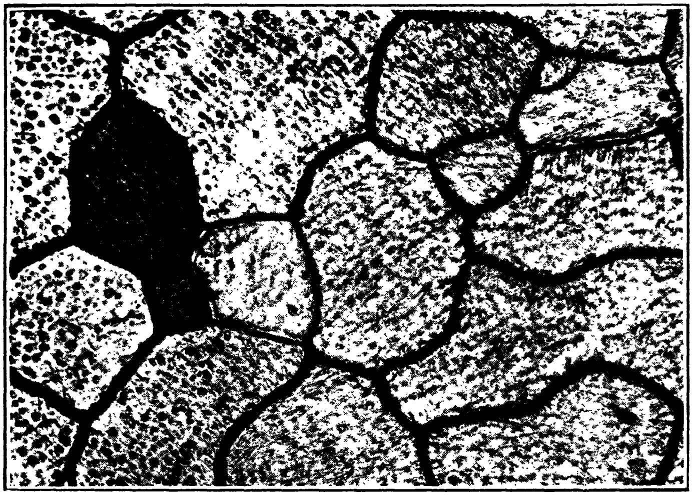


Fig. 125.—Micrograph of Defective Aluminium Bronze Casting, burst during drilling operation. Note coarse structure due to casting at too high a temperature. Magnification 75 diameters; etched with chromic acid.

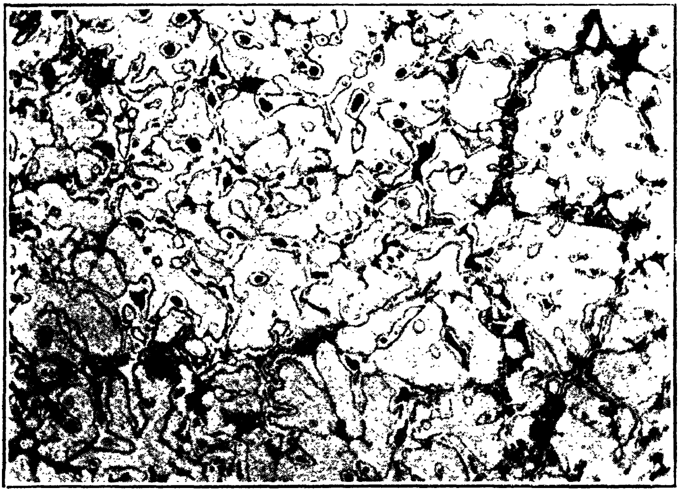


Fig. 126.—Micrograph of Aluminium Alloy Casting showing normal good structure free from blowholes. Magnification 75 diameters; etched with caustic soda.

With non-ferrous alloys a common trouble is casting at too high a tempera-

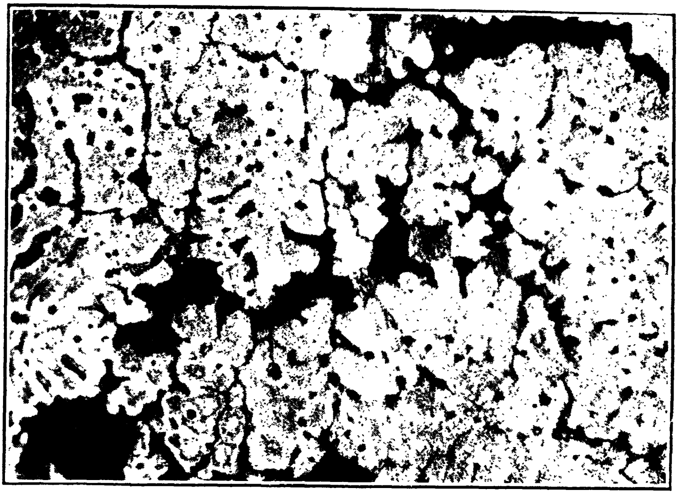


FIG. 127.—Micrograph of Aluminium Alloy Casting, same composition as that Fig. 126, showing presence of blowholes and dross; very poor. Magnification 75 diameters; etched with caustic soda.

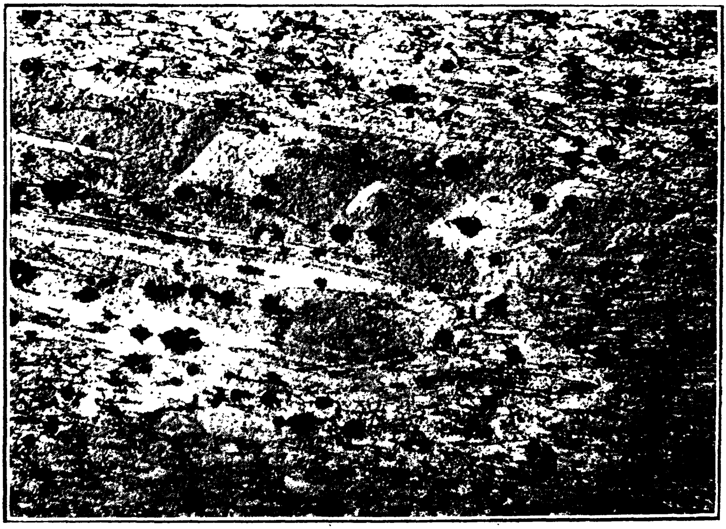


FIG. 128.—Micrograph of Drawn Copper Tubing, defective because of the oxide or scale contained in the metal (shown as black oval patches). Composition good, but metal very brittle. Magnification 150 diameters; etched with ammonia.

ture or sometimes at too low a temperature. An example of the coarse structure resulting from the first is shown in Fig. 125, which is a micrograph of an aluminium bronze casting which kept bursting while being drilled. The metal had no strength and split quite readily. In the case of aluminium bronze alloys a similar structure results from quenching.

Aluminium alloys often prove to be porous and are sometimes so bad that their strength is greatly impaired. The difference between a good casting and one that is very porous is shown by Figs. 126 and 127.

An example of defective copper is shown by Fig. 128. This micrograph shows the structure of a piece of copper tubing which, on analysis, was found to be very free from the usual impurities, but contained a proportion of oxide. This oxide is clearly shown by the black oval-shaped masses which in all probability are pieces of scale not removed before rolling or drawing, but have been forced into the body of metal and, during rolling or drawing, have broken up and become distributed over the material. It will be noticed that in places the pieces appear to run in chains, and that the copper has actually been cut by the scale as it has separated and been drawn apart. The actual effect on the material was its tendency to split longitudinally, a fault which rendered it worthless.

CHAPTER X

THE HEAT TREATMENT OF STEEL AND OTHER MATERIALS

STRICTLY speaking the heat treatment of steel commences with the reheating of the ingot for rolling or cogging down into billets, bars, or whatever form it is to be put on the market. This and other heat treatments, such as annealing during rolling or drawing, are carried out by the steel maker and the rolling mill people, and therefore in one way do not concern the user, who has to fashion his products from the steel as supplied. Although the engineer may not be concerned about this previous treatment, he will soon find that it has a considerable influence on the quality of the final material, and that it is necessary for him to watch out for many failings in the steel which if overlooked may lead to disaster and loss, both of life and money.

This important fact regarding the condition of the steel on arrival should not be lost sight of because, unless the material is in a suitable condition, no amount of work on the part of the "Hardener" will produce a satisfactory article. This warning will suffice for the present, but later the whole aspect will be dealt with in greater detail. What should be clearly realised now is the fact that the heat treatment of steel does not commence in the hardening shop (or, using its more modern title, the "Heat Treatment Department").

Some Theoretical Considerations

In Chapter VIII the effect of heating and cooling steel is explained and the changes in its constitution that take place at certain temperatures (or change points) are given. These changes from one state to another and the properties of the different constituents which form at each state are highly important, but the means by which certain of these constituents with their associated properties are obtained and then retained in the finished steel are more important still. So important is it to have a knowledge of these internal changes that they are (at the risk of repeating some of the matter already given) dealt with here in a manner which will enable the engineer to follow the "mechanism" of the more common treatments now in general use.

The changes during the cooling of a piece of medium carbon steel (0·35 per cent. carbon), starting from the liquid state, are shown in Fig. 129, which is the same as Fig. 77, and is repeated here for convenience. The properties of the constituents mentioned are given in Chapter VIII, and, having a knowledge of these and the extent to which such properties are communicated to the steel itself, it simply remains to secure their presence in the final product. This may be accomplished by heating the steel up to the *Ac*3 range and then cooling it either slowly or rapidly. The constituents present then depend on the rapidity of cooling, because the changes from one phase to the next require a certain time in which to take place, and therefore if this time is not allowed, the change cannot take place and the steel will be arrested while in one of these phases, and the constituents normal to this phase will be present. Thus if the steel is cooled very rapidly (by quenching it in ice-cold water or brine), the change from austenite into martensite (see Fig. 129) cannot take place and the structure will show the presence of austenite. As a matter of fact, however, austenite changes very rapidly into martensite and in low carbon steels it is very difficult to prevent the change taking place, with the result that martensite is generally the only constituent found (together with ferrite in low carbon steels). The presence of nickel and manganese have a retarding influence on the austenite—martensite change and in consequence these steels can be retained to some extent in the austenitic state.

Slower cooling, by quenching in oil for instance, will allow the steel to pass through the austenite—martensite change and also through the martensite — troostite change, and the resulting structure will probably contain troostite, with possibly a little martensite in high carbon steels or sorbite in medium and low carbon steels.

Still slower cooling, in air for example, will permit the steel to pass through more of the changes, and it may not be arrested until the sorbite phase is reached, and then the structure will be sorbitic or possibly pearlitic.

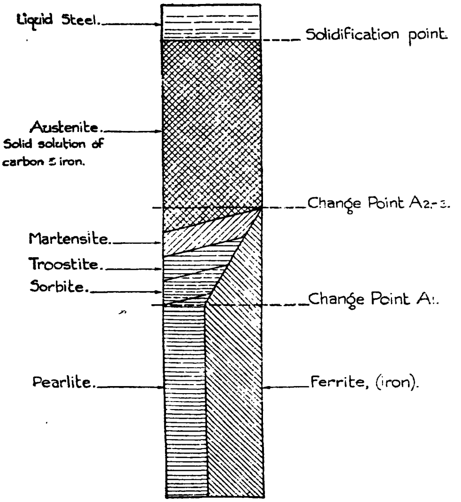


FIG. 129.—Diagram showing the Principal Constituents formed during the cooling of 0·35 per cent. Carbon Steel from a high temperature. The different constituents are indicated.

When the conditions are such as to produce very slow cooling the steel will pass through all the changes without disturbance and the structure will be pearlitic.

The above statements refer to the carbon-containing constituent only. The effect of the cooling rate on ferrite is important in so far as it decides to some extent to what size the ferrite areas will grow. Slow cooling allows the ferrite, as it is thrown out of solution, to coalesce and form large areas, or to take the form of a very coarse network surrounding the carbon constituents, whereas rapid cooling prevents this, and the ferrite areas will be found to be much smaller and more uniformly distributed.

Should the steel contain more than 0·85 per cent. carbon (*i.e.* more than that required for saturation) free cementite will be formed, and this in very slowly cooled steel will be found in the form of a fine network surrounding the grains of pearlite (or other carbon constituent). On the other hand, in steel which has been cooled at a moderate rate only, the cementite will not be thrown out of the crystal grains to the boundaries, but will be found as needles or plates in the grains themselves—a very dangerous form of structure.

At this stage a warning must be issued, namely, that everything depends on the rate of cooling, which it will be clearly understood depends (1) on the ratio of mass to surface, and (2) on the medium in which the cooling is effected. Thus a thin-sectioned piece, having a large cooling surface compared with its mass, may give the same structure when cooled in air as another piece having a small surface and large cross-section when cooled in oil or perhaps water. In large masses of steel the centre must inevitably cool more slowly than the outside, and therefore permit the structure to undergo more changes, producing say a pearlitic centre while the outside structure may be sorbitic or even troostitic.

Although the rapid cooling of most carbon steels will produce a martensitic structure with fair certainty, there is not the same degree of certainty in the production of troostite or sorbite by slower cooling rates. To obtain such structures by cooling alone, it is necessary to vary the medium employed and sometimes the method for each different article. This is done to some extent in practice as in the case of rail steels and structural work, which are cooled in air under certain conditions to produce a sorbitic structure.

It is undoubtedly better to cool the steel at such a rate as to produce a martensitic structure, *i.e.* that in which the carbon constituent is hard, and then to reheat it while in this condition to a temperature which will allow the martensite to change into troostite or further into sorbite. The rapid cooling promotes a fine-grain structure, giving no time for the ferrite or other constituents to coalesce, thus securing the maximum of uniformity, while the reheating can be controlled better than cooling, since it becomes simply a question of attaining a certain temperature and giving time at that temperature for the steel to change into the state required.

The rapid cooling by quenching is generally referred to as hardening, as it produces the hardening constituent martensite, and the reheating is known as tempering or toughening according to the constituent produced.

To understand this reheating Fig. 130 should be referred to. From this it will be seen that commencing with a martensitic structure no change takes place until at about 180° C., when the martensite begins to change into troostite, a softer constituent. This change is referred to as tempering, *i.e.* the partial softening of the hard martensite, and is well known to tool-makers as the means for reducing the brittleness so characteristic of hardened steel. Further heating converts more of the martensite into troostite till eventually the whole mass is troostitic and the steel has lost its hard character, but is tough and still not very ductile. At 400° C. the troostite commences changing into sorbite and has now entered into what is known as the toughening range, which extends from 400° C. to about 680° C. This range is of considerable importance commercially, owing to the high tensile strength the sorbite formation imparts to mild and medium carbon steels and the improved ductility of the material. At the higher temperature of this range the steel takes up a partially pearlitic structure and eventually passes into the pearlitic state pure and simple, having the character of extreme softness and maximum ductility.

From the above explanations it is evident that having hardened a steel by quenching it, any constituent desired can be obtained by simply reheating it to the temperature at which this constituent forms. This is the most satisfactory method of imparting definite properties to the steel, although as explained already it may be desirable or even compulsory to obtain the same results by the single heating and controlled cooling method.

The processes in actual practice for obtaining definite results are known under certain well-recognised terms, and use will be made of these terms, thus connecting them at once with the brief technical descriptions that follow.

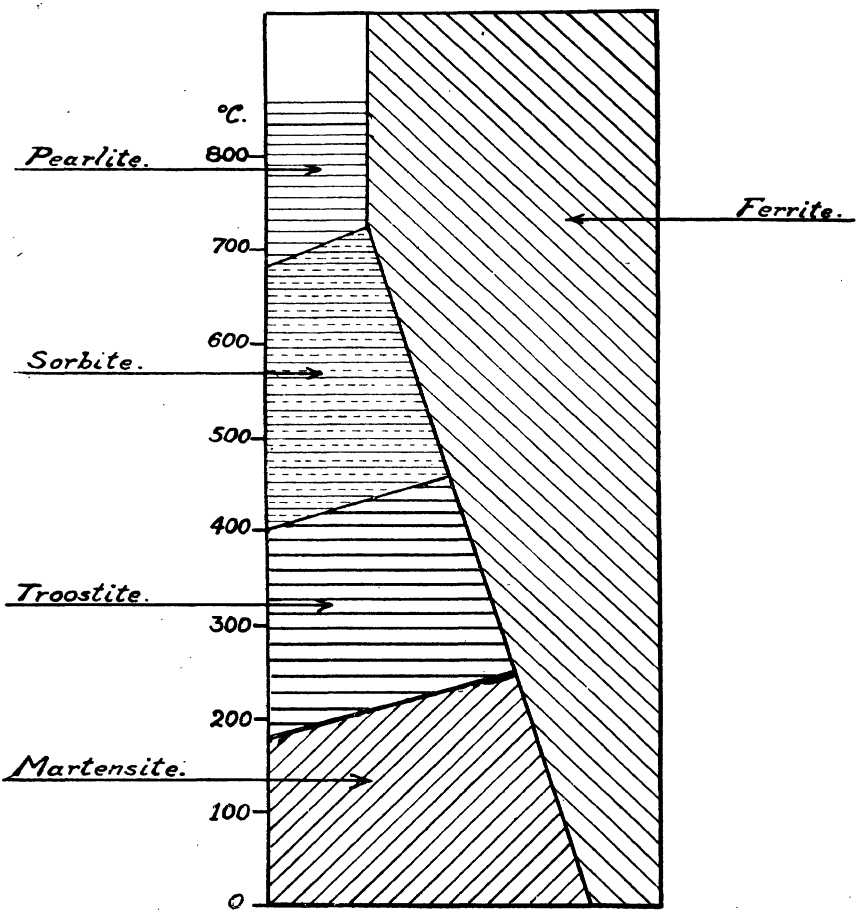


Fig 130.—Diagram showing Effect of Reheating "Hardened" or Quenched Steel (*i.e.* while in the martensitic condition to commence with).

Normalising.—This process, as its name implies, has for its object the reducing of steel from any other state to its normal state. Commercially it is carried out to remove all forging, rolling, and other defects due to working and also to reduce the grain size of the material to as small dimensions as possible.

It is often confused with annealing, some writers applying the latter term to this process. The results produced by normalising and annealing may often be similar, but the objects aimed at are different and therefore the two processes should be kept distinct.

The process is simply that of heating the steel to a temperature above the Ac3 range and then allowing it to cool in air at its normal rate. The heating to the Ac3 range throws all the constituents into solution and, as explained in Chapter VIII, the grain size will be a minimum if the temperature is only just above this range. The effects of forging and rolling and other work, however, may or may not be removed because they are often in the nature of lack of uniformity, and can only be remedied by diffusion ; a rather slow operation. When the finishing temperature * is low, as it should be, the time required for diffusion will be short and the temperature need only be just above the Ac3 range. But if the finishing temperature is high, *i.e.* the working or forging of the steel has been finished at a temperature much above the upper range, the structure will be coarse grained and the ferrite masses large, thus necessitating a longer period for diffusion to be completed or, perhaps, a higher "normalising" temperature to facilitate its completion. Both the longer period of heating and the higher temperature produce increased grain size and, therefore, if the normalising is limited to a single heating a compromise must be effected between poor diffusion and grain size, and a temperature will have to be selected (by trial) which will produce the minimum of grain size with the maximum of diffusion obtainable. When it is essential that both shall be secured the steel must be heated twice, the first heating to well over the upper range to facilitate rapid diffusion and the second to only just above the upper range to obtain the minimum grain size. Such a treatment may be termed double normalising.

Although the steel is cooled in air the actual rate of cooling will depend on the mass and surface, a thin-sectioned piece cooling much more rapidly than a thick, massive piece. The resulting structure depends on this cooling rate and therefore on the ratio of mass to surface. Slow cooling will allow the steel to pass through the different phases or changes undisturbed, eventually reaching the pearlitic state normal at atmospheric temperatures. Rapid cooling, on the other hand, will overtake these changes and the steel will be arrested in one of the transitional phases, and the constituents normal to that phase will be found in the steel. Usually the steel is arrested in the sorbitic phase (see Fig. 130), and will contain sorbite, but in some cases it may contain troostite due to more rapid cooling.

Annealing.—The object of annealing is to produce a soft ductile material suitable for cold pressing and drawing and in many cases to facilitate machining. The softest and most ductile constituent in steel apart from ferrite (pure iron) is pearlite, [illegible] therefore it follows that a steel with a pearlitic structure will be most ductile. Now, as explained, pearlite is formed as the result of slow cooling, hence the process of annealing is one involving slow cooling.

Since much [illegible] the work to be annealed has been worked either hot or cold and may require refinement (*i.e.* diffusion and small grain size), the process is almost identical with that of normalising and the remarks concerning finishing temperatures apply in the same manner. In order, however, to secure the

---

* By this is meant the temperature at which forging, rolling, or other work is finished.

pearlitic structure the cooling of the steel is prolonged (by leaving the material to cool in the furnace for example), so that the changes through the different phases are not disturbed.

This procedure has one failing in so far that the slow cooling promotes the growth of large masses of ferrite and also a coarse pearlitic structure. This is probably of small importance for the majority of steel parts which are required in the annealed state, but if it is important to secure the finest structure possible use must be made of the double process outlined on p. 175. In this the steel is heated to just above the Ac3 range and then cooled rapidly by quenching, thus obtaining a martensitic or martensitic-troostitic structure. Then it is reheated while in this condition to a temperature of about 700° C. and allowed to remain at this temperature until the pearlitic structure is formed. By this method the fine-grained structure due to rapid cooling through the critical ranges is retained and yet the maximum ductility due to the presence of ferrite and fine pearlite is obtained.

Finally attention should be drawn to the case of very mild steels containing 0·1 per cent. carbon or less, which can be quenched in water instead of being cooled slowly and which by this treatment will often be more satisfactory. The rapid cooling prevents the massing of the ferrite and instead causes the carbon constituent to be uniformly distributed in small but many patches, and although these may not be entirely pearlitic in character, they will be in a state probably sorbitic, which although not quite so ductile as pearlite will have little influence on the mass of the steel so far as this property is concerned. This sorbitic formation will tend if anything to toughen up the steel and increase its elasticity, at the same time improving its machining qualities by eliminating "drag."

Hardening.—This process is one in which the hard constituents austenite and martensite are secured in the steel. These are obtained by cooling the steel very rapidly from above the Ac3 range and thus preventing the change into troostite taking place, although in low carbon steels a certain proportion of this constituent is always found. Austenite is not often present, the change into martensite taking place so rapidly. Martensite is, however, the harder constituent and gives the required result. In high carbon steels (above 0·9 per cent.) free cementite will be found which will increase the brittleness of the already brittle martensitic structure, thus these steels will have to be treated very carefully on account of their weak structure and because of the ease with which they fracture or crack under the stresses set up with such rapid cooling. A steel having a wholly martensitic or martensitic-cementitic structure is of little use in practice and it becomes necessary to convert a portion of the martensite into troostite, a softer constituent and one which gives the still hardened steel a degree of toughness and elasticity. This partial change from martensite into troostite is referred to as tempering.

Tempering.—This process, as just explained, is a partial changing of the martensite into troostite (see Fig. 130). It is employed for removing the extreme brittleness of hardened steel and consists of simply reheating the steel to a temperature above 180° C. when the above change begins to take place.

Apart from tool hardening this process in engineering practice has an important application in raising the dynamic strength of steels used for gears, etc., which must retain the hardness due to martensite and yet possesses some of the toughness due to troostite. Such work is usually reheated to about 150° C. (or a little higher) when, in the case of alloy steels particularly, the troostite forms and many of the hardening stresses are relieved.

Toughening.—This process may be regarded as an extension of the tempering process, for it is a reheating process following hardening. It is one of the most important phases in heat treatment from an engineering point of view, for by this means the steel can be given some of its best properties such as high tensile strength combined with good ductility and high dynamic strength.

The range of results obtainable is remarkable, especially with alloy steels, and the desired result is well under control, which means easy repetition, a factor so important commercially.

Reference should be made to Fig. 130 showing the effect of reheating hardened steel having a martensitic structure.

STRUCTURES.

Mechanical properties.	Martensitic.	Troostitic.	Sorbitic.	Pearlitic.
Hardness	Maximum	Very tough	Tough	Soft
Tensile	Maximum	Very high	High	Minimum
Ductility	Minimum	Poor	High	Highest
Dynamic strength, Izod impact	Minimum	Poor	High	Highest
	0° C.	200° C.	400° C.	670° C. Approximate reheating temperature

The above table serves to give a general impression of the properties possessed by the different structures shown in this diagram. The changes do not take place in steps but proceed gradually from one into another, and while doing so the mechanical properties change in like manner. For convenience the approximate temperatures are also given, but it must be borne in mind that the carbon content affects the results and so also does the addition of nickel, chromium, vanadium, and other alloying metals.

It will be seen that the most useful range is from 400° C. to 670° C., where a high tensile strength is obtained combined with high ductility and high dynamic strength. On the other hand, the range 200° C. to 400° C. is the least serviceable since the steel, although possessing a high tensile strength, is poor as regards ductility and dynamic strength. In fact, it may be taken as a general rule that if the tensile strength required can only be obtained with a certain steel by means of this range then the steel should be abandoned and another chosen which will give the desired tensile strength but in the range 400° C. to 670° C.

This phase of heat treatment, or rather the results that can be obtained by it, will be dealt with more fully when considering the individual steels in Chapters XI and XII.

Practical Considerations

At the commencement of this chapter reference was made to the questionable state of the steel as delivered by the steel suppliers. The importance of this will be explained.

At the outset it is necessary to appreciate that steel, whether "plain carbon" or "alloy," in its "natural" state (*i.e.* rolled, drawn or forged, etc.), does not possess the best physical properties which are so desirable and which commercial practice demands. Further, the condition or structure is so inconsistent and variable that it cannot be considered safe to use such material in such a state. It has now become a recognised fact that heat treatment is not only advisable, but in the majority of cases absolutely necessary.

There is another advantage gained by heat treatment, and that is the possible substitution of a cheaper steel for a more expensive one such as an alloy steel, giving the cheaper steel such treatment as will produce results equivalent to those obtained from the more expensive steel which has not been heat treated, or which has received only a very simple treatment.

When does Heat Treatment commence ?—This is a point very often overlooked by manufacturers who are apt to apply certain instructions to manufactured parts without considering what state the steel is already in, with the result that in many instances unsatisfactory results are obtained. This applies particularly to forged parts—drop stampings which may be produced at various temperatures and with a varying amount of work put into the material, the result being coarse crystalline structures, or good fine structures, as the case may be. Even in bar material such as mild steel it will be found that the makers have given little attention to the condition of the structure, and in many cases bars having coarse crystalline structures will be supplied. In fact, it may be said, unfortunately but truly, that many steel manufacturers do not appear to understand or, at any rate, are incapable of heat treating correctly the material they supply. It will be clear that a specified heat treatment will not give the same results in a rolled bar which has been more or less overheated as in a bar rolled at a much lower heat. Thus some knowledge as to the previous treatment of the material is required before uniformly successful results can be obtained in the hardening shop of an engineering firm.

That the varying state of the material before treatment is responsible for the varying results obtained in many hardening shops is not appreciated, and that failures due to it are often wrongly attributed to lack of skill on the part of the hardener, is quite a common case even at the present time. When the steel is supplied in good condition it is often spoilt during forging, with the result that the hardener blames the steel maker and a controversy is set up between two innocent parties, while the real cause of the difficulty is overlooked.

Heat treatment is therefore a process commencing at the steelmaker's works during reheating prior to the operation of cogging down and rolling, and continued by drawing or forging, and then finished finally in the works of the engineer. The greatest offenders so far as the ill-treatment of steel is concerned are usually the drop stampers and forgers, and it is advisable to realise how the material is treated during the making of drop stampings and forgings.

To obtain consistent results it is necessary to start from the same point; uniform results cannot be expected from diverse starting-points, and hence a preliminary treatment such as normalising is important. This treatment tends to put the steel into what may be described as the normal state, and this gives a uniform starting-point.

Drop Stampings and Forgings.—With forging should be considered the operation of cogging down and rolling of the steel when supplied in bar or billet form. These initial operations are too often neglected by the steelmaker in so far that the heating previous to rolling is not controlled. The practice, at present so common, of employing furnaces which are run at too high temperatures and which are so badly designed that the metal is unequally heated, is really responsible for much defective work. Thus all material supplied as billets or as black or rolled bar, supplied by other than well-tried makers, should be carefully examined and tested. Defects in the original ingot are often carried right through to the rolled bar and may eventually exist in the finished stamping or forging. Leaving these original defects for the moment, the further matters to be considered are the effects of over and unequal heating.

What has been said about the steelmaker and the rolling-mill people applies with even more force to the drop stamper and forger. The tendency of these workers to overheat or badly heat the steel is very great, and forms a serious obstacle in the production of really good work. It is impossible to give too much attention to the steel at this stage, and the time and trouble so expended will be amply repaid by the successful results obtained from the subsequent heat treatment of the parts manufactured.

Briefly, the correct conditions * of heating for forging are (1) the use of a furnace which is run at the correct forging temperature, or at the most only a little higher. (2) Heating the material uniformly and thoroughly, allowing plenty of time for the heat to soak right through the piece.

Instead of this it is usual to employ furnaces which are so badly designed that one portion of the billet will be at a "white heat" when another portion is only just "red." Another condition is one that will give surface temperatures which are apparently correct while the centres are really quite cool and much below the forging temperature. In other cases a billet, when removed from the furnace, will splutter and drop while the centre is yet too cold, in many cases the steel is heated through to so high a temperature that it is shaped by only a few blows, unless, of course, it happens to fly to pieces. The result of such high temperatures is shown by Fig. 131, representing a large nickel steel forging which had cracked during use. The large crystalline structure and the spine growth of the ferrite are clearly shown and are responsible for the breakdown.

Further examples of overheating are given in Chapter IX.

---

* Although these conditions are stated, the authors appreciate the commercial aspect of drop stamping which almost compels the trade to adopt speedy heating methods. At the same time there are a number of drop stampers who have installed well-designed furnaces in which the steel is thoroughly and uniformly heated without overheating.

While it is possible to correct many of the ill effects of this disastrous practice, it should be borne in mind that the treatment required to do this is expensive.

Further, such special refining treatments are not always successful, for if the steel has been severely overheated it can only be restored by prolonged annealing, or by many successive treatments, and this ceases to be a commercial proposition. If the steel has actually been burnt, as sometimes happens, then nothing short of remelting, etc., will make it serviceable again.

So severe is this faulty practice, and so hidebound are the workers in their old and crude methods, that it is absolutely essential that all forgings and drop stampings should be tested either in the raw state or after an ordinary normalising treatment.

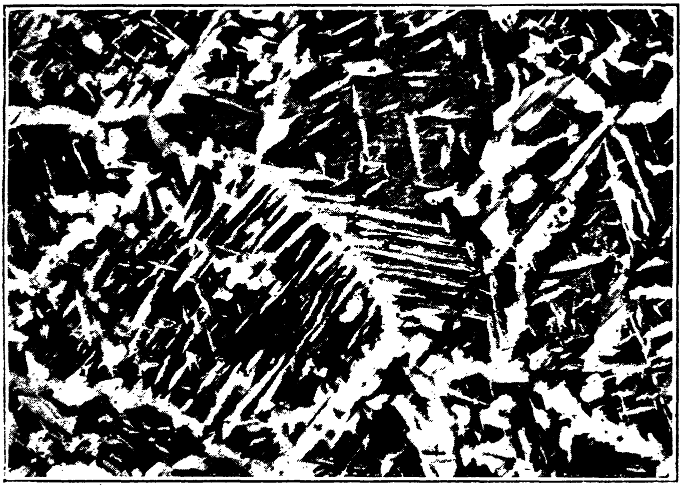


FIG. 131.—Micrograph showing Coarse-grained Structure in Nickel Steel due to Overheating for Forging. Note the tendency to spine growth of the ferrite (white). Magnification 150 diameters; etched with picric acid.

Unfortunately the forging and stamping of alloy steels is often done side by side with mild or medium carbon steels and the same men work intermittently on either class of steel. This practice should be stopped as it leads to much faulty work. Mild and medium carbon steels are more plastic than alloy steels and in addition can be worked at higher temperatures without fear of burning, thus the production of stampings from such material is easier and more rapid than from alloy steels.

Alloy steels require more careful heating (*i.e.* slower heating) and a longer time for soaking in order to obtain the maximum state of plasticity and to prevent cracking.

When, therefore, a drop stamper is "changed over" from a plain carbon steel to an alloy steel he should accommodate himself to the new material: a very difficult thing to do in actual practice, especially in a shop where both classes of steel are being handled. He almost unconsciously begin increasing the temperature to increase the plasticity of the steel and so to speed up his production. It may be advisable to fix different piece-work rates for carbon and alloy steels to remove the incentive for overheating the latter.

A further condition for the production of a good forging or stamping is the correct finishing temperature. Whenever possible the heating should be such that the actual work of forging should be finished at a temperature just a little above the critical range. The importance of this will be appreciated when, as is pointed out in Chapter VIII, it is realised that the "work" put into the steel breaks up the crystal structure as it forms and that the size of the crystal grains in the finished piece is smaller as the finishing temperature is lower.

As the ultimate object of heat treatment is to reduce the size of the crystal grains to as small dimensions as is practicable, it will be seen that the question of finishing temperatures is one to be carefully attended to, for the higher these are (and the less the amount of work put into the metal), the larger will be the crystal grains and consequently the more drastic must be the subsequent heat treatment to restore the structure.

Production of Drop Stampings and Forgings.—The remarks given above can be summarised as follows :—

(1) Material to be heated slowly and uniformly in a furnace maintained at the correct forging temperature to suit the steel and the part to be made from it.

(2) "Work" to be put into the metal up to the time it has cooled to a temperature just above the critical range of steel.

Except in the case of large or complicated forgings and stampings there is no difficulty in adhering to the above conditions, and the question now arises how must the more difficult parts be produced? When the part is a simple one (requiring only a little work) but of great mass it is clearly necessary to work at as low a temperature as possible, so as to avoid the formation of large crystal grains. This may require more time for forging owing to the greater sluggishness of the metal, which of course is less plastic at low temperatures, but the result produced is so much to be desired that it amply repays the extra time spent upon it.

Complicated parts which require a lot of work to form them and which have not sufficient mass to retain the heat required for forging, should be reheated at different stages. When this is the case care should be taken in arranging the different stages, so that during the finishing stage every portion of the forging receives a certain amount of work before it actually cools down to the critical range. It is not advisable to finish one end of a forging or stamping first and then to reheat the whole and finish the other end. The end already finished suffers by reason of the formation of large crystal grains during the heating and cooling while the other end is perhaps quite good because of the "work" put into it and the consequent breaking up of the grains formed.

To make this point quite clear and to serve as a concrete example the production of the drop stampings required for the special shaft shown by Fig. 132 will be considered.

When these were first put in hand the stampers contrived to produce the whole forging at one heating, a masterly operation without doubt, but one which proved to be disastrous, for the subsequent heat treatment failed entirely to render the material sound enough to meet the requirements; the structure of the shaft portions was coarsely crystalline although the flange

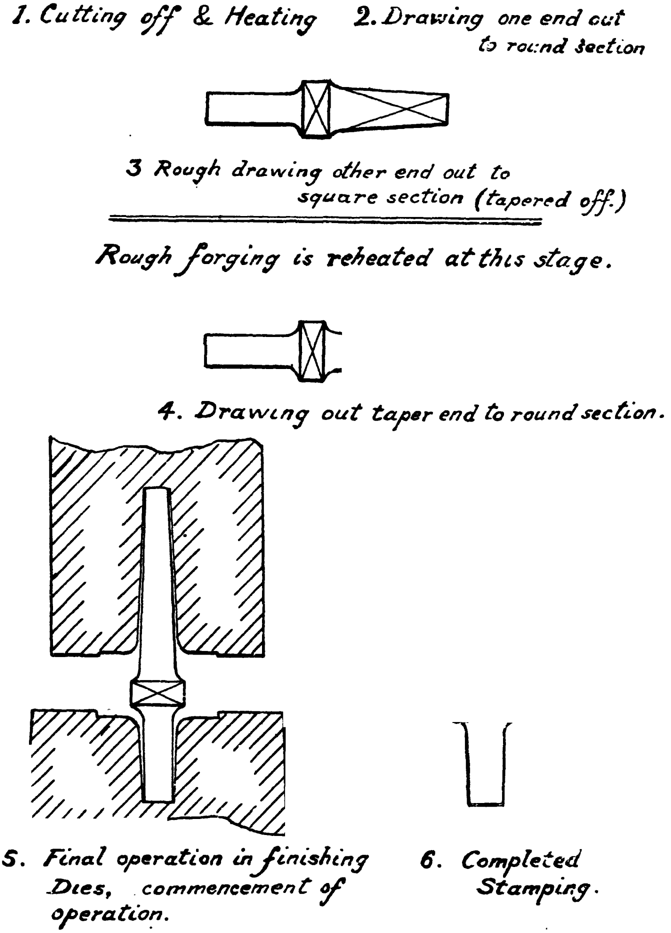


FIG. 132.—Diagrams showing Different Operations in the Forging and Drop Stamping of a Special Shaft with Flange at Centre. A difficult stamping to produce.

was comparatively in good condition. This state of affairs was entirely due to excessive heating and too little working of the shaft portions. The size of the original billet was only slightly larger than the shaft and thus only required a small amount of work to reduce it to size, whereas to produce the flange from such small material a large amount of work was required and, because the flange was thin and cooled quickly, the material was raised to a very high temperature in order that this could be done at one heat. The shaft consequently suffered, being overheated and in many cases actually burnt in parts.

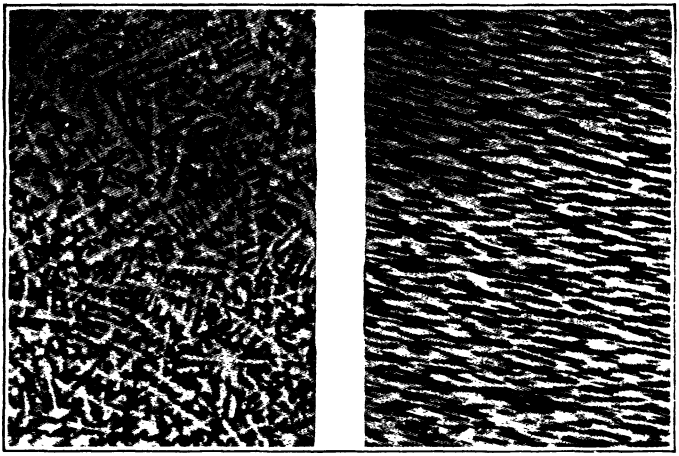
The difficulty was overcome by carrying out the forging in two stages, the material being reheated for the second stage. The operations are shown diagrammatically in Fig. 132. The billets were cut up into pieces and these, after heating, were forged down as shown in operations 2 and 3. One end was forged round to a diameter less than that required in the final stamping, but was made longer so that it would require "jumping up" to bring it to the correct size. The other end was forged out square and slightly taper so that further work would be required to bring it down to size. The centre of the piece was not touched at this stage, but was left at the original size of the billet.

The forging was then reheated for the final operations, which were (4) the drawing down of the square tapered end into a round section somewhat smaller than the final size but longer, followed by (5) the forming of the flange. This last operation is shown at its commencement in the finishing dies, and, as will be seen, every portion of the stamping receives a certain amount of work before the flange was completed. Thus the complete stamping was finished at an almost equal temperature, although of course the thin flange was generally a little cooler in spite of the centre mass retaining more heat and being actually hotter at the commencement of the operation.

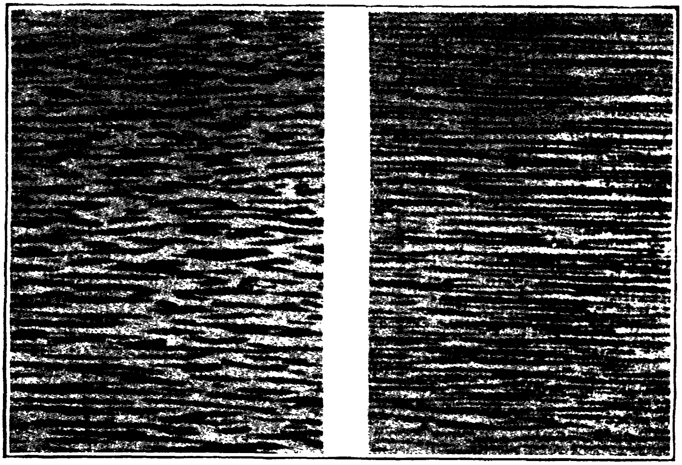
If the steel is allowed to cool below the lower critical range Ac1 (about 700° C.) and work is still continued below this temperature, the crystal grains will become distorted and the material will be less ductile and may be even brittle. An example of this is shown in Fig. 119. This will show up sometimes in the form of cracks or fissures which may be attributed to faulty steel or to bad surface defects in the original billet such as rolling marks, roaks, etc.

From the foregoing remarks it will readily be understood how difficult it is to stamp out parts of widely varying cross section and of difficult shapes with thin webs and cross connections. It is sometimes impossible to produce such parts without leaving the material in a poor state at some portion or other. Simplicity in design is therefore the keynote to success in all stampings and forgings as it is in most other processes.

Flow of Metal during Forging.—During the process of forging and stamping the metal is caused to flow into the shape required, and, if a forging is cut up and examined, the direction of flow can be traced out, giving information which is sometimes extremely important. The presence of slag and other impurities which tend to produce segregation in the steel are responsible for the formation of planes of weakness in the material. When rolled or forged out these areas are drawn out or elongated into thin lines or planes which, while not affecting the strength of the material in the direction of rolling or drawing out (*i.e.* the direction of flow), have a considerable influence on the strength in a direction at right angles to the drawing out. This direction of flow is generally referred to under the expression "grain," and is looked upon in much the same manner as the grain in timber, in fact it is analogous to this and offers difficulties in much the same way as the grain in timber does. The formation of this structure is illustrated by the four micrographs in Fig. 133, starting from the ingot which shows the primary dendritic crystal formation of the cast metal and followed by the rolling in different stages.



A.—Ingot, natural size. B.—First Rolling (elongation 5/1).



C.—Second Rolling (elongation 30/1). D.—Third Rolling (elongation 150/1).

Fig. 133.—Deformation of Dendrites of the Original Ingot by Successive Rollings. A—ingot, natural state; B—first rolling (elongation 5/1); C—second rolling (elongation 30/1); D—third rolling (elongation 150/1).—(*Engineering.*)

The importance of this "grain" in the metal is shown by the following tests carried out by Mr. H. Brearley, and published in a leaflet by Messrs. Brown, Bayley and Co., Ltd., of Sheffield (see Fig. 134).

The following diagram shows that while the static strength as represented by the tensile figures does not alter much, the dynamic strength as shown by the impact tests falls off considerably when the slag lines are in a direction at right angles to the length of the test piece. The ductility also falls off, the

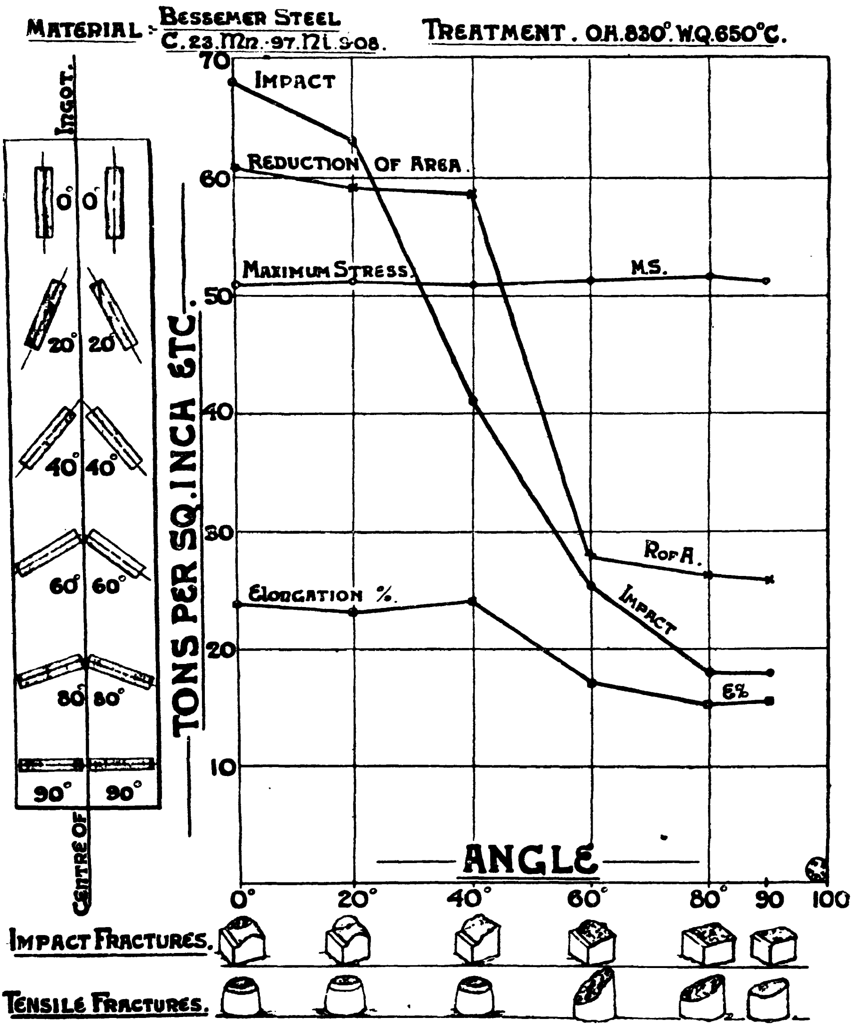


FIG. 134.—Influence of Slag Lines in Steel (Brearley), showing their Effect in Relation to the Direction of Stress

elongation and reduction of area being less when the test piece is cut across the billet; but this falling off is much less marked than that in the dynamic strength.

The importance of studying the grain of the steel and the direction it takes in the finished stamping is shown in the following examples.

Crankshafts.—These are sometimes made from slabs which have portions cut out, leaving the webs and crank pins ready for twisting to the correct angles relative to each other. In such crankshafts there are two important defects : (1) that portion of the shaft lying between two webs is in a twisted state—the fibres are in a state of stress ; (2) the grain of the steel in the webs themselves is in the worst direction. These defects are clearly shown in Fig. 135. By adopting the more modern way of forging in dies the amount of twisting is reduced very considerably and the flow of grain is in a more favourable direction, as is also shown in Fig. 135.

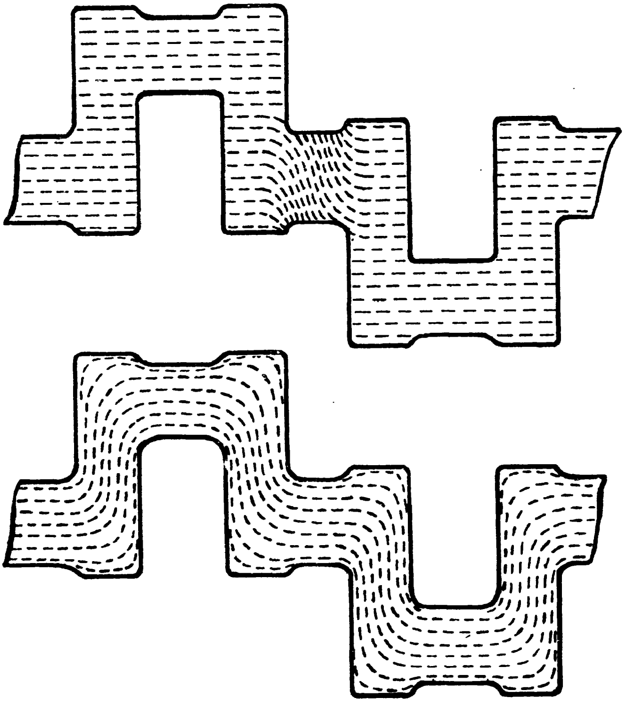


Fig. 135.—Diagram showing two Methods of Forging out Crankshafts. Direction of grain indicated.

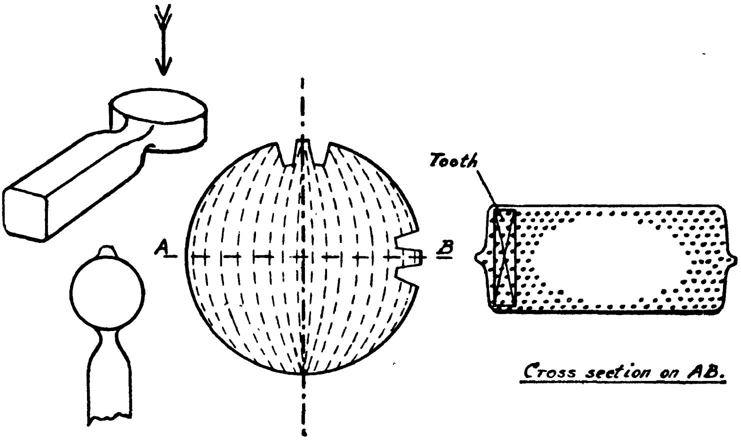
Gear Wheels.—Two methods of stamping gear blanks are shown in Fig. 136. The first of these is the more common. The blanks are stamped from a bar, usually square or gothic section, laid across the die and the stamping so produced has the grain running across it in a nearly parallel direction as shown. Thus some of the teeth have the grain running across their roots and others have it running radially from the centre. Should the steel contain much slag the influence of this on the strength of the respective teeth will be readily understood, while even in the best steel there will be a considerable difference in the dynamic strength.

The second method of stamping a gear blank consists of cutting the bar or billet into lengths sufficient for each gear and then stamping these "end on."

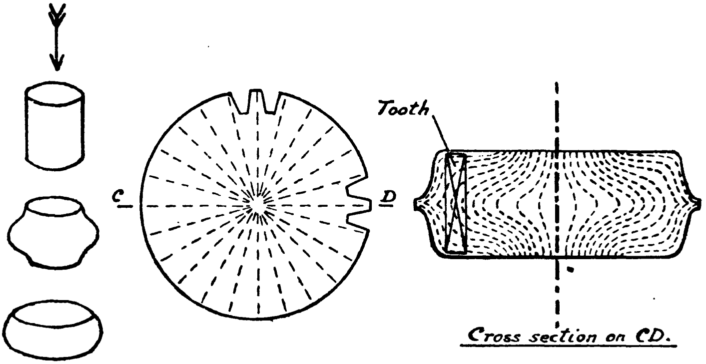
As a result the grain tends to assume a direction which is radial and in none of the teeth does it travel across the root.

A comparison of the two methods shows how much better the second method is than the first, a fact which is borne out by the results of actual experiments which are illustrated in Fig. 137.

These experiments were carried out to determine approximately the relative value of the two methods. The direction of the grain in the first gear blank is shown by the dotted lines running across it, the thick chain line being the centre line of the original billet. The second gear blank was stamped end on, and the grain is therefore approximately radial. Impact test pieces *



Stamped Lengthways.



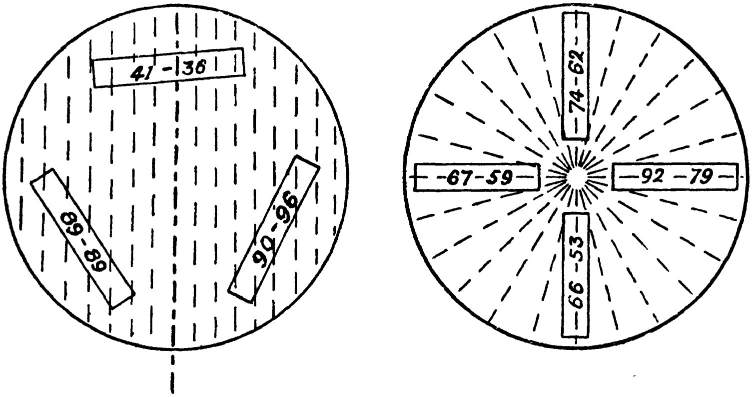
Stamped Endways.

FIG. 136.—Diagram showing two Methods of Forging or Drop-stamping Gear Wheel Blanks, and the Direction of Grain in relation to the Gear Teeth.

---

* The two figures in each case refer to tests on two successive notches made in the same test piece.

were cut out as shown and the values obtained (Izod machine) are stated on the diagrams for convenience. Referring to these, it is interesting to notice that the value obtained from the test piece which was cut in the direction of the grain is more than twice that obtained from the piece cut across the grain. Also in the case of the gear stamped end on all the values are about twice that of this latter piece. Both gear blanks were made from the same steel (a nickel chrome case-hardening steel) and both were given the same heat treatment, and from the high values of the impacts it is evident that the steel was of good quality. Yet in spite of this fact the effect of the flow of grain is very evident. Further, it was found in practice that those gears which broke down (all were heavily stressed) were those in which the grain ran across the root of the tooth, and it was these teeth that fractured first.



Lengthways.   Endways.

FIG. 137.—Diagram showing Izod Impact Test Results obtained from its two Gear-wheel Blanks forged by the two methods shown in Fig. 136.

Radii.—A few words should be said about the size of fillets and their radii. Generally it is advisable to keep on the liberal side, but some cases form an exception to this rule. The two diagrams given in Fig. 138 will explain why this is so. In the first case the radius in the stamping is large and the shaft sweeps gradually into the flange. The final machined size is shown by the thick continuous line, the original forging by the outer dotted line, and the flow of the grain also by dotted lines. An examination of this diagram shows that in machining, a number of the fibres are cut through and their tail ends come to the surface, both in the flange and in the shaft. Now if the machining is at all rough and the part is to be hardened there will be a serious risk of a crack starting from the bottom of a tool cut and following the direction of the grain, *i.e.* the line of least resistance. This form of breakdown is by no means uncommon, and yet the underlying cause is too often ignored in practice.

In the second case the radius of the stamping approaches that of the final part and, as will be seen, there are fewer fibres cut through and, what is very important, those that are cut through travel at very oblique angles to the flange and shaft respectively.

Furnace Conditions.—The importance of uniform and steady heating has been already referred to in connection with forging and drop stamping. For the final heat treatment processes it is even more important.

The furnaces intended for the heating of parts which are being "treated" should be carefully chosen for the kind of work they are required to do.

There has been, and is even now, a great tendency simply to use any furnace the makers recommend, the arguments about uniform heating of the chamber, low fuel consumption, etc., appearing to remove all doubts as to the successful operation of the furnace.

The designing of furnaces is a matter beyond the scope of this book, but the following points will be of service in the selecting of suitable furnaces.

1. The volume of the furnace chamber should be large in comparison with the volume of the work done.

2. The work should be so disposed as to enable free circulation of the gases around each part, *i.e.* all parts should be raised above the hearth on narrow transverse supports, or better still, there should be a "bottom heat," *i.e.* combustion should take place under the hearth as well as in gas ports.

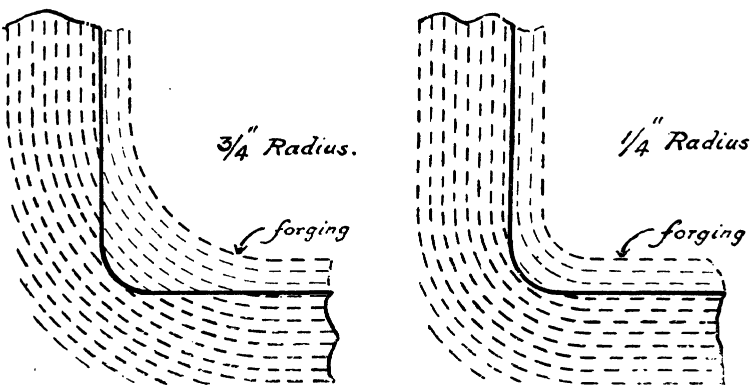


FIG. 138.—Diagram showing Importance of Radii in Stampings and Forgings.

3. No piece or portion of the work should be placed in the furnace in close proximity to a gas port or flame which would tend to give high local or unequal heating effects. These results are often a consequence of using too small a furnace for the work or loading the furnace with too many parts.

4. The zone of combustion * should be kept back from the furnace chamber and only the hot gases actually allowed to reach the work. This is often overlooked and the fuel (gas) is allowed to burn in the chamber, thus causing unequal and excessive local heating.

5. Whenever possible the furnace should be gas fired, either with town's gas or producer gas. The adjustment and control of gas-fired furnaces is simpler and better than that of direct coal-fired † or even oil-fired furnaces.

---

* This condition has been realised most successfully in the "Smallwood Patent" furnaces supplied by the Incandescent Heat Co., Ltd., Smethwick. With these furnaces the authors have been able to maintain uniform heating conditions with a maximum variation of 5° C.

† The Incandescent Heat Co., Ltd., build a type of coal-fired furnace in which the coal is gasified in a small natural draught producer attached to the furnace. This can

Then as to running the furnace, the points requiring attention are :—

1. Condition of gases, whether oxidising or reducing. For nearly all work the furnace atmosphere should be slightly reducing.

2. Adjustment of gas at different points to produce, if possible, uniform heating of the different sections of the work should this vary in dimensions along its length, etc.

3. That the temperature of no portion of the work be allowed to exceed that required for its heat treatment.

4. That the work be heated slowly (there are exceptions to this), and be allowed to soak thoroughly at the correct temperature. It is good practice commercially, to pre-heat the work in one furnace to a temperature below that required and then to transfer it to the second furnace, which is maintained at the correct temperature, the first furnace being only roughly controlled.

5. That the pyrometer be in close proximity to the work if not actually in contact with it.

The principal furnace builders in England are beginning to turn their attention to the development of furnaces which are really suitable for the heat treatment of steel, and in the near future some of these will be of an automatic or semi-automatic character. In these days of mass production there is obviously need for mechanical devices for the handling and treating of the thousands of parts required, say, in the manufacture of automobiles, motor cycles, etc., on a large scale. That these should be handled by manual labour cannot but seem inconsistent when they are machined by automatic or semi-automatic tools. A device that will convey a stream of parts of one kind through zones of increasing temperature until they reach one of a constant temperature, after which they will be quenched or otherwise cooled, must be better than handling the work with ordinary labour. The steady flow at a constant rate through a zone of constant heating must produce a degree of uniformity which cannot be attained, or at any rate maintained for any length of time, by hand methods. That there are difficulties in the development of such furnaces is certain, but that these difficulties can be overcome is equally certain. Already one firm of furnace builders * has developed mechanical appliances, both hand and power driven, for the charging and discharging of furnaces and many of these are now in work in the larger motor and other engineering workshops in this country and abroad.

Pyrometers.—The importance of these instruments for measuring the temperature of the furnaces will be readily understood when it is realised that the best work is only obtained by heating to within limits of 5° C. to 10° C. Wider temperature limits are, of course, permissible with a considerable proportion of the work, and it is possible to divide the heat treatment operations into those necessitating "*fine*" *limits* and those requiring only *rough limits*. Thus pyrometers for these two classes of work should be selected in accordance with their accuracy and reliability at the temperatures at which they will be used.

There are three main types of electric pyrometers made, and the selection of a suitable instrument from these, and from the different makers, may offer difficulty. These three types are as follows :—

---

be controlled in the same manner as a producer gas-fired furnace, and where large quantities have to be heat treated is the most economical furnace to use.

* The Incandescent Heat Co., Ltd., Smethwick.

1. Resistance Pyrometers, which depend on the change in the electric resistance of a small coil of pure platinum wire suitably mounted and protected, and placed in the furnace. This change in resistance has a definite relation to the temperature and is registered on an indicating instrument or, if required, on a recording instrument, producing a permanent record of the temperature of the furnace. This is the most sensitive method of determining temperatures and at the same time the most accurate. It can be used commercially for continuous use at temperatures up to about 800° C. and for intermittent use, such as checking other pyrometers, up to 950° C. Above these temperatures its accuracy is likely to be impaired and its use becomes a laboratory proposition.

2. Thermo Electric Pyrometers are based on the principle that an electric current is generated at the junction of two dissimilar metals or alloys when heated. This junction or "thermo-couple," as it is commonly called, is placed in the furnace and when connected to an indicating instrument of the voltmeter type (or galvanometer) gives an indication of the furnace temperature. The current generated increases with the temperature and the relation between these is determined empirically.

This type of pyrometer is the one that is in greatest use in industrial work, and is certainly the simplest and easiest to maintain. Instruments for indicating and recording are made.

The thermo-couples are made either of noble metals of the platinum series or of base metals such as iron, copper, nickel, chromium, or their alloys, and are called noble-metal and base-metal couples respectively. Those made of platinum and platinum alloys with rhodium, for example, are suitable for the higher temperatures up to 1100° C., but although certain of the base-metal couples can be used up to such temperatures they are not, commercially, so reliable as the noble-metal couples. In general the accuracy of thermo-electric pyrometers is sufficiently high for all heat treatment work although it is inferior to that of the resistance type.

3. Radiation Pyrometers depend on the heat or light (or both) radiated from the interior of the furnace and are only designed for measuring high temperatures, above, say, 900° C. They can be had in both the plain indicating pattern and the recording patterns. The principal feature of this type is that no portion of the outfit is placed in the furnace, and there is nothing therefore subjected to the deteriorating influences of the hot gases.

To assist in judging these different types of pyrometers the following chart is given. The expressions "fine heats" and "rough heats" mean heat treatment processes which require an accuracy of ±10° C. and ±20° C. respectively.

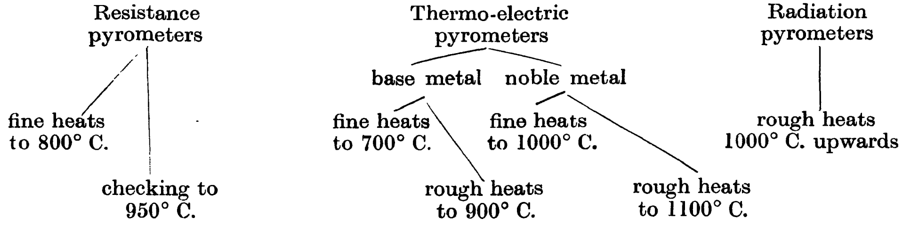


Chart showing Practical Working Limits of the different Types of Pyrometer in use.

This chart must not be looked upon as infallible, because there are many features in the different makes of pyrometers which render them suitable for higher temperatures or for more accurate work. Further, the conditions under which a pyrometer works have a most important influence on its accuracy and life, and the advice therefore of the maker should always be secured in order to get the best service from his instruments.

Cooling and Quenching.—The cooling of the heated metal should be considered not only in relation to the kind of steel used and the results desired, but also in regard to the actual part itself. Heat treatments * specified by steel makers for their steels do not, and very often cannot, take account of the varying uses to which the steel is put, and in consequence the blind following of their instructions, sometimes leads to unsatisfactory work or even absolute failure. Apart from the temperature of the work, widely differing results can be obtained by varying the rate of cooling. This rate of cooling can be controlled in two ways (1) by artificially increasing the mass of the work, and (2) by the use of different cooling or quenching media.

In the first case the mass can be increased by increasing the volume of metal and then machining this off after treatment. Another way is to allow the work to cool in the furnace, or in a box packed with iron turnings, sand, charcoal or other suitable material, thus adding the mass of the furnace or the box of added material. All these are methods for retarding the cooling, and the medium in each case is air.

Normal cooling can be defined as cooling in still air at ordinary temperatures, the work being neither lagged nor packed in any way.

In the second case the cooling is controlled by using media such as those given below. In this case the cooling is accelerated, and the process is called "quenching."

Quenching media in general use :—

1. Air blast.
2. Oil bath.
3. Water bath and water spray.
4. Brine or similar solutions.

For a given set of conditions these media will be found to cool the work the more rapidly in the order in which they are given, *i.e.* oil will cool the work more quickly than an ordinary air blast, while water is more drastic still, and so on. The efficiency of these media is dependent on their temperature, particularly in the case of water, and it is therefore necessary to arrange for the quenching bath to be maintained within a reasonable range of temperature in order to secure consistent results.

Air blast cooling is not applied to much work, but is mainly confined to tool work and for hardening high speed steel.

Oil is the safest of all quenching liquids because it is least affected † by temperature rise and has the least distorting effect on the work. Generally there is little difference between one oil and another, except that animal and

---

* These are generally the results of experiments on standard size test pieces, a practice which is, perhaps, the only practical one open to the makers.

† An increase in the temperature of the quenching oil does not have any serious effect on the hardness produced in the steel. A hot bath will give almost the same degree of hardness in steel as a cold bath. In this respect oil differs very considerably from water. There is a limit in the temperature, of course, beyond which the oil should not be allowed to rise. Quenching oils generally, should have a high "flash" temperature.

vegetable oils cool the work more quickly than mineral oils and are more often used. A few such oils in use are : sperm or whale oil, rape oil, lard oil, and also some of the thick mineral oils.

Water is the commonest of quenching liquids and is essential when a glass-hard surface is required, especially with carbon steels. It has, however, a serious distorting influence, although for low carbon steels (say up to 0·5 per cent.) it is fairly safe, but even then where the prevention of distortion is of importance it is advisable to employ oil. Water quenching is conducive to cracking, owing to internal stresses which are set up in the steel because of the cooling of the outer surface before the interior portions.

Brine is used when an extremely hard surface is required with certain tools, such as files, etc. It is a little more drastic than water and consequently the difficulties in its use are greater, cracking being the commonest trouble.

Method of Quenching.—On the manner in which the work is actually immersed in the quenching liquid depends, more often than not, the final shape of the treated parts. This operation in heat treatment is very often badly neglected, but yet it is one of considerable importance in so far as much of the distortion and cracking of hardened parts is due to the way in which the part was immersed. No golden rule can be laid down for this ; it is necessary to carry out tests on the actual parts themselves, " dipping " them in different directions so as to find out which direction produces the least change in shape.

The importance of this matter is clearly demonstrated in the quenching of a straight bar or shaft. If this is immersed at an angle such as when swinging it into the liquid, unequal hardening stresses are immediately set up owing to cooling of the side which strikes the liquid first, and as a consequence the shaft curls and is bent. If, on the other hand, the shaft is immersed vertically and rapidly the cooling proceeds on all sides simultaneously and the result is a fairly straight shaft.

Another example is the hardening of wheels such as gears which may be of light section. If these are immersed face downwards (*i.e.* flatways) the side that strikes the liquid first will be a different diameter to the other side, with the result that the periphery of the wheel is tapered. In addition the wheel is very often oval. This trouble can be overcome to a considerable extent by " dipping " the wheel edgeways with a sweeping motion.

In many cases the distortion produced by careless quenching methods is of little importance, but where gears, shafts and other portions of machinery such as are required in the automobile industry and aeroplane engine manufacture have to be heat treated, then such difficulties become manifest and much ingenuity is required to overcome them. Some examples of these troubles are dealt with at the end of this chapter, under " distortion difficulties."

One fact of great importance is the necessity of keeping the part moving in the quenching liquid until it is practically cold. This eliminates to a great extent the formation of soft spots.

Cleanliness.—This is too often overlooked and much work is spoilt by not removing scale, burnt oil, and dirt, which by preventing the quenching medium coming into contact with the steel causes soft spots. Any work where the surface hardness is important should be thoroughly cleaned with boiling soda solution or by means of the sand blast; the latter method being more efficient as it removes the scale more thoroughly.

Forgings and stampings should be rough machined before treatment, as the scale is often thick enough to prevent successful treatment, the scale acting as a non-conductor, thus preventing rapid cooling which is essential for hardening or toughening.

Scaling or Oxidation of Work.—Steel when heated in an oxidising atmosphere soon scales or oxidises. This scale must be removed before the parts can be finished and this involves the use of a sand blast.

What is more serious, however, than the scaling is the decarburisation that accompanies it. Work which is intended to be dead hard is ruined by oxidation because the carbon in the steel is oxidised away, often to a considerable depth, and as a result a skin or layer of low carbon steel is formed which will not harden. This is a frequent source of trouble with case-hardened parts, and much work is spoilt by decarburisation of the surface during the refining and hardening heats that usually follow the carburising process.

It is essential therefore that the atmosphere of the furnace should be " reducing " and not " oxidising." This is secured by using a slight excess of fuel or by limiting the supply of air a little so that incomplete combustion is obtained. It is sometimes helpful to place a little coke in the furnace so that this can burn with any excess air that reaches the chamber. This practice, however, should not be necessary with a well-designed furnace.

Normalising

This is the simplest treatment of all, and because it is so it often becomes a mere perfunctory operation, having little or no value, owing to the non-observance of the conditions required to produce good work.

The object of normalising steel is to remove all forging, rolling, and drawing stressess, and to reduce the grain size of the structure to as small dimensions as is commercially practicable.

It is often the forerunner of more elaborate treatments to be given the parts, but in many cases it is the only treatment required, and it is therefore necessary that its possibilities should be understood.

The treatment consists of three phases: (1) heating, (2) soaking, and (3) cooling.

Heating.—The work may be placed in a furnace which is already hot, but not hotter than say 600° C. or 700° C. This operation of loading lowers the temperature of the furnace considerably, and in the case of large furnaces dealing with large batches of work, the time taken to reach the " normalising " temperature will be such that the heating is sufficiently gradual and all portions will attain the same temperature at about the same time. Of course, parts which vary in section considerably should be placed in a furnace which is either cold or only at 200° C. or 300° C. Also in the case of certain alloy steels or carbon steels of high carbon content (above 0·5 per cent.), such precaution is necessary. The furnace can then be heated up slowly to the correct temperature, or instead, the work can be transferred when at a temperature of, say 600° C. to another furnace which is working at about the right temperature. The first furnace is simply used to preheat and the second to finish. Such method of working is, of course, expensive and in some cases prohibitive, in which case it is advisable to select steels which are not so sensitive to sudden temperature changes. As a rough guide the following steels are arranged approximately in order of their sensitiveness, the least sensitive being placed first :—

1. Mild (C 0·05 to 0·25 per cent.).
2. Mild Case-hardening (C 0·2 per cent.).
3. Nickel Case-hardening (C 0·18 per cent., Ni 3·0 per cent.).
4. Medium Carbon (C 0·25 to 0·5 per cent.).
5. Nickel Case-hardening (C 0·18 per cent., Ni 5·0 per cent.).
6. Nickel Chrome Case-hardening (C 0·15, Ni 2·0, Cr 0·8 per cent.).
7. ,, ,, (C 0·15, Ni 3·5, Cr 1·1 ,,).
8. Nickel Oil-hardening (C 0·4, Ni 3·0 per cent.).
9. Nickel Chrome Oil-hardening (C 0·3, Ni 2·0, Cr 1·0 per cent.).
10. ,, ,, (C 0·35, Ni 1·2, Cr 1·2 ,,).
11. High Carbon (C 0·5 to 0·9 per cent.).
12. Nickel Chrome Case-hardening (C 0·15, Ni 4·5, Cr 1·5 per cent.).
13. Nickel Chrome Oil-hardening (C 0·3, Ni 3·0, Cr 1·0 per cent.).
14. ,, ,, (C 0·4, Ni 4·0, Cr 1·5 ,,).

The compositions given above are only "types" and must not be taken literally as exact compositions, the figures simply act as a guide. From the above it will be seen that the carbon content is, first, a measure of the sensitiveness, then chromium, and finally nickel in a lesser degree. The ratio of nickel to chromium is also important, and it would seem that when this is 3 to 1, the risk of cracking is much greater than if the ratio is 2 to 1 or 1 to 1, even though the chromium and carbon content be the same in each case.

Generally for light work, such as aero-engine connecting rods (stampings), gear wheels stampings, etc., the steels from 8 to 14 should be preheated. No hard and fast rule, however, can be laid down and much will have to be determined by experience under the actual conditions of furnaces, labour, and intricacy of shape of the parts, etc.

In any case, it should be remembered that slow and uniform heating always gives the best results, relieving the internal stresses due to forging, stamping, or rolling more gradually and reducing the chances of warping or cracking to the minimum. This is particularly important in steels 11 to 14, and even more so if the stamping or forgings have been allowed to cool on the floor without protection from draughts.

The temperature to which the work should be heated depends on the following factors :—

1. Composition of steel.
2. Finishing temperature of forging, stamping or rolled bar.
3. The commercial aspect—factor of safety, etc.

The composition of the steel is the first consideration because the position of the critical range is dependent on this. The critical range diagram (Fig. 70) for carbon steels shows how the temperature of the upper critical range varies with the carbon content. A mild steel of 0·1 per cent. carbon content has a critical range temperature of about 860° C., while in a medium carbon steel of say 0·4 per cent. carbon content, the same point occurs at about 760° C. or about 100° C. lower. Now, the most satisfactory temperature in practice to produce a fine grain structure is one about 30° C. above the upper critical range. This is explained by the fact that when the steel is heated to just above the critical range there is a complete refining of the grain (in steel which has not been overheated), and the grains become very small. On heating further the grains enlarge or coarsen and the strength of the steel is reduced.

Thus for carbon steels the normalising temperature should be given at from 20° C. to 50° C. above the critical range. For convenience these temperatures are set out in the list given below, the different steels being identified by their carbon content. Other factors in the composition, of course, may have to be considered and these temperatures modified. Manganese, for instance, lowers the critical range by about 3° C. for each 0·1 per cent. increase.

Alloy steels in general have a much lower critical range than carbon steels. Nickel up to about 6 per cent. lowers the upper critical range by about 10° C. for each 1 per cent. addition ; other constituents remaining the same. Further additions lower the range still more until at about 25 per cent. nickel content the critical range on cooling is actually below ordinary atmospheric temperatures and the steel is permanently hard.

Chromium, on the other hand, raises the upper critical range, the increase being about 16° C. for each 1 per cent. increase in chromium up to 4 per cent.

In nickel chrome steels the two additional elements naturally operate to fix the critical range at a temperature depending on their respective proportions.

Vanadium appears to have a more powerful effect than chromium, while the combination of the two, chromium and vanadium, is still greater in its effect on the range.

In the case of alloy steels, however, the general rule laid down for carbon steels is not so successful, owing to the more "sluggish" nature of these steels. The transformation from one state to another is much slower and the grain structure does not grow so rapidly in size at high temperatures as in the case of carbon steels. Thus to meet this more sluggish action it is necessary (commercially) to normalise such steels at temperatures higher than 30° C. above the upper critical range. As the variety of these alloy steels is considerable and their properties and behaviour under treatment vary to a great extent, only a very approximate rule may be given for calculating the normalising temperature. This temperature for most purposes can be taken at 100° C. above the upper critical range.

Normalising Temperatures.—The following list gives approximately the normalising temperatures for the more usual commercial steels :—

APPROXIMATE NORMALISING TEMPERATURES.

	Degrees Cent.
Mild (0·05 to 0·15 per cent. carbon)	870 to 900
,, (0·15 ,, 0·25 ,, ,,)	840 ,, 870
Medium Carbon (0·25 to 0·35 per cent. carbon)	810 ,, 840
,, ,, (0·35 ,, 0·5 ,, ,,)	780 ,, 800
High Carbon (0·5 to 0·6 per cent. carbon)	770 ,, 790
,, ,, (0·6 ,, 0·7 ,, ,,)	760 ,, 780
,, ,, (0·7 ,, 0·8 ,, ,,)	750 ,, 780
,, ,, (0·8 ,, 0·9 ,, ,,)	745 ,, 765
Nickel 2 per cent. (C 0·3, Ni 2·0 per cent.)	850 ,, 870
,, 3 ,, (C 0·3, Ni 3·0 ,,)	840 ,, 860
Nickel Chrome, oil-hardening (C 0·35, Ni 1·2, Cr 1·2 per cent.)	840 ,, 860
,, ,, (C 0·30, Ni 2·0, Cr 1·0 ,,)	830 ,, 850
,, ,, (C 0·30, Ni 3·0, Cr 1·0 ,,)	820 ,, 840
,, ,, (C 0·40, Ni 4·0, Cr 1·5 ,,)	810 ,, 830
,, ,, (C 0·3, Ni 3·5, Cr 0·5 ,,)	800 ,, 820

		Degrees Cent.
Chrome Vanadium oil-hardening	(C 0·4, V 0·2, Cr 1·3 per cent.)	800 ,, 820
Mild Case-hardening	(C. 0·05 to 0·20 per cent.)	870 ,, 900
2 per cent. Nickel Case-hardening	(C 0·15, Ni 2·0 per cent.)	900 ,, 930
3 ,, ,,	(C 0·15, Ni 3·0 ,,)	890 ,, 920
5 ,, ,,	(C 0·15, Ni 5·0 ,,)	870 ,, 900
Nickel Chrome Case-hardening	(C 0·15, Ni 2·0, Cr 0·8 per cent.)	870 ,, 900
,, ,,	(C 0·15, Ni 3·5, Cr 1·1 ,,)	860 ,, 880
,, ,,	(C 0·15, Ni 4·5, Cr 1·5 ,,)	840 ,, 860

The importance of the finishing temperature in forging, stamping, or rolling, etc., is referred to in the section dealing with "drop stampings and forgings." It influences the selection of normalising temperatures very considerably. If the finishing temperature is only a little above the upper critical range and the work is cooled in air and is of comparatively small section, the grain structure will be fine, but if the work is finished at higher temperatures or is of large cross-section, then the grain structure will be coarser. The fine grain structure will offer no difficulties in normalising at the temperatures specified above, but when the grain size is large the treatment may fail to refine the steel sufficiently and the structure will still remain coarse, or at any rate it will not be homogeneous, signs of the original structure being still present. This is due to the slowness with which the constituents diffuse in the mass. Large areas of pearlite adjoining other large areas of ferrite do not diffuse so quickly at the lower temperatures (just above the critical range) as at the higher temperatures, and it therefore becomes a question as to whether the steel should be allowed to remain for a long time at the lower temperature or if it should be normalised at a higher temperature. Prolonged heating ties up the furnace and is objectionable commercially, and higher temperatures coarsen what was originally a fine structure, but produce a more refined structure (but still coarse) in those parts that are very coarse grained. Thus the final product is not ideal, although for commercial purposes it may be all that is required. Thus in the case of forgings and stampings in which the finishing temperatures have not been regulated carefully, and have varied considerably for each part, the normalising temperature must be a compromise between that which gives the best structure, and that giving rapid production but inferior structure. Then the nature of the work and the commercial conditions ruling must settle this temperature. The treatment may be modified in another way to produce good work, but this will be explained later (see Double Normalising).

Soaking.—The soaking period or time the work should be allowed to remain in the furnace after this has attained the correct temperature may be roughly calculated on the basis of allowing 30 minutes for each inch thickness of section. This, however, must only be taken as a very approximate rule, because much depends on furnace operation and the initial state of the steel. With very large sections the soaking time is a serious factor, and where many pieces have to be heat-treated, it is advisable to determine the correct duration by trial or actual measurement, using a pyrometer to indicate when the centre is up to the correct temperature.

Cooling.—This is the last phase in normalising and is carried out usually by withdrawing the work from the furnace and placing it on the floor to cool in air.

Unfortunately, this operation is often badly carried out, and does not receive the attention due to it. In the heating operation care is probably taken to ensure that the parts are uniformly heated by spacing them so that the hot gases circulate freely and radiated heat reaches them, but in cooling the practice is to pile the hot parts into a heap, often on a wet or damp floor, and in a draughty place near a door for example.

The result of such treatment is that some of the parts are cooled more quickly than others—those in the centre of the pile cooling very slowly, and consequently have different mechanical strengths. In the case of low carbon (0·3 per cent.) steels the effect may only be slight so far as tensile strength is concerned, but it is noticeable when impact tests are made. It becomes more serious with medium carbon steels, and in the case of high carbon steels and most alloy steels attention to the cooling arrangements becomes imperative. With many alloy steels there is a tendency to self-harden, which is easily accentuated by draughts, with the result that such forgings and drop stampings, etc., are difficult and sometimes impossible to machine, and easily develop cracks.

The cooling of the work should be conducted either on the floor in sheltered spaces, *i.e.* the floor should be divided by brick or metal screens two or three feet high or, instead, metal racks of very open construction should be employed. The work should then be spaced out in order to secure uniform cooling. In other words, the cooling should be conducted with the same care as the heating.

Double Normalising.—This is simply the normalising process repeated again and has for its object the refining of stampings and forgings, etc., that are coarsely crystalline due to the finishing temperature of forging being too high. Such stampings are not completely refined by the ordinary or single normalising process, because the rate of diffusion of the constituents is slow at temperatures that give fine-grained structures and, unless a prolonged soaking at these temperatures is allowed, the diffusion will have to be assisted by raising the temperature. Then the steel behaves as though it were more "fluid" and the carbon areas diffuse into the ferrite areas with greater facility and speed.

The coarse "overheated" structure in most cases will be broken down by heating to a temperature of 100° C. to 150° C. above the upper critical range of the steel in the case of carbon steels, and from 150° C. to 200° C. in the case of alloy steels. With carbon steels the soaking time at this high temperature should not be prolonged, but should be of the same order as for ordinary normalising. Alloy steels, however, can be given longer soaking times with advantage because they are more "sluggish" than carbon steels. The structure resulting from this treatment will still be coarse-grained, but will be such that a second heating to a lower temperature will produce the fine-grained structure desired.

Thus double normalising consists of (1) treatment at a high temperature to break up rapidly and diffuse a coarse-grained structure into a finer but still fairly coarse structure, and then (2) a second treatment to refine this latter structure into a fine-grained one. The temperatures for this treatment can be arrived at by adopting the following rules :—

Carbon Steels.

Temperature for 1st heating = upper critical range + 130° C.
" 2nd " = " + 30° C.

Alloy Steels.

Add 50° C. to these temperatures.

The commercial aspect may be such that it will not be permissible to treat the work in this manner. Unfortunately, the older and less scientific methods of treating steel have instilled in the minds of many engineers the idea that single treatments are sufficient—any attempt to secure better results from the material by double treatments such as this are opposed on the question of costs, both in production and on plant. In this connection a common statement is that, "we cannot hope to attain the ideal condition in commercial practice, and that to spend money on more perfect treatments which give results only a little better than simpler treatments is a waste." Yet many will, without hesitation, pay a big price for an alloy steel to obtain great strength and allow it to be nearly ruined by the stampers, and will then quibble over the heat treatment so necessary to secure the good qualities inherent in the steel, simply because the cost amounts to a few shillings per cwt.

Fortunately recent years have produced a great advance in the attention given to the heat treatment of steel, and most engineers now look on this operation as a most essential one for producing the best results from the materials used. Previously the heat treatment of steel was a process known only to a few so-called practical hardeners, who obtained more or less satisfactory results by crude "trial and error" methods. Owing to lack of exact knowledge of the internal constitution of steel, the hardening shop of the average engineering firm did not advance at the same rate as other departments, and it was not unusual to find the hardeners working under difficulties in regard to plant, and in badly lighted and unhealthy shops. Furthermore, no serious attempt was made to check the quality of the work or to ensure that it was consistent.

The development of the aeroplane and the expansion of the automobile industry have undoubtedly given an impetus to the practical application of heat treatment processes to materials. Many engineering firms have installed heat treatment plants complete in every detail. The railway companies long ago appreciated the importance of heat treating axles, tyres, crankshafts, connecting rods, and other forgings, in fact, safety considerations more than economic ones have made such treatment compulsory.

The improvements in furnace design, pyrometers, quenching appliances, and the development of labour-saving devices have kept pace with the demand for more efficient plant. Furnaces that may be controlled to within the finest limits as regards temperature and uniformity of heating are readily obtainable. The maintenance of a non-scaling atmosphere in the heating chamber is now a regular proceeding with the better types of furnaces. At the same time large outputs combined with economy in running are reducing the cost of heat treatment to figures less than half of those obtaining with the older types of turnace plant.

Ease of furnace operation combined with pyrometric control ensures regular production consistent in quality. Efficient cooling plant to maintain the quenching boshes at a constant working temperature, again ensures regularity in quality.

The heat treatment department of an engineering works should rank equal with other departments, and a system of checking the work should be adopted which is more rigorous even than that used for checking mechanical operations, for although an incorrectly machined part may pass through several subsequent operations, it is eventually found defective, say, during assembly, and is thrown out, whereas a badly heat-treated part presents no visible evidence of such maltreatment and may be assembled and dispatched without any one realising the fact until the inevitable breakdown occurs, bringing the usual letters of complaint or condemnation from the customer.

Annealing

Annealing and Normalising are terms which are often confused, and are often regarded as meaning one and the same thing. The two processes are practically alike, the main difference being in the rate of cooling.

Annealing has been defined as a process which reduces the material to its softest state for easy machining or other mechanical working. It also has for an object the relieving of internal stresses and strains set up by previous operations such as forging, stamping, rolling, drawing and machining. Finally (like normalising) it is intended to produce a refined structure and also to increase the ductility of the metal to its highest pitch.

Unlike the normalising process, however, the temperature need not necessarily be taken above the critical range; indeed, with some alloy steels the heating to a temperature above the critical range and then cooling produce hardness instead of softness, owing to their tendency to self-harden.

The principal difference between annealing and normalising lies in the rate of cooling, which is generally much slower for annealing.

Heating.—The precautions outlined under normalising should be adopted, with, however, such modifications as are required to produce slower cooling, such as packing the work in boxes containing some heat-insulating material.

The temperature to which the steel should be brought depends, as already explained, on (1) the composition of the steel, (2) the finishing temperature of forging, etc., and (3) the commercial aspect. The composition of the steel fixes the critical range, and with the exception of certain alloy steels, the correct temperature for annealing will be the same as for normalising. The list given on p. 198 should be worked to except for a few steels which do not anneal perfectly at the temperature given, and are dealt with later.

The finishing temperature of forging, etc., will have to be considered, as it will affect the quality of the work unless the treatment is modified or added to in some manner. Prolonged heating will overcome moderately coarse structures, but cannot be adopted to refine very coarse ones, owing to questions of cost, locking up of plant, etc., the time required being excessive. With such work a special treatment must be employed (see "Special Annealing Processes"), but with material having a normal-sized grain structure the temperature quoted in the table will produce satisfactory results.

Soaking.—About 30 minutes for each inch thickness of section should be allowed after the furnace has attained the correct temperature. This is only a very approximate rule and is not applicable to work packed in boxes. The time required to heat thoroughly the work packed in boxes will have to be determined by trial, as so much depends on the nature of the material used for packing, the furnace and on the men firing or controlling it. Under good conditions of firing and when the box is placed cold into a furnace at full heat (correct temperature), a rough estimate may be formed by assuming that the correct temperature travels towards the centre of the box at the rate of 1½ inches per hour.

Cooling.—In the case of normalising this is effected by placing the work on the floor and allowing it to cool in still air. The rate of cooling by this method may be termed the "normal rate." In annealing, however, the rate is usually slower than the normal rate and this is obtained by one of the following methods :—

(1) Leaving as much metal on the part as possible, or by actually arranging for the parts to be much heavier (machining the excess metal off after treatment) and cooling on the floor.

(2) Packing the parts in open trays with either iron turnings or steel swarf, burnt sand, lime, or ashes, then removing these trays to cool on the floor.

(3) Packing the parts in closed boxes with any of the above substances or with sawdust or exhausted carburising compound, then removing these boxes to cool on the floor.

(4) By removing the parts from the furnace and placing them in a built-in space or pit, covering them with ashes, sand, or lime.

(5) By allowing the furnace to cool down with the work inside.

The first method is not often employed owing to waste of metal or cost of machining, but occasionally a large mass of metal is desirable in order to reduce distortion in subsequent heat treatments, and its presence can then be taken advantage of during annealing.

Methods (2) and (3) are useful for small parts, sheet metal pressings, or stampings, etc.—sawdust is particularly effective in preventing oxidation—the parts often being as bright on removal from the box as when they were placed in it. The time element in heating, however, is a drawback with this method.

Method (4) is a very practical method for medium or fairly large work and has the important advantage of enabling fairly rapid heating to be obtained and, at the same time, relieving the furnace of its load as soon as the soaking heat is completed.

Method (5) is used mainly for large work—perhaps in single pieces, each occupying a furnace to itself. This method has the disadvantage of locking up the furnace for a considerable time (during cooling), thus extra furnaces are required, and for small work is not as practical or economical as method (4).

Special Annealing Processes.—When the structure of the material is coarse-grained due to overheating the steel, such as when forging and finishing at too high a temperature, ordinary methods of annealing fail to produce the required refinement. In such cases it is advisable to break up the structure and aid diffusion by heating to a high temperature, cooling in air and then to give the work the standard annealing treatment already described.

A suitable scheme of treatment is to heat up to a temperature about 150° C. above the upper critical range, soaking the work at this temperature for a period of about 45 minutes for each inch thickness of section, and allowing it to cool on the floor as for normalising. The original structure is then reduced to a finer grain, although still too coarse, but the constituents are diffused more equally. By then giving the work a second heating, following the lines of ordinary annealing, the fine-grained, well-diffused structure will be obtained. With alloy steels the temperature of the first heating may be higher, say, 200° C. above the upper critical range, and the soaking time greater, with advantage to the final result.

With severely overheated steels the treatment is more difficult and may be commercially impracticable, the cost being greater than the value of the work to be restored. An exceedingly coarse-grained structure such as that shown by Fig. 131, may require many heatings or, instead, one or two very prolonged heatings before a satisfactory state is obtained; while if the steel has been so overheated as to produce burning, nothing short of complete remelting and refining can restore it.

Annealing Alloy Steels.—Some alloy steels do not respond to the ordinary annealing treatment. This is on account of their tendency to self-harden due to the presence of chromium in large amounts, or to certain critical ratios of the nickel and chromium in conjunction with high percentages of carbon. A few such steels are given in the following list, which for safety's sake includes a few which behave doubtfully under commercial conditions, sometimes appearing to be hard and at other times moderately soft:—

List of Alloy Steels requiring Special Annealing Treatment.

Nickel Chrome Oil-hardening	(C 0·35, Ni 1·2, Cr 1·2 per cent.)
,, ,,	(C 0·30, Ni 3·0, Cr 1·0 ,,)
,, ,,	(C 0·40, Ni 4·0, Cr 1·5 ,,)
Nickel Chrome Case-hardening	(C 0·15, Ni 3·5, Cr 1·1 ,,)
,, ,,	(C 0·15, Ni 4·5, Cr 1·5 ,,)

Also the carburised surfaces of the following:—

Nickel Case-hardening	(C 0·15, Ni 3·0 per cent.)
,, ,,	(C 0·15, Ni 5·0 ,,)
Nickel Chrome Case-hardening	(C 0·15, Ni 2·0, Cr 0·8 per cent.)
,, ,,	(C 0·15, Ni 3·5, Cr 1·1 ,,)
,, ,,	(C 0·15, Ni 4·5, Cr 1·5 ,,)

The case-hardening steels in the above list do not self-harden if cooled slowly in a furnace or pit, but if air-cooled as in normalising they will be found to have hard places or spots which will interfere with such machining operations as milling, gear cutting, etc., even though the Brinell hardness may appear low enough for all ordinary machining. When carburised and allowed to cool slowly in the carburising pots the case will often be found quite hard, and where delicate machining operations must be done on the case it becomes necessary to anneal.

With such steels the annealing should be done at temperatures below the upper critical range Ac3, the best temperature being a little below the A*r*1 range. A very satisfactory temperature for this class of steels, ignoring the difference in composition and the various critical ranges, is 650° C. This temperature is almost a "noble" point in the temperature scale because almost all steels, whether carbon or alloy, can be annealed for machining by simply heating them to 650° C. and allowing them to cool on the floor.

It should, however, be borne in mind that this treatment does not have any appreciable effect on the grain size and cannot therefore be regarded as a refining heat. Where the grain size has to be reduced and diffusion effected it will be necessary to normalise the work before annealing it in this manner.

The double treatment just described is applicable to all steels and will be found to give the best combination of ductility, strength, and machining properties. So important is it that space is well devoted in laying the treatment out in the following form.

Carbon Steels

(1) Heat to a temperature 30° C. above upper critical range, soak 30 minutes for each inch of section, cool on floor as for normalising.

(2) Reheat to a temperature 50° C. below upper critical range, soak 30 minutes for each inch of section, cool on floor as above.

Alloy Steels

(1) Heat to a temperature 100° C. above upper critical range, soak 30 minutes for each inch of section, cool on floor as for normalising.

(2) Reheat to a temperature 100° C. below upper critical range, soak 30 minutes for each inch of section, cool on floor as for normalising.

When the maximum of ductility is required and strength is a minor consideration as, for example, in the case of press work and other cold stampings, the above treatment should be modified and carried out as follows :—

Carbon Steels

(1) Heat to a temperature 30° C. above upper critical range Ac3, soak 30 minutes for each inch of section, cool slowly in box, pit, or furnace.

(2) Reheat to a temperature 10° C. above the A*r*1 point, soak 30 minutes for each inch of section, cool slowly in box, pit, or furnace.

Hardening

With the process of hardening there must be associated the subsequent process of tempering or toughening, for it is very seldom that the former is carried out without the latter. Most steels when hardened by quenching are unsafe for use owing to their brittleness and tendency to crack, hence the subsequent or complimentary operation of tempering or toughening (sometimes referred to as " letting down ") must be applied to reduce this brittleness and to remove the internal stresses and strains which produce the cracks.

In the case of low carbon steels (0·3 per cent.) and with some alloy steels containing low percentages of nickel and chromium, etc., the hardening process may not be followed by tempering as this is not so necessary. The " hardening " of such steels does not produce the result that is usually associated with the word " hardness," because these steels are incapable of being hardened in that sense. In such cases the operation is often referred to as toughening.

Now the word " hardness " has very different meanings, depending on the nature of the work and on the requirements of the machine shop. Work which has been treated may be considered soft by the turner and yet be " too hard " for the miller, in fact, the opinions of different machinists will be found to vary according to the class of machine or machining operation and the nature of the operation.

It is good practice, and is becoming more general, to heat treat the work in the rough state either as a forging or after rough machining and then to machine to the finished size. It is, therefore, important for the designer to know what the hardness limits are for different machining operations, so that he can fix on a certain maximum tensile strength (which is usually co-related with hardness) that will render it possible for the work to be machined with ease at each stage. Of course, when the designer is compelled to adopt high stresses for certain parts it will be necessary to treat the work after machining, taking precautions to avoid excessive distortion and then to grind to final size.

Unfortunately it is not possible to state definitely what the hardness limits for the different machining operations should be; the latter vary so much, and depend so much on the type of machine used, the kind of tool steel employed, and, perhaps more than anything else, on the commercial aspect, *i.e.* cost of the operation, which depends on the feeds and speeds employed.

The hardness as measured by the Brinell machine serves as a useful indication of the machinability of the treated steel, and as the tensile strength is related to these measurements a rough connection is established between the strength of the part and its machining qualities.

The following table has been drawn up by the authors on the basis of general observations. It is the result of a series of measurements co-relating the Brinnell values with the general behaviour of the steel under machining operations. The standard taken is mild steel of about 25 tons per square inch tensile strength with 0·2 to 0·25 per cent. carbon, and for the sake of comparison. the value assigned for the cutting property of this steel is 100 when turned in a lathe with a single-point cutting tool.

Brinell Values.		Tensile Strength.		Cutting Properties (approx.).			
		Tons per sq. in.		Single-point test.			
Hardness No.	Diam. of Impression, mm.	Carbon steel.	Alloy steel.	Turning.	Planing.	Milling.	Drilling.
80	6·50	21·7	—	95	95	75	60
97	5·95	25·5	—	100	100	80	70
118	5·45	30·2	—	95	95	75	65
140	5·05	34·8	—	90	90	70	60
166	4·65	40·2	42·0	80	80	65	55
192	4·35	45·0	47·0	65	65	50	40
207	4·20	48·0	49·8	50	50	35	30
235	3·95	53·4	55·0	35	35	25	20
262	3·75	58·0	60·0	25	25	15	10
286	3·60	—	65·0	20	20	10	5
311	3·45	—	70·0	15	15	7	3
340	3·30	—	76·0	10	10	5	2
364	3·20	—	81·0	7	7	3	1
387	3·10	—	85·0	5	5	2	—
402	3·05	—	88·0	3	3	1	—
418	3·00	—	92·0	2	2	—	—
444	2·90	—	97·0	1	1	—	—
477	2·80	—	104·0	—	—	—	—
512	2·70	—	112·0	—	—	—	—

The commercial limit for machining may be taken at about 30, because from the practical point of view the machining of large quantities of work harder than that given in the table is not a success. It is, of course, possible to machine material harder than this, but the operations become such as to require care, time, and the close attention of skilled men.

The operation of hardening, like that of normalising or annealing, consists of three phases : (1) Heating, (2) Soaking, and (3) Cooling.

The precautions in heating are the same as with normalising, but are more necessary because of the subsequent rapid cooling or quenching phase.

The temperature is of great importance as the results produced are affected, often very considerably, by an alteration of 10° to 20° C., while with some steels an alteration of 30° C. means all the difference between good and bad results.

Since the object of hardening is to refine the steel as well as to obtain the maximum hardness, it follows that the best temperature is one which is only a little above the upper critical range. But here again the initial structure of the material has to be considered, and if this be coarse-grained and badly diffused the temperature of the operation will have to be modified to suit.

It should, however, be made a most rigid rule that all work to be hardened should be normalised or perhaps annealed at some stage previous to hardening. The hardening operation can then be conducted on work in which the initial structure is fine-grained and the constituents are well diffused, thus securing every opportunity for obtaining the maximum hardness and greatest refinement of grain, etc. The importance of this procedure cannot be too strongly emphasised. The hardening operation may give a degree of hardness or a tensile result which is satisfactory, but if the grain is coarse and the structure badly diffused the ductility of the material will be poor (as shown by the elongation and reduction of area) while the dynamic strength will be exceedingly poor (as shown by the impact value).

Commercially, much hardened work is checked by the Brinell machine or by the scleroscope ; most admirable methods which unfortunately, however, do not indicate the degree of refinement of the steel and consequently its dynamic strength. The impact test cannot be applied to each piece unless a test piece forms part of it and this is practically prohibitive on account of cost, etc. To secure immunity from trouble, therefore, the work should be either normalised or else well annealed, preferably the former. The hardening operation can then fulfil its proper function without being called upon to correct the bad results due to forging, stamping or rolling, etc.

Assuming, therefore, that the steel is in a good state, the following general rule can be laid down :—The lowest temperature giving the required result is the best temperature and should be adopted. Higher temperatures so often advocated only increase the grain-size and bring about greater distortion effects. Without doubt many troubles attributed to the steel maker are really caused by this tendency to overheat the steel when hardening.

As a rough guide the hardening temperatures can be taken to be the same as for normalising (see list of normalising temperatures), but no definite schedule of temperatures can be given ; each part should be considered specially, and if possible experiments carried out to determine the best temperature. Particulars of suitable treatments are given as a guide in Chapters XI, XII, XIII, dealing with each class of steel.

Soaking Time.—This should be about 30 minutes for each inch thickness of section, but although this figure is given it is necessary to bear in mind that much depends on the steel itself and the conditions ruling at the time. Carbon steels do not require as much time as alloy steels, and steel that has been normalised carefully does not require so much time as steel possessing a coarse or badly diffused structure. Some tests on a nickel chrome steel are shown graphically in Fig. 139, and these demonstrate the importance of soaking the steel well before quenching.

In this series of tests each bar was $1\frac{1}{8}$ inches diameter and all were heated to a temperature of 825° C. The first bar was withdrawn when this temperature had been maintained for five minutes and the other bars were taken out at ten-minute intervals, each being quenched in oil and then reheated to 550° C., soaked thirty minutes, and quenched again.

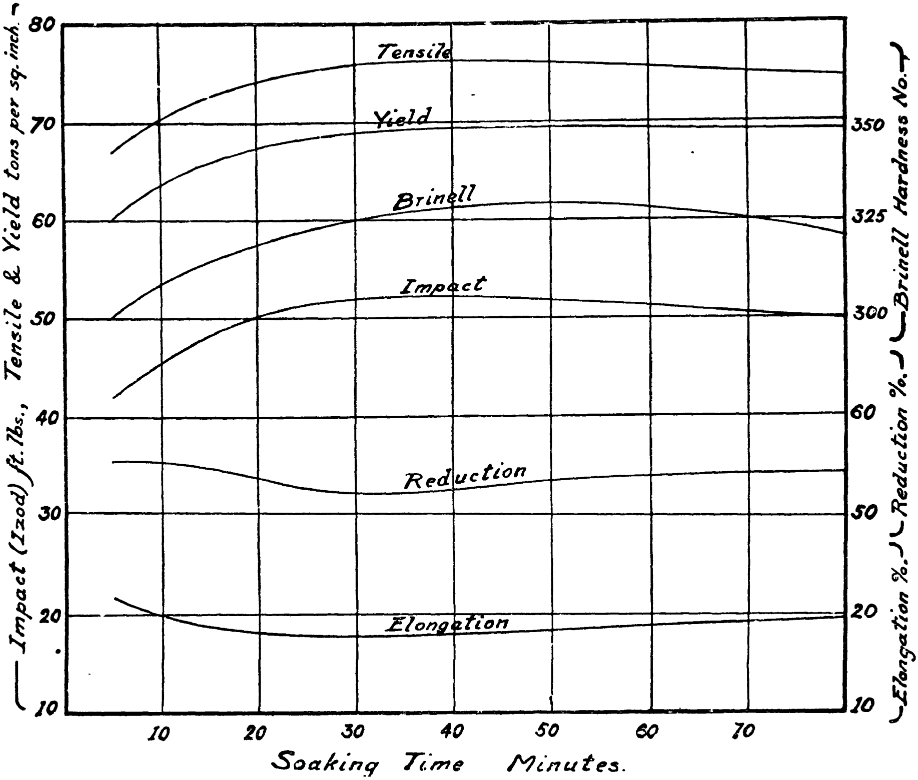


FIG. 139.—Effect of " Soaking " Time in the Hardening Operation. Nickel chrome oil-hardening steel. See also Fig. 140 for reheating or toughening operation.

Cooling or Quenching.—This important phase is dealt with already under " Method of Quenching." One point, however, which should be mentioned again is the selection of the quenching medium. This should be oil whenever possible and wherever distortion is to be avoided. Also the uniformity of temperature at the time of quenching should be attended to carefully in order to prevent excessive distortion and possible cracking. Certain alloy steels should be cooled simply in still air in order to obtain the desired degree of hardness and at the same time to avoid distortion. These steels belong to the " air-hardening " class and for convenience are dealt with later in this chapter and also in Chapter XII.

Tempering and Toughening

This operation, as has been already explained, is really a continuation of the hardening process. No hardened steel should be put into service until it has been tempered, even when it is desired to retain the maximum degree of hardness. The simple reheating of the hardened steel to a low temperature, perhaps only a little hotter than boiling water, will relieve a good deal of the internal strain caused by hardening, and so reduce its brittleness and tendency to crack. This treatment improves the dynamic strength of the steel considerably.

Steel when heated to a higher temperature commences to lose its hardness but becomes tougher (see Fig. 159).

Heating.—Tool makers have made use of the oxidation colours that appear on polished steel when gradually heated, and such expressions as "tempering to a straw colour" are still in use. But while such a method is more or less successful with a few tools, it cannot be applied to mass production in an engineering works, particularly to engine and other parts. Therefore, whether or not the use of this colour method is satisfactory need not be debated here. What must be firmly decided upon, however, is the use of thermometers or pyrometers for controlling the temperature of the work under treatment.

For low temperatures up to 250° C. an oil bath is the best medium for heating the work. Any other method is too uncertain as regards temperature, and too slow commercially. Uniformity of heating is secured, the thin sections being heated to the same temperature as the more massive portions.

Higher temperatures can be obtained by using lead or a tin-lead alloy, or better still a salt bath. These may have the compositions given below.

MOLTEN METAL BATHS.

	Melting point.
Lead	320° to 330° C.
Lead 65 per cent., Tin 35 per cent.	220° C. approx.
Lead 83 per cent., Tin 17 per cent.	260° C. approx.

SALT BATHS.

Potassium Nitrate	335° C. approx.
Sodium Nitrate	280° C. approx.
Potassium Nitrate 40 per cent., Sodium Nitrate 60 per cent.	180° C. approx.
Potassium Chloride 40 per cent., Sodium Chloride 60 per cent.	500° C. approx.

Above the temperature of 550° C. an ordinary gas-fired furnace can be used, for in this region of the temperature range a variation of a few degrees will not affect the result seriously. At the lower temperatures, however, the accuracy of heating is very important, a variation of 10° C. having a considerable influence on the results.

Soaking.—At the lower temperatures the soaking time should be about 30 minutes for small parts such as automobile gears. The hardening strains are practically removed during the heating, and it is only necessary to ensure that the piece has been uniformly heated and well soaked through.

At higher temperatures, more time must be given for the internal changes to take place. At about 200° C. the martensite begins to change into troostite, and as the temperature is raised, more and more troostite is formed. Then at about 400° C. the troostite begins changing into sorbite, and the amount of this increases as the temperature is raised. Sorbite in its turn goes through different modifications, passing into sorbitic pearlite and then slowly into granular pearlite, and eventually into lamellar pearlite.

These changes not only depend on the temperature but also on the duration of heating (or soaking time) and it is important therefore that work should be given time enough to obtain the full advantage of the treatment. The dynamic strength of the material is considerably affected by modifying the soaking time, so also is the ductility. This fact is shown by Fig. 140, which represents the results of some tests carried out on bars $1\frac{1}{8}$ inches diameter of a nickel chrome steel. These bars had been hardened by quenching in oil from a temperature of 825° C., and to determine the effect of the soaking time they were reheated for different periods of time at a temperature of 600° C. and then machined into test pieces and tested. It will be noticed that not until the soaking time is 30 minutes have the test pieces attained a stable condition. Above this time there is little improvement in the qualities of the steel. The dynamic strength as represented by the impact tests (Izod machine) shows the greatest change throughout.

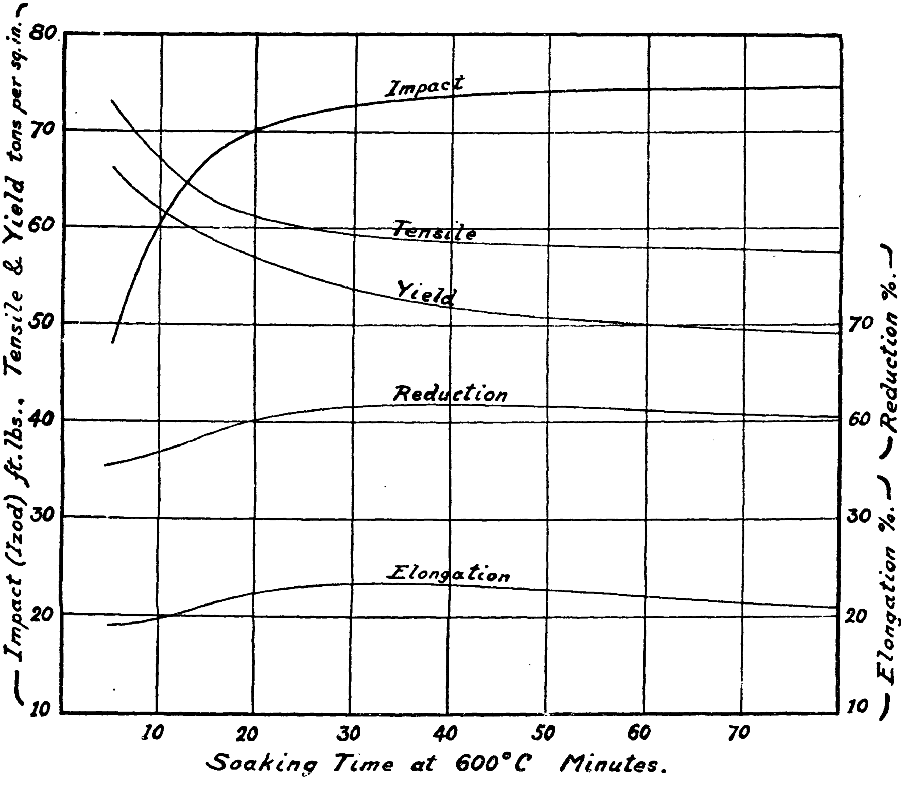


FIG. 140.—Effect of "Soaking" Time in the "Toughening" Operation. Nickel Chrome Oil-hardening Steel. (See Fig. 139.)

Cooling.—At the lower temperatures (up to 250° C.) the cooling can take place in air (on the floor), there being no appreciable change in the steel at this low temperature. But at higher temperatures it is necessary to take account of the composition of steel and either to cool slowly or to quench in water or oil.

With carbon steels slow cooling either in the furnace or pit (or in boxes) may be adopted. Alloy steels, however, if treated this way will give, in most cases, inferior impact values and poor ductility; and it is now an established fact that quenching in oil or water after the toughening heat gives the best results.

Commercially the carbon steel parts can be placed in a heap in an enclosed space so that they cool slowly. This tends to prevent stresses being set up in the material.

At this stage it is advisable to draw attention to an important point concerning alloy steels which is dealt with in Chapter XII, but which is intimately connected with the toughening operation. Tests carried out on many of the alloy steels show that the majority are really only suitable when tempered at temperatures below 250° C. or else toughened at temperatures above 500° C. Steel hardened and then reheated (for toughening) to temperatures between these two figures is found to have a very low dynamic strength, and in other respects to be very unstable—a few degrees variation causing a considerable change in its properities.

It should be made a rule that only steels which give the desired results after tempering at temperatures not exceeding 250° C. or after toughening at temperatures above 550° C. should be used. A steel which requires toughening at a temperature between 250° C. and 550° C. to give the correct tensile strength should be regarded with suspicion and not be put into service until tests have been carried out to determine the impact qualities or dynamic strength.

From the working point of view steels which require toughening at 600° to 650° C. are better to handle. They come just within the visible red heats, which fact makes it easier for the hardener to judge the thoroughness of heating and soaking. Also as a rule these steels are less sensitive to a variation in temperature, and the operation therefore is better from the commercial point of view.

Air-hardening

Alloy steels containing a high percentage of chromium or manganese, in conjunction with a fairly high percentage of carbon, do not require quenching in oil or water to secure hardness. After heating to above the critical range temperature, the requisite degree of hardness can be obtained by simply cooling the steel in still air. Such steels are known as "air-hardening" or "self-hardening" steels.

Reference has been made, already, to the tendency of some steels to self-harden, particularly the nickel chrome series containing high percentages of nickel and chromium, but although this tendency to harden in air is quite pronounced, many of these steels do not harden completely when cooled in air. There is no sharp line separating the air-hardening steels from the rest. The property of self-hardening is dependent on the slowness with which the solid solution transforms into its components cementite, pearlite, and ferrite, and as nickel, chromium, and manganese appear to retard the change, it is evident that this property is controlled by the amount of these alloying metals that is added to the steel. Thus, as is explained under the heading "Annealing Alloy Steels," several steels appear to harden at times and at others are soft enough to machine.

Those steels that can be hardened definitely by cooling in air are usually of the following compositions:—

NICKEL CHROME AIR-HARDENING STEELS.

	Approximate Percentage of Elements.	
	No. 1.	No. 2.
Carbon	0·35	0·30
Manganese	0·60	0·60
Nickel	4·00	4·50
Chromium	1·25	1·50
Sulphur	0·04	0·03
Phosphorus	0·04	0·03
Silicon	0·25	0·25

These steels should be heated to a temperature of 820° C. and then cooled in still air; the usual precautions as to heating and soaking being observed. An air blast is unnecessary and does not increase the hardness. Oil or water quenching may produce a very slightly higher tensile strength, but the risk of cracking is very great.

Tempering or toughening is necessary to obtain the best qualities, and air-hardening steel, after hardening, should be reheated to a temperature that gives the desired mechanical strength. Usually, this class of steel is employed for gears requring the maximum degree of hardness, but even then it is advisable to reheat the steel in boiling water to relieve to some extent the hardening stresses. A slightly higher temperature (160–180° C.) will further improve the steel and increase its dynamic strength.

Reheating to still higher temperatures brings about results similar to those obtained with the usual oil-hardening alloy steels.

Case-hardening

The object of case-hardening is to obtain a material having a hard wearing surface and yet sufficiently ductile to resist shock or bending stresses without breaking. In other words, it should have the properties of both high and low carbon steels. A high carbon steel gives the requisite hardness, but is too brittle, while a mild steel which is not brittle will not harden sufficiently. To obtain a combination of the two it is necessary to select a steel having a low carbon content, giving the required toughness and ductility, and then to impregnate the surface with carbon so that a layer of high carbon steel is formed which when suitably heat-treated will give the hardness desired.

The process of case-hardening is, therefore, first to carburise (or impregnate the surface of the steel with carbon), and then to heat treat the carburised steel so that both the high carbon surface and the low carbon interior give the desired mechanical properties.

The high carbon surface is known as the "case" and the low carbon centre the "core," these terms being universally understood in this sense.

Selection of Steel.—Much care is required in selecting steel for case-hardened work, for not only is it necessary to obtain a core which will not show signs of brittleness, but it is desirable that it should be free from those impurities and defects which lead to cracks and other troubles in the case. So important is the selection of case-hardening steel that the authors have devoted a chapter to it entirely, and in this have explained at some length the principal difficulties and defects that arise during the handling of such material. Thus reference should be made to this chapter (XIII) for particulars of the steels used, and the effects of various impurities.

Carburising Process.—The impregnation of the steel with carbon is accomplished by surrounding it with a substance or mixture * rich in carbon and then heating both to a high temperature, when the steel will be found to take up carbon and hold it in the combined form. The depth to which the carbon penetrates depends on the temperature, the time of heating, and also on the carbon-containing material which surrounds the steel. The nature of these carburising materials and the complete operation are described below.

Selection of Carburising Medium.—It is not possible in this book to detail the constitution and behaviour of the various carburising media in use at the present time, but it is evident that such media must contain carbon in some form or other which at the correct temperature can be taken up by the steel and enter into combination with it.

It is established that the deposition of carbon in the steel is mainly brought about by the presence of gases containing carbon, which enter the "pores of the steel" and by coming into contact with the metal give up a portion of their carbon. This carbon at the proper temperature forms iron carbide and goes into solution, thus increasing the percentage of carbon in the steel. Naturally this action commences at the surface and then gradually penetrates into the metal, raising the carbon content progressively as it continues.

It is essential, therefore, that the medium should be capable of producing gases rich in carbon at a temperature which is high enough for the steel to take the carbon into solution.

There are three classes of carburising media, viz., solid, liquid, and gaseous, each of which is particularly suitable for a certain class of work. The solid medium is the one generally used, the liquid (or fused compound) being used mainly for giving a thin but intensely hard case, while the gaseous method is more or less a modern development and would appear to be applicable only to small work in great quantities.

Solid Carburising Compounds.—The necessary qualities of the solid medium are as follows :—

(1) To be rich in carbonaceous matter capable of generating gases rich in carbon at the correct carburising temperature for the steel (generally about 900° C.).
(2) To contain a minimum amount of moisture and other substances forming gases at low temperature (below 600° C.).
(3) To be free from phosphates, which impart phosphorus to the steel.
(4) To be free from sulphur compounds, which dissociate and give up sulphur to the steel.

---

* Gases rich in carbon also are used but have not found much application commercially.

(5) To remain firm during carburising and not to sink to any great extent in the pot and thus cause distortion in the parts.

(6) To be a good heat conductor in order to reduce the time taken up in heating the contents of the box, thus reducing the total time for the operation.

(7) To be porous enough to facilitate the passage of the active gases required for carburising.

Plain carbon such as wood charcoal is not often used alone because the rate of carburisation is too slow, but when used in conjunction with some of the alkaline salts the process is much more efficient. Thus a mixture containing 60 per cent. wood charcoal and 40 per cent. barium carbonate is one of the best known carburising media.

In place of wood charcoal it is common to use charred leather or charred bone or bone black, and in practice these are favoured to a great extent because the carburising operation can be carried out at a lower temperature and a case richer in carbon is obtained. Animal charcoal such as this owes its more intense action to the generation of volatile hydrocarbons, which deposit carbon in steel much more rapidly than the gases produced by plain carbon and oxygen. Unfortunately this class of charcoal contains a large amount of calcium phosphate (derived from the bones), and there is a risk of this dissociating in the presence of iron and carbon and giving up some phosphorus to the steel itself. Sulphur is also liable to be given up and thus constitute a danger.

The better carburising compounds now on the market appear to contain a proportion of wood charcoal and animal charcoal, together with a small amount of barium carbonate. Thus the rapid carburising tendency of the animal charcoal is tempered by the slower wood charcoal and barium carbonate mixture.

Such compounds on analysis will be found to contain from 45 to 60 per cent. of total carbon, the volatile matter representing the hydrocarbons amounting to as much as 10 per cent. in some cases. The amount of barium carbonate appears to vary from 10 to 20 per cent. The analyses of a few of these compounds are given below.

CARBURISING COMPOUNDS.

——	No. 1.	No. 2.	No. 3.
Total Carbon	59·15	47·3	40·08
Loss at 100° C. (moisture)	5·83	6·46	10·0
Total volatile matter	12·50	15·10	33·84
Barium Carbonate	13·02	20·70	Nil
Sulphur as sulphides	0·12	0·12	0·035
Sulphur as sulphate	2·78	2·57	1·04
Phosphorus	0·25	0·29	0·27
Phosphorus as phosphoric acid	0·56	0·67	1·17

When these compounds are burnt there is usually an ash left, amounting to 20 to 40 per cent., and a close analysis of this reveals the probable composition of the compound so far as the sulphur and phosphorus are concerned. In the compounds Nos. 1 and 2 above, the bulk of the sulphur existed as calcium sulphate, which is harmless so far as the steel is concerned. That sulphur which existed as a sulphide is, however, chemically active and would combine with the steel producing soft spots in the "case." The amount of sulphur, therefore, in this form must be watched, but provided it does not exceed 0·5 per cent. its presence can be neglected.

Phosphorus is detrimental in so far as it tends to combine with the iron to form iron phosphide and to produce a brittle case which will crack or splinter. It also causes blistering of the surface, due to the fact that phosphide of iron melts at a temperature about 950° C., and if the carburising operation is conducted at this temperature this defect may appear.

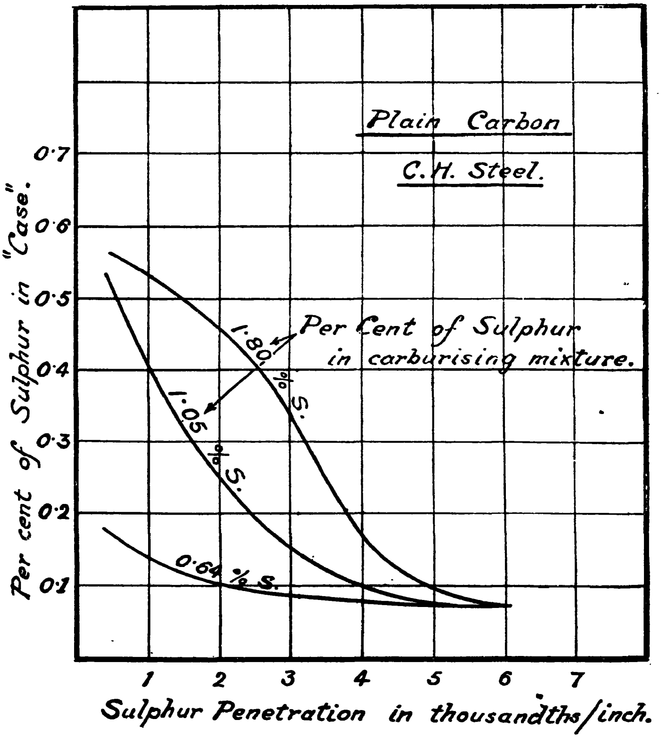


FIG. 141.—Effect of Sulphur in Carburising Compound on Case-hardened Parts. Curves showing penetration of sulphur in a plain carbon steel, using 3 compounds containing different proportions of sulphur.

Both sulphur and phosphorus penetrate only to a very slight depth and are usually machined or ground away in the subsequent finishing operations.

The authors have carried out tests to determine the "penetrative" power of sulphur. The results of these tests are shown in Figs. 141 and 142, which are graphs showing the percentage of sulphur found in the case at different depths when using compounds containing different percentages of sulphur in the form of active sulphides. The compound used was the same throughout, but additions of ferrous sulphide were made, and the figures given are the actual analyses of the "doctored" compound. After carburising, layers were machined off and the turnings collected and analysed, each layer being 1¼ thousandths deep.

Fig. 141 is for a plain carbon steel, and Fig. 142 is for a 3 per cent. nickel steel. In both cases it will be noticed that the sulphur falls off very rapidly with increase of depth, and in all cases it is not dangerous at a depth of 0·005 to 0·006 inch even when the compound contains 1·8 per cent. of active sulphur. Thus as it is quite usual to grind as much as ·005 inch off case-hardened parts the sulphur-rich portions are removed.

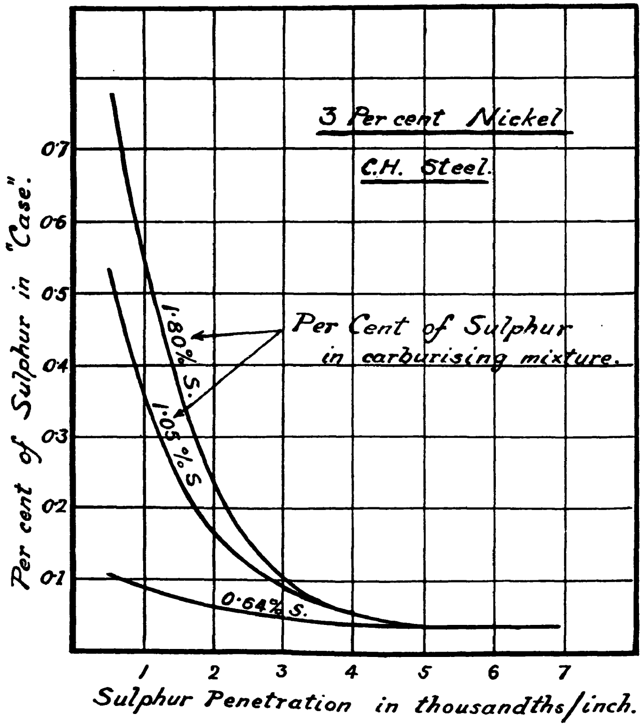


FIG. 142.—Effect of Sulphur in Carburising Compound on Case-hardened Parts. Curves showing penetration of sulphur in a 3 per cent. nickel steel, using 3 compounds containing different proportions of sulphur.

Moisture in the compound is simply waste money and should not exceed 5 or 6 per cent. It is evaporated, of course, during the early stages of the heating, and is a source of nuisance in that it breaks the sealing or luting round the lid of the box, thus making way for the escape of the active gases when these are formed later.

Some carburising compounds contain oils rich in hydrocarbons, and No. 3 compound given above is an example of such. This compound is intended to be a rapid one to give very rich cases. Such compounds are easily recognised by their oil-sticky character and by their high volatility figures.

There are many carburising compounds on the market which cannot be regarded as efficient and which often are distinct frauds. Such compounds will be found to contain common salt, saltpetre, fluor, limestone, sawdust, potassium ferrocyanide, or vegetable husks. One which was examined appeared to consist principally (80 per cent.) of a white clay that had been baked and then crushed in small pieces. This was porous and appeared to hold an oily mixture of soot. The total carbon only amounted to 9 or 10 per cent. and the compound was a complete failure when a depth of case of 1 mm. (0·039″) was required.

Anti-Carburising Compounds.—It is necessary in many instances to prevent the formation of " case " on some portions of an article. A common example of this is the threaded portion on a spindle or shaft which has to be case-hardened. The threads, owing to their comparatively small section, would be carburised right through, and therefore would be too brittle to resist normal stresses.

There are several methods which are more or less successful in preventing the penetration of carbon into the steel. Of these, copper plating has been used extensively, but unless the coating is thick and close grained a small amount of carbon will penetrate it. A common but very unreliable material is ordinary fireclay. This when heated cracks and tends to peel off, thus allowing the carburising gases to reach the steel.

Several compounds are now on the market and some of these are fairly efficient. Usually they are in the form of a powder which must be mixed with water to the consistency of putty or (in some cases) paint, and then applied to those portions of the article which require protection.

The most reliable method consists in leaving an excess of metal on all those portions that are intended to be " soft." After carburising this excess is machined off and the part is then hardened. The amount of metal must be such that the machining operation completely removes the carburised zone. Thus when the depth of case in the hard areas is 1 mm. (0·039″) the excess of metal in the soft areas should be at least 1·5 mm. (0·058″) to ensure the complete absence of the carburising influence at the finished size.

Carburising Operation.—The parts to be carburised are packed in boxes with the compound and are then heated gradually to the carburising temperature, usually about 900° C. to 950° C., and allowed to remain at this temperature until the required depth of case is obtained, when the boxes are withdrawn from the furnace and placed on one side to cool before being opened.

The boxes should be chosen carefully to suit the work and, if possible, should follow the outline of the parts, allowing about 2 inches clearance for packing, etc. Much ignorance is displayed over this matter, and large boxes are very often filled with a number of small parts, some of which are placed near the sides and others in the centre. The result is unequal depths of carburising, due to the time (often many hours) taken to heat the centre of the box up to the correct temperature after the outer portions have attained that temperature. The work placed near the sides and top or bottom commences taking up carbon hours before the work placed in the centre and consequently receives a deeper case, while that in the centre is carburised to an insufficient depth.

Another factor often overlooked is the provision of feet or other means for raising the bottom of the box above the furnace floor and so allowing the free circulation of hot furnace gases all round the box. Usually the bottom of the box rests direct on the furnace floor; and, consequently, work placed at the bottom of the box is the last to be heated up. With furnaces which are bottom-heated this difficulty is not so serious.

The boxes must be provided with close-fitting covers.

The usual materials for carburising boxes are malleable iron, wrought iron, or mild steel. Cast iron is used sometimes but does not stand many heatings and, further, is porous. Malleable iron is the best of these. All of them suffer badly through oxidation and soon become very thin and weak. Lately, boxes cast from special cobalt chrome or nickel chrome steel are finding favour, on account of the non-corrodibility of these alloys and consequent long life. The objection to these lies in initial expense, but this is probably counterbalanced by increased life, which appears to be limited only by resistance to repeated heating and cooling which tends to crack the material.

The boxes, and covers also, when very long, should be strengthened with ribs or flanges to prevent warping, further they should be narrow so as to facilitate heating through, and should not be deeper than is absolutely necessary. It is also advisable to make them slightly taper so that the top is wider than the bottom, when the contents are more easily tipped out.

The packing of the work should receive careful consideration so as to secure uniformity of results; even heating must be aimed at. Regularly-shaped articles and heavy work do not require the same care as slender pieces or irregularly shaped parts, which should be packed specially. The possibility of sagging during carburisation must be borne in mind, and if possible delicate spindles or shafts should be packed in a vertical position, the heaviest portion being placed at the bottom.

Gear wheels and pinions should be packed in boxes of circular form so that the teeth are close to the wall and at a uniform distance from it (about 1½ to 2 inches).

Old compounds * may be used next to portions where a deep case is not required, or where one portion is likely to be heated much in advance of the other portions.

The procedure in packing a box is first to place a layer of compound on the bottom to a depth of about 1½ inches, and to tamp it down solidly. Next, the parts to be carburised are placed on this, and carefully spaced out so that they are about 1 inch from each other, and from the sides of the box. More compound then is put in and carefully tamped in between the work so as to be in close contact with it, but yet not so tightly packed as to hinder the free movement of the carburising gases when formed. Further quantities of compound are tamped into position, and if necessary a second layer of parts is placed in position, care being taken to ensure the presence of 1 to 1½ inches of compound between the layers. Finally, a layer of compound at least 2 inches thick is added and the cover placed in position and luted up with fireclay or cement. Sometimes the top portion of the box is filled in with old compound, but at least 1 inch of new compound should be placed above the work.

---

* Old compounds are those that have been used once or twice. In practice a proportion of new compound is added to the used compound for ordinary carburising. The amount added depends on the class of compound used and may vary from 10 to 30 per cent. of the total. Usually it is sufficient to make good the loss by wastage, thus maintaining a constant quantity of compound in use.

Heating.—It is advisable to heat the loaded boxes slowly, up to 700° C., and then uniformly and steadily to the correct carburising heat. At a temperature a little under 700° C. gases are liberated from the compound, and at 800° C., unless the whole of the box is approximately at the same temperature, some of these gases will be lost without depositing any carbon in the steel.

Commercially, however, it is not possible always to carry out the heating so gradually; usually the furnace after having one load discharged is re-charged almost at once. The introduction of the cold boxes lowers the temperature of the furnace, of course, very considerably, but it is not long before the outer portions of the boxes are "up to heat" while the centres are probably only warm. In practice this does not appear to be serious, in fact with most work the results are quite satisfactory. It is, of course, very essential that the packing and distribution of the parts should be attended to carefully. The penetration of carbon proceeds more rapidly at the commencement, but when the depth of case required is about 1 mm. or ·039 inch the time occupied in carburising may be 6 to 8 hours, and therefore any small difference in the rate of heating of the work is not of great importance, owing to the slowness of the penetration at such depths.

For shallow cases requiring only a short carburising period, the rate of heating becomes more important, owing to the rapid penetration of the carbon at these small depths.

Carburising Temperature.—The temperature at which carburising should take place depends (1) on the compound, (2) on the steel, and (3) on the depth of case required.

Most commercial carburising compounds commence giving off gases at 600° C. and at 700° to 800° C. the evolution is very rapid, hence it is unnecessary to raise the temperature higher to obtain the required carburising gases. On the other hand, the steel will not take up the carbon * with sufficient rapidity until it is raised to a temperature above its upper critical range when the carbon can go into solution in the steel. Now with plain carbon steel containing less than 0·2 per cent. carbon the critical range is about 850° C., which means that it is necessary to carburise above this temperature.

Further, the rate of penetration of the carbon increases with temperature, and sometimes, in order to secure great depths of case in as short a time as possible, the temperature is raised considerably, sometimes as high as 1,050° to 1,100° C. Such high temperatures, however, are not to be recommended owing to the coarse crystalline structure produced by the prolonged heating at such temperature (see Fig. 143). The difficulty of refining the steel afterwards is great, moreover the distortion of the work is often serious and causes much trouble subsequently. The case produced is also very rich in carbon and contains, in consequence, much free cementite which, while imparting great hardness, is also responsible for cracking and peeling, and certainly renders grinding a delicate operation.

Such high temperatures are also costly to maintain, both on account of fuel and on account of furnace deterioration and upkeep.

With plain carbon steels of less than 0·2 per cent. carbon content, the best

---

* The absorption of carbon commences at temperatures as low as 780° C., but in such small amount that, commercially, it is insignificant. The whole subject is dealt with most exhaustively in Giolitti's book, "The Cementation of Iron and Steel."

working temperature is 900° to 925° C. This temperature is sufficiently high to enable the carbon deposited from the gases to enter readily into solution in the steel, and is yet not too high to be uneconomical either in regard to the carburising compound, the fuel bill, or furnace upkeep.

In the case of alloy case-hardening steels the upper critical range is lower than for carbon steels of the same carbon content, and for that reason they can be carburised at lower temperatures. As, however, the rate of penetration is generally slower and, further, as the effect of prolonged heating on this structure is not so serious, it is good practice to carburise these at about 900° to 925° C.

Cooling.—It is recognised generally that cooling in the boxes is the best practice, and the boxes, therefore, should be removed from the furnace to a sheltered position where they will require several hours to cool down to say 200° or 300° C. The older practice of removing the parts from the box while hot and quenching them is exceedingly bad, especially if there is to be no subsequent refining treatment. It is impossible to obtain consistent results owing to the practical difficulties in such a procedure.

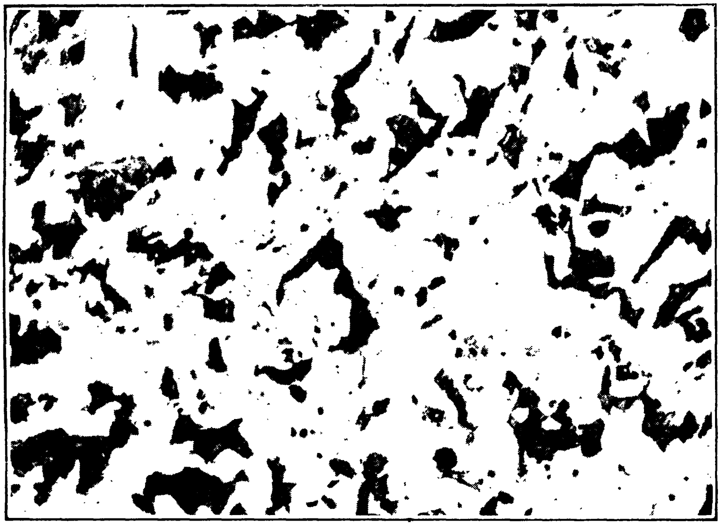


Fig. 143.—Micrograph of Plain Carbon Steel after the Carburising Operation, showing Coarse Structure due to Prolonged Heating. View of core. Magnification 150 diameters; etched with picric acid.

Further, as has been explained already, the carburising process has a deteriorating effect upon the core of the parts, and it is necessary to reheat the steel from a low temperature to above the critical range in order to refine it. The quenching of the steel, just as it is removed from the box, while hot simply fixes the coarse crystalline structure which has been formed during carburising, and produces work which will not withstand any serious shock.

In many instances it is necessary to carry out certain machining operations after carburising, but before actually hardening the part. This occurs constantly with parts which are required to have hardened surfaces on certain portions only, while the remainder is to be left soft. In such instances the soft portions are left larger and then, after carburising, the excess metal (which includes the carburised area or zone) is machined off, the case disappearing with it.

For such machining operations it is necessary that the steel should be soft, and to obtain this condition it should be cooled slowly in the boxes. This is particularly important in the case of alloy steels, some of which have a great tendency to self-harden and may do so even when cooled in the box.

Refinement of Carburised Steel.—The steel during the long period of heating in the carburising operation develops a coarse crystalline structure which is useless for service. This coarse-grained and badly diffused structure is shown by the micrographs in Figs. 143 and 144, which show the core and case respectively. It is essential that this should be rectified by some form of refining treatment.

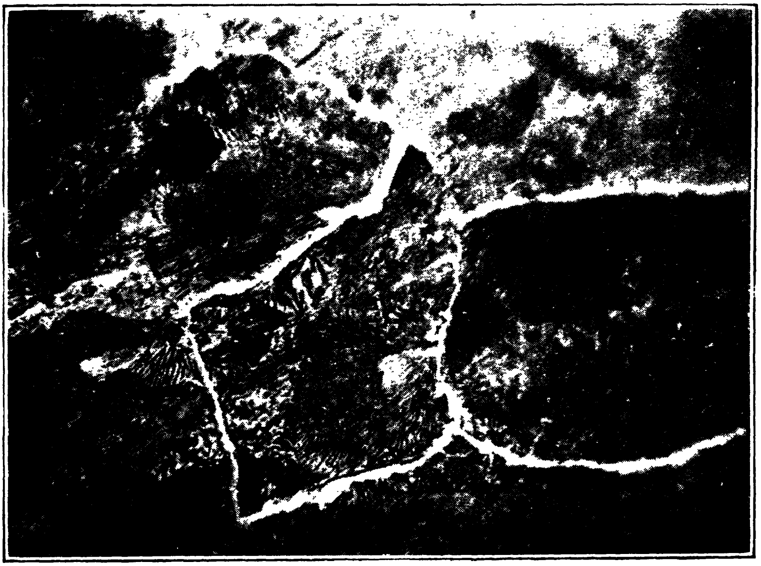


Fig. 144.—Micrograph of Plain Carbon Steel after Carburising Operation, showing Coarse Structure due to Prolonged Heating. View of "case." Magnification 400 diameters; etched with picric acid.

Again, the parts after cooling in the box are soft, and it is neccessary to apply a treatment that will harden the case itself. Thus at least two operations must be carried out, one to refine the structure of the core and the other to harden the case. Sometimes, however, these two objects can be attained by a single operation.

It is clear that in considering the heat treatment of such work, at least two classes of steel have to be taken into account; one containing only a low percentage of carbon, and the other a high percentage like tool steel. With plain carbon steel the upper critical ranges of the two classes are widely apart, that for the low carbon (under 0·2 per cent.) being about 850° C., and that for the case (0·9 per cent.) being about 750° C. Thus to refine the core, it is necessary to heat the steel to a temperature above 850° C. and to quench, but to harden the case it is only necessary to heat to above 750° C. and to quench.

Heating to, say, 900° C. and quenching will refine the core, and will also harden the case, but while apparently it does both operations at once, it really leaves the case in a coarse, crystalline state, even though it may be better than in its original condition just after carburisation. The case, owing to its lower "critical range," naturally assumes a coarser-grained structure at the high temperature of 900° C. than it would at the lower temperature of 750° C. to 770° C.

On the other hand, heating to, say, 770° C. and quenching, may produce a refined case which is perfectly hard, but the core will not be affected appreciably, and will remain in the original coarse-grained state found after carburisation.

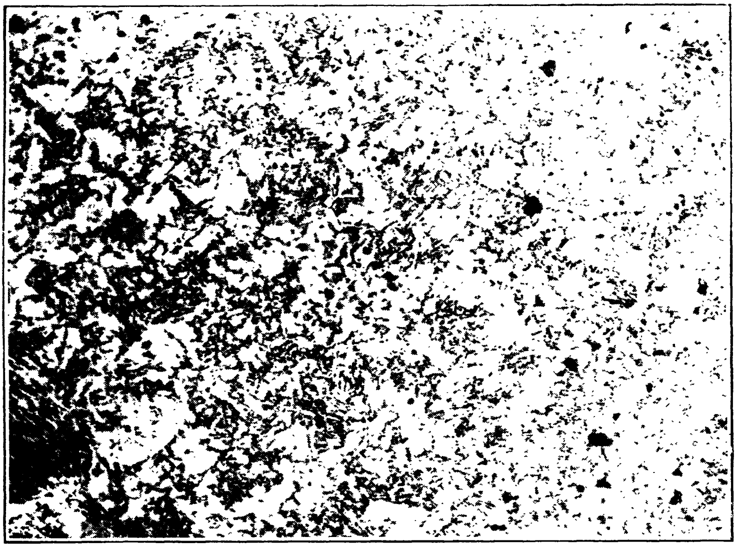


Fig. 145.—Micrograph of Plain Carbon Steel (Fig. 143), after being "Refined," showing how the Carbon Areas have diffused. View of core. Magnification 150 diameters; etched with picric acid.

To obtain both a good core and a good case it is necessary, therefore, to heat and quench the carburised steel twice, first at about 900° C. to refine the core and second at about 770° C. to refine and harden the case.

The effect of this double treatment is shown by the micrographs in Figs. 145 and 146.

The sensitiveness of the steel to this double treatment depends on whether it is a plain carbon, or an alloy, steel. Carbon steels have to be heated to within close limits as regards temperature, to secure the best results, whereas a nickel steel, or even a nickel chrome steel, will give good results over a fairly wide range of temperature. At the same time the dynamic strength of the core is closely affected, in all steels, by the quenching temperatures, and it is always advisable to determine carefully the best temperatures by actual trial. In Chapter XIII, on Case-hardening Steels, the curves given in Figs. 174–5–6–7–8 show how much latitude may be taken in the heat treatment of nickel case-hardening steels.

While it is imperative that plain carbon steels should receive two heats to refine and harden them, only one heat is necessary in the case of some of the alloy steels, *e.g.* nickel or nickel chrome. Nickel steel, particularly, is one which can be refined and hardened both with a single heating and quenching. This is mainly due to the fact that the nickel retards the grain growth, and thus the prolonged heating during carburisation has a much less effect upon the structure than in the case of a plain carbon steel. Hence the necessity for a refining heat does not exist, except in those cases where the maximum properties of the steel are required. Chromium, having an opposite effect to nickel, tends to neutralise this feature of nickel steel and, because of this, nickel chrome steels require, more often than not, a double heat treatment, although a single heat will give fairly good results in many cases. This question is dealt with more fully in Chapter XIII, to which reference should be made.

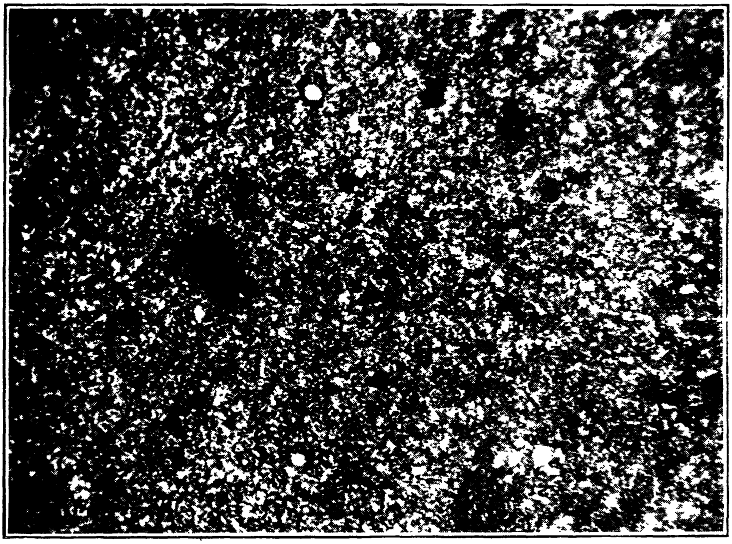


FIG. 146.—Micrograph of Plain Carbon Steel (Fig. 144), after being "Refined," showing how the Grain Structure has been Reduced in Size. View of "case." Magnification 150 diameters; etched with picric acid.

High Carbon Case.—In the preceding paragraphs it has been taken for granted that the carbon content of the case has not exceeded 0·9 to 1·0 per cent., and that in consequence there is little or no free cementite present. When, however, the steel has been carburised in a rapid compound or at a high temperature (950° to 1,050° C.), the carbon content will often exceed 0·9 per cent., and may reach, in some instances, as high a figure as 1·5 per cent. Since the saturation figure is 0·9 per cent. approximately, the excess of carbon, during cooling, is thrown out of solution in the form of free cementite, which will be found in the cold steel as a fine network, the free cementite forming the boundaries of the crystal grains. It also appears in the form of spines or needles projecting into the crystal grains. Such a structure is shown by Fig. 147.

This constituent (free cementite) is extremely hard and also excessively brittle, and it is most essential that it should be diffused well into the steel, otherwise it will tend to produce a brittle case which may crack or flake off. The fine films or network, and the spines, form lines of weakness which cannot be ignored if reliable work is required.

Now at the high temperature of carburising this excess of cementite is in solution (in the austenite), and it is only thrown out during the slow cooling subsequent to carburising ; this slow cooling actually assisting it to form into the network, etc., already mentioned.

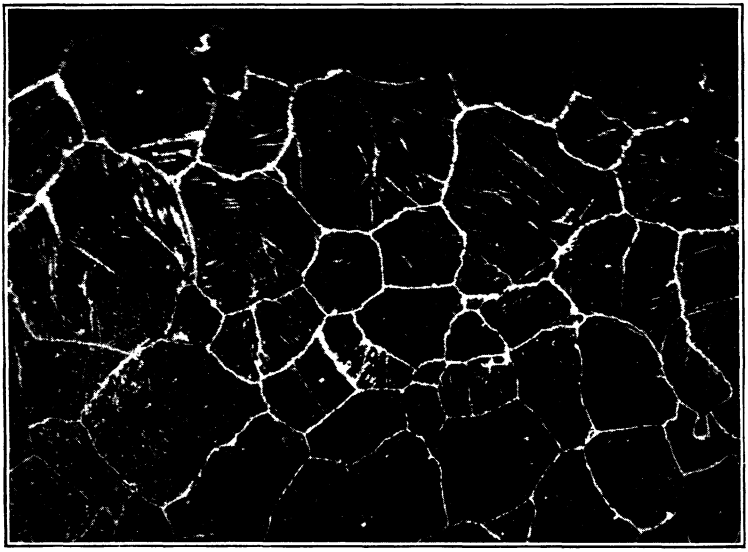


FIG. 147.—Micrograph showing Free Cementite in " Case " (network surrounding grains, also needles in centre of grains). Magnification 150 diameters; etched with picric acid.

If the steel is quenched directly from the box while still at the carburising temperature, the free cementite will be retained in solution, and the danger of cracking and peeling of the case to a great extent will disappear. This operation, however, of quenching from the box is difficult, as it must be carried out at the full carburising temperature (*i.e.* while the free cementite is in solution), otherwise if done at a temperature below the *Acm* point its object will be defeated.

If this procedure is adopted the work is hard and brittle and will have to be carefully handled. In the quenching operation, however, the following precaution should be taken : on account of the tendency of the high carbon case to crack when quenched from a high temperature, it is advisable to remove the steel from the water when its red colour is seen to disappear. This occurs just under the lowest critical range, and it is evident that it will affect in no way the refining of the core, while with the "case" the importance of hardness is not great at this stage and any softening effect can be neglected.

If the work has to undergo further machining operations previous to final hardening, it will be necessary to anneal it at a temperature of about 600° to 650° C. (*i.e.* simply heating it to this temperature, soaking a suitable period, and then allowing it to cool on the floor or some sheltered spot). It will then be machinable, but very weak and delicate so far as bending or straightening is concerned.

The subsequent treatments, to refine the core and to refine and harden the case, will be the same as for ordinary carburised work (containing less than 1·0 per cent. carbon in the case).

The result of such treatment is to produce what may be regarded as the best wearing case. The free cementite, instead of appearing as a network or in the form of needles, will now exist mainly in the form of small specks or spheroids which are supported in a mass of martensite. The cementite is extremely hard while the martensite is softer and tougher, and the result of wearing is that the martensite wears away first leaving innumerable rounded points of the hard cementite to act as the bearing surface, these points, of course, being embedded in the mass of tough martensite. This forms the ideal wearing surface.

The lubrication is effected in the spaces between the two levels corresponding to the surface of the cementite points and the lower surface of the martensite.

High Carbon Case, Alternative Method.—The treatment just described necessitates the removal of the parts from the box and their immediate quenching, an operation which is difficult in practice. As an alternative to this, the following treatment can be adopted, although it does not give quite the same result.

The parts may be allowed to cool in the box and then may be treated to secure the complete solution of the free cementite, which is probably in its worst form, due to the slow cooling. To do this, it is necessary to heat the steel to a temperature above the *Acm* range of the case and then to quench it.

The following is a table of *Acm* temperatures corresponding to different carbon contents :—

Carbon in case.	*Acm* temperature, deg. C.
0·9 per cent.	740°
1·0 ,,	790°
1·1 ,,	830°
1·2 ,,	880°
1·3 ,,	920°
1·4 ,,	970°

From the above table it is evident that if the case contains a zone of carbon exceeding 1·2 per cent., it will be necessary to heat it to a temperature of at least 880° C. in order to cause the free cementite to go into solution. This temperature is practically identical with that required to refine the core (900° C.) and presumably the heating for this purpose will at the same time destroy the network of free cementite in the case. This, however, is a moot point on account of the sluggishness with which the free cementite enters into solution and diffuses in the austenite.

Clearly, if the cementite network is not destroyed at this high temperature, it will not disappear at the lower, or refining, temperature for the case, and in consequence the case will be weak and brittle.

Probably the first heat, 900° C., will cause some of the cementite to diffuse in the solution and only traces of a network will be found in the final product.

When the carbon in the case exceeds 1·2 per cent. it will be seen that the A*cm* temperature exceeds the upper critical range of the core considerably, and therefore the usual refining heat for the core will be useless so far as the free cementite is concerned. To get rid of the cementite it is necessary to raise the refining temperature to above the A*cm* temperature corresponding to the carbon content of the case. This it will be seen may be as high as 970° C. for a case not exceeding 1·4 per cent. carbon content.

The effect of such high temperatures on the core is not very serious although, of course, the result will not be the most satisfactory that can be obtained. It will be realised, that in such an instance, the effect will be least when the core contains a low percentage of carbon, for then its upper critical range will be highest, and the tendency to develop a coarse-grained structure will be least.

Once the free cementite is fixed in solution, the refining of the case is simple, being the same as the ordinary refining treatment to secure as small a grain structure as possible. The temperature of 770° C. secures this.

Owing, however, to the slowness with which cementite dissolves and diffuses a considerable time may be required to complete this operation, or it may be necessary to raise the temperature in order to accelerate diffusion. These operations are difficult and also are inadvisable because : (1) prolonged heating at a high temperature would diffuse the carbon over the different layers thus counteracting the object of securing a high carbon "case," and (2) any further increase in the temperature simply tends to reduce the qualities required in the core.

Simpler Treatments.—When the steel has been carburised at a temperature only a little above the upper critical range of the core, the size of the crystal grains will not be very large, and hence in the subsequent treatment it will not be so necessary to refine the core. The case only will require refining and this is easily effected, as already explained, by simply heating to a point a little above the A1–2–3 temperature and quenching. This quenching temperature in practice is about 760° to 770° C. The core, which was previously soft, will now be tougher, this treatment converting the structure partly into a martensitic one. Thus the single treatment not only refines and hardens the case, but it also toughens the core.

This simple treatment, although in the main satisfactory, does not give the best work and should be regarded only as a good second best. It depends on careful carburising, both as to temperature control and quality of carburising compound.

Other methods of treating or refining carburised steel are as follows :—

(1) Work in which a hard surface only is required and where brittleness and enfoliation are not of serious importance.

Quench directly from box (without slow cooling) at a temperature not less than 760° C. By varying the temperature a wide range of results may be obtained.

(2) Work in which the state of the core is more important than the hardness of the case, which may be only comparatively hard.

(*a*) Cool slowly in box.

(*b*) Quench from 930° to 860° C. (according to the carbon content of the original steel).

Liquid Carburising Compounds.—The most common of these are the "cyanides," such as potassium cyanide and sodium cyanide, but mixtures, containing potassium carbonate and sodium carbonate together with one of the above cyanide salts, are sometimes used.

These compounds are melted in iron vessels, generally known as "cyanide pot-furnaces," and the molten salt is maintained at a temperature of about 800° C., or a little over the upper critical range of the steel. The steel parts are immersed until thoroughly heated and are then quenched in cold water.

This method of case-hardening produces an extremely hard wearing surface, but, owing to the thinness of the case, the parts will not withstand much shock or carry a heavy concentrated load. The case is usually only a few thousandths of an inch thick and is therefore only superficial. If the parts are kept in the molten "cyanide" for 20 to 30 minutes after heating through, the thickness of the case will be about 0·010 to 0·015 inch, but this will depend on the "strength" of the cyanide bath.

Unfortunately, the cyanide salts decompose very rapidly in the molten state and form carbonates which are not effective. Thus a cyanide bath requires constant additions of fresh cyanide to maintain it in working order. As an example of daily practice, using a sodium cyanide bath, the authors found after a period of 7½ hours, working (5 hours at 800° C.) the loss of sodium cyanide amounted to 81 per cent. This loss occurs whether the bath is used for case-hardening or not. The loss in cyanide can be reduced by mixing a proportion of sodium carbonate and sodium chloride with the sodium cyanide. A mixture containing the above salts in the proportions 49 per cent. sodium carbonate, 35 per cent. sodium chloride, and 16 per cent. sodium cyanide produced a satisfactory "case" and the loss was such that the amount of sodium cyanide to be added during each day to keep the bath in order, only amounted to 15 per cent. of the total mixture. About 15 per cent. sodium carbonate and 10 per cent. sodium chloride where required also, to keep the mixture up to its correct level in the bath.

The fumes given off are extremely dangerous to health owing to the highly poisonous character of all cyanides, and it is most essential that some form of hood should be provided over the molten bath to carry these fumes away. Should any of the salts enter a cut or sore the effect is quite as deadly as when taken internally.

As an alternative to immersing the parts in the molten salt it is sometimes more convenient to sprinkle finely powdered potassium cyanide (or potassium ferro-cyanide) on to the part and to heat this to a temperature of 800° to 850° C. after the salt melts, and to quench direct in water. This method is not so satisfactory as the immersion method on account of unequal heating, oxidation and distortion. On the other hand, for local hardening it is very suitable.

In general, cyanide case-hardening is suitable for parts such as small bevel, and gear, wheels required for transmitting light loads, pawls and rachet wheels, snap gauges, small thread gauges, worms, small cams, and light spindles.

It should be remembered that the hardness is only skin deep and that any attempt to increase the depth by prolonged heating is extremely risky owing to the highly cementitic character of the carbon-rich zone and consequently the ease with which it flakes off.

Depth of Hardening

The depth to which hardening takes place when a piece of steel is cooled is a factor that becomes important when heat treating large forgings and other sections. Nearly all the results quoted in this book have been obtained from test bars 1⅛ inches diameter or thereabouts. When the thickness of the part to be heat treated departs to any great extent from one inch, the average tensile strength after treatment will also vary considerably from that obtained with a standard bar. As an example showing the effects produced by quenching bars of different sizes (but not varying greatly from the standard bar, 1⅛ inch diameter), the following results are of interest. The steel used was a nickel case-hardening steel containing 0·14 per cent. carbon, 3·42 per cent. nickel, and 0·57 per cent. manganese. Four bars of different diameters were prepared and all were heated to 760° C. and thoroughly soaked, after which they were quenched in cold water. All the bars after quenching were machined to the standard size of tensile test piece (0·564 inch diameter) and tested, the results obtained being those given in the following table. The variation due to varying mass is very considerable and as the test pieces were machined from the middle of the bars it is clear that the degree of hardening in the centres of the bars depends very much on their thickness.

EFFECT OF MASS ON HEAT TREATMENT RESULTS.

Diameter of Bar.	Yield.	Ultimate strength.	Elongation.	Reduction of area.	Impact (Izod).
Inches.	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.	Ft.-lbs.
1·75	37·4	47·8	21·2	38·4	49
1·25	45·8	54·9	18·4	42·6	42
1·00	53·9	59·3	16·1	41·2	38
0·56	67·8	80·9	13·2	42·9	28

Now the hardness of steel depends on the retention of a partly austenitic or martensitic structure, and this is obtained only by cooling the steel at a rate which is in excess of the rate at which the transformation takes place. In carbon steels the transformation is very rapid and therefore the cooling must be rapid (*e.g.* quenching in water) in order to retain the steel in the same condition as before (or during) the transformation phase. With alloy steels the addition of nickel, chromium, vanadium, and manganese retards the transformation, and for this reason the cooling of these steels to obtain hardness need not be so rapid as is necessary with carbon steels. The addition of 7 per cent. of chromium to a steel retards the transformation to such an extent that cooling in air is sufficiently rapid to secure hardness. A steel containing about 4·0 per cent. of nickel and 1·25 per cent. of chromium also passes through the transformation phase so slowly that cooling in air will arrest it in the pre-transformation condition and it will be hard. Such a condition is, of course, the basis of the so-called air-hardening steels.

When a piece of steel is cooled the portion that loses its heat most rapidly is the surface; the centre portion being the last to cool. Thus in the case of a comparatively large piece the rate of cooling at the surface may be sufficient to retain the outer portions of the steel in the hardened condition while the centre portion, owing to the slower rate of cooling, may pass through the transformation range and thus be comparatively soft. In such a case the outer layers will be hard, and the successive inner layers will be found less hard, becoming softer as the centre is approached.

With an air-hardening steel all portions from the surface to the centre will harden (unless the piece is extremely large) because the rate of cooling of all portions is sufficient to prevent transformation, but with a plain carbon steel the rate of transformation may be much more rapid than the cooling in the centre portions and these portions in consequence will not be so hard.

It is evident, therefore, that the alloy steels will harden to a greater depth than the plain carbon steels, taking pieces of equal dimensions and cooling them at the same rate. This feature of the alloy steels is an important one since it tends to produce a more uniform degree of hardness throughout the section of a large forging than can be obtained with plain carbon steels. Furthermore, when dealing with parts of different thicknesses there is less variation in the hardness between one and another if they are made from an alloy steel than would be the case if they were made from carbon steel.

This quality in alloy steels, however, is dependent on the percentage of the alloying element and the degree of its influence on retarding the transformation. A low nickel (under 2·0 per cent.) is only a little better than a plain carbon steel of the same carbon content, but the addition of 1·0 per cent. of chromium will make it possible to obtain a uniform degree of hardness throughout a 2-inch diameter bar when quenched in oil, whereas the variation in hardness in a similar bar of plain carbon steel will exceed 30 per cent. of the hardness of the centre portion.

The cooling media, of course, have an important influence on the depth of hardness since they control the average rate of cooling of the piece. Thus water quenching hardens the steel to a greater depth than oil quenching, which again is better than cooling in air. This, however, only applies to those steels that should be hardened by quenching in water or oil. Steels that harden in air do not harden as, a rule, to any greater extent when quenched in water or oil.

Distortion Due to Heat Treatment

The distortion that takes place so often during hardening, or in other forms of heat treatment, is in some instances a very serious factor, especially where accuracy is of paramount importance. Unfortunately, the changes in dimensions or shape that occur appear to be erratic and perplexing, not following any governing laws.

There are, however, a few facts of an elementary character, and these can be laid down almost as fundamental laws relating to the distortion that takes place during hardening, etc. To obtain a clear realisation of the possible effects of heat treatment, it should be understood at once that three changes of a distinctly different nature are liable to take place.

The first change is the ordinary thermal expansion common to most materials. The steel, when heated, increases in volume, and when cooled returns to its original dimensions. This change, therefore, is reversible, or can, for practical, purposes be considered so, a fact which renders it of little importance provided the heating and cooling are carried out slowly. Rapid heating, of course, may introduce lack of uniformity in temperature, and consequently, may cause unequal expansion which may have disastrous results. The same applies to cooling, e.g. when quenching. This, however, will be considered independently of the changes that are being dealt with here, and will be referred to later. For the moment ordinary thermal expansion can be taken as of no account.

The second change that occurs is intimately connected with the internal changes that take place when the steel passes through the critical range. The transformations of the constituents involve definite changes in volume. For example, during the cooling, the steel actually expands at the moment it passes through the critical range, with the result that if the cooling is sufficiently rapid to retain the structure in the martensitic condition (*i.e.* hardened) the volume of the steel will be greater than in the original softened state. On the other hand, it may be assumed that if the cooling is slow enough, this volume change will be passed through, and the steel will possess the volume it should have when in the softened condition.

The remaining change to be considered is of a totally different character. It is the tendency of steel to adopt a spheroidal form, *i.e.* a cube will tend to form a sphere. This tendency probably applies to all materials when heated and cooled. It is, in fact, of considerable magnitude, and takes place whether the steel is hardened or not. Further, the fact that it is not reversible, and continues with each successive heating, makes it a change of some importance. In practice, it means that the parts lose their flatness; the centre tending to bulge outwards, producing a convex surface. It also means that the more heatings the steel has, the greater will be the deformation due to this cause. This important molecular movement has an important bearing on the heat treatment of highly accurate work as will be seen later.

Neglecting the first mentioned change the above statements may be summarised as follows, and thus form fundamental laws concerning the distortion of steel during heat treatment.

(1) Steel when hardened increases in volume, or conversely, if no change in volume takes place, the steel is not in the hardened state.

(2) Steel during the process of heating and cooling tends to adopt a spheroidal form, and this continues each time it is heated, the change being almost independent of the rate of cooling.

There is need for much research which would, no doubt, render necessary some modification of the above summarised statements. As they stand, however, they form a useful basis on which to construct the remaining factors concerning distortion.

A third law might be drawn up as follows :—

(3) The volume change during hardening increases with increasing carbon content.

This naturally follows from the remarks already made concerning the first law. The change in volume is due to the change in the constituents, and it is the carbon-bearing constituents that appear to have the greatest effect. Thus the amount of carbon in the steel controls to a very great extent the amount of expansion during hardening.

When hardened steel is tempered or toughened by reheating, the volume is reduced, but the relation between the two (volume and hardness) is not definite, because in many cases the reheating, if carried out to a temperature which produces softness almost equivalent to annealing, will cause the volume of the piece to be actually less than that of the original unhardened piece. This, however, may be due to the greater refinement of the steel, and the size of the crystal grains.

To reduce the amount of volume change during the hardening of a steel part, there is one very clear way, and that is to reduce the proportion of steel hardened, keeping as much as possible in the unhardened condition. In practice this can be carried out in several ways, of which the following are the more common :—

(1) Case-hardening low carbon steel.
(2) Oil-hardening or air-hardening.
(3) Use of two quenching media (water and oil).

The use of a low carbon case-hardening steel means that the proportion of hardening constituent is small, and that therefore the volume change is small. The case, although high in carbon, may be so small in volume compared with the mass of the piece that its volume change during hardening will not seriously influence the size of the piece. By this means a hardened part can be obtained with a minimum of volume change.

To harden by quenching in oil, a suitable steel must be selected, such as one of the alloy steels. The action of the oil, although it cools the surface of the part with sufficient rapidity to ensure hardness, is to allow the interior to cool more slowly, and thus to pass through the volume change without actually being retained in the expanded condition. With air hardening the process is the same.

The use of two quenching media is not a commercial one, but for tool work it is often essential. The result is the same as with the above methods. The part is quenched, first in water for a few seconds, and then immediately transferred to an oil bosh, where it is finally cooled. This is very successful with high carbon steels, the initial water quenching just giving the requisite depth of hardness while the oil allows the interior to cool slowly enough to enable it to pass through the critical range without fixing in that state. The time of immersion in the water is obviously an important factor.

Linear Expansion.—So far only the change in volume has been considered, questions of length or diameter have not been taken into account, and these are of great importance in practice.

It is evident, if a piece of steel tends to adopt a spheroidal shape, that both expansion and contraction may take place, some portions expanding while others actually contract. If no contraction takes place the expansion in any case will not be equal in all directions. Thus although the part may expand in volume it does not follow that the length or breadth or any other particular dimension must necessarily expand. Contraction even may take place in some directions and expansion in others.

In practice, however, the greatest factor is the manner in which the cooling or quenching is conducted. The dimensions of a part are often seriously altered by the direction in which it is immersed in the quenching fluid, and by changing the direction the difficulty is overcome. This important factor in controlling distortion will be found to obey the following general law which might be regarded as a supplement to the first law :—

(4) The expansion produced by hardening is generally greatest in the direction in which cooling has been effected.

To make this clear, consider the hardening of two pieces of steel cut from the same bar, one piece being short (say about the same length as its diameter) and the other piece being longer (say fifty times its diameter). The result of hardening is that the short piece increases, while the long piece does not alter, in length. The volume of both will have increased, but in the case of the short piece the end faces form such a large proportion of the cooling surface that expansion takes place in those directions. With the long piece of bar the end faces are so small in comparison with the peripheral surface that the cooling there is practically negligible, and in consequence expansion takes place in the diameter (to such an extent that very often the length contracts).

The importance of this new condition will be realised when the quenching of a ring is considered. When the dimensions are such that normal quenching does not cause any appreciable change in the internal diameter, it will be found that if the ring is quenched by means of a spray acting on the inside surface only, the internal diameter will be reduced, *i.e.* the expansion proceeds towards the centre, which is the direction of cooling. This method of quenching has been applied successfully to save parts which have been machined too large in the hole.

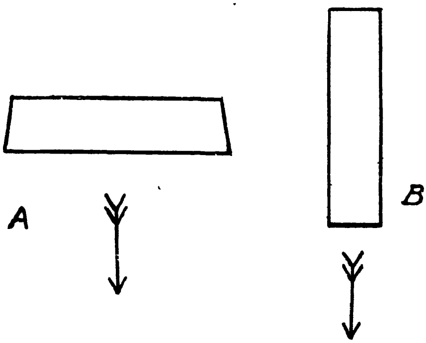


Fig. 148.—Diagram showing Effect of Quenching Discs such as Gear Wheels, Flatways and Edgeways. The latter is best because the former causes one side to expand more than the other.

The same effect takes place in the quenching of such parts as gear wheels when these are immersed flatways in the quenching medium. The surface that strikes the liquid first is usually greater in diameter than the opposite surface, the result being a tapered gear wheel; the teeth only engaging over a small proportion of their width. This is shown in Fig. 148. To overcome this the wheel should be quenched edgeways, thus allowing both sides to cool simultaneously. The concentricity does not appear to be affected.

The distortion difficulty increases as the section of the parts becomes thinner. Parts which are large in relation to their thickness suffer more from distortion than heavy thick parts, hence it is often advisable to make such parts as thick in section as is commercially practicable and then, after the final hardening operation, to machine the excess metal off. This proceeding, of course, is only applicable to case-hardened parts where the case has been machined off the selected portions before hardening.

Hardening machines such as the "Gleason" gear hardener are now used for preventing distortion. The part to be hardened is placed while hot in a jig which is immediately immersed in the quenching medium. Usually the jig is arranged so that the shape of the part is maintained under a high pressure, and buckling and other distortions are prevented. The jig is perforated in all directions to facilitate the quenching action.

Some very simple expedients, however, can be resorted to in order to reduce distortion and it is always advisable to carry out a few experiments to overcome the difficulty. For example, the crown wheel belonging to the differential gear of a motor car is usually a thin-sectioned disc with the vital portion (*i.e.* the gear teeth) situated on one side, near to the edge, where any slight buckling will cause a change in the angle of most of the teeth, a condition which will have a marked effect on the silent running of the gear.

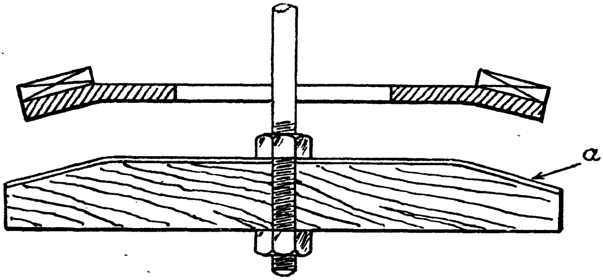


FIG. 149.—Diagram showing Method of Supporting Differential Gears during Quenching to reduce Distortion.

To reduce the buckling of this wheel during the hardening, a block of wood, turned to suit the contour of the back side of the wheel and faced with a piece of asbestos, was used to support it during the actual quenching. The hot wheel was simply laid on the block and immediately lowered into the oil bosh.

Repeated heating and cooling accentuates the tendency to adopt a spheroidal shape and flat surfaces soon become convex. Thus it will be found that while the diameter of a disc will increase at the centre of its periphery the diameter at the edges will often decrease. The effect is shown in Fig. 150, which also shows the behaviour of a ring under the same treatment.

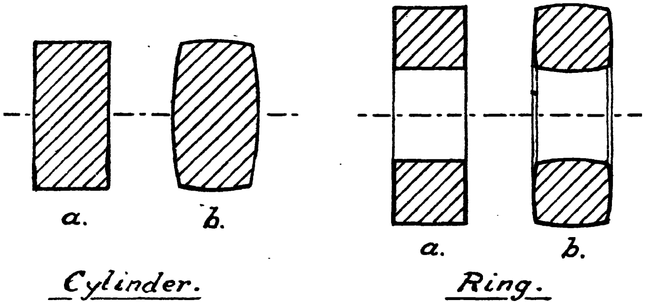


FIG. 150.—Diagram showing Tendency of Steel to adopt a Spheroidal Shape during repeated Heating and Cooling.

The fewer heatings a part receives the less will be the distortion due to this molecular effect.

How to reduce Distortion.—The foregoing paragraphs are mainly of a general character, and it is now necessary to consider the steps that should be taken to reduce distortion. These may be summarised as follows :—

(1) Selection of quenching medium.
(2) Selection of steel.
(3) Adoption of certain practical expedients.

The quenching medium is placed first for without doubt the differences obtained between one medium and another are very great. Water is most drastic, and causes more distortion than any other medium, while oil is much "softer" in its action, and air is even better as a cooling medium. To obtain a rough impression of the relative action of these three cooling media the following approximate ratios are given.

Air	1·5	Approximate ratio of distorting action.
Oil	2	
Water	10	

So great is the difference that in many cases the quenching medium should be chosen first and next the steel that will harden in it.

In the selection of steel the first consideration is the carbon content, for as has been stated the amount of distortion is approximately proportional to the amount of carbon present. Thus a mild or low carbon steel will give less trouble than a high carbon or tool steel. For this reason it is often advisable to employ case-hardening steel, and thus secure the maximum of hardness (for wearing) with the minimum of distortion. In the hardening of gear wheels which have been carburised, it will be found that the teeth expand to a greater extent than the body of the wheel, due of course partly to the larger amount of high carbon steel present, and also to the more rapid cooling that is bound to take place.

Plain carbon steel, except in thin sections, cannot be hardened in any other medium than water, hence owing to the drastic action of the latter, distortion troubles are usually associated with this class of steel.

Nickel when added to steel does not exert much influence one way or another, so far as distortion is concerned, probably because it goes into solution in the iron, and remains there at all temperatures. It confers on steel, however, important oil-hardening properties, and thus, while securing the requisite hardness in this way, it also secures the reduced distortion due to the use of oil instead of water for quenching.

Chromium has a decided effect on the expansion and contraction, and must be regarded as an enemy agent where work of great accuracy is required. Although it imparts air-hardening properties to alloy steels, it nullifies to some extent the advantages gained by using air as a quenching medium.

For ordinary commercial purposes a nickel case-hardening steel of about 3 per cent. nickel and 0·15 per cent. carbon, quenched in oil to harden the case, will give the minimum of distortion. The ordinary air-hardening and oil-hardening alloy steels come next, followed by the plain carbon steels, which are the worst.

The adoption of various practical expedients has already been discussed. These cover the various methods for immersing the parts in the quenching medium, the use of machines, or in making suitable jigs or holders for supporting the parts at the moment of quenching.

Heat Treatment of Iron and Steel Castings

The usual form of heat treatment for iron and steel castings is annealing, but in the case of steel castings it is quite sound practice to treat them as though they were steel forgings, bearing in mind, of course, the coarse structure common to such castings.

The annealing operation relieves the internal stresses due to shrinkage and contraction of the metal during comparatively rapid cooling. It also tends to stabilise the crystalline structure and to diffuse the constituents more uniformly, thus improving the mechanical properties of the material, especially its resistance to shock. Another object of annealing is to improve the machineability of the castings, thus saving time and tools.

Grey Cast-iron.—There are two distinct annealing treatments for grey cast-iron, the first being simply one to relieve the internal stresses in the casting before machining finally to shape, and the second to increase the machining qualities to a maximum.

The first form of annealing is applied to castings that have been rough machined and consists of heating the castings to a temperature of 350° to 400° C. (which turns the machined surface to a blue-grey colour). After soaking for about an hour the stresses set up by machining are removed and to some extent the casting stresses are relieved. Castings treated in this manner can be machined (usually by grinding) to the final dimensions and will then remain true to size for some considerable time. One of the most common applications of this treatment is in connection with cylinder castings for internal combustion engines, such as car and aero engines.

The second form of annealing is applied only when it is desired to obtain extreme softness for rapid machining. The hardness, and to a great extent the machineability, of cast-iron depends on the percentage of combined carbon in the metal. The more carbon that exists in the combined state the harder will be the metal, and consequently the object of annealing is to bring about the dissociation of the combined carbon. This can be done by heating the castings to a temperature of about 750° to 800° C., when the carbon is released in the form of graphite. A casting containing 0·5 per cent. of combined carbon will, after suitable annealing, contain only 0·05 to 0·10 per cent.

This treatment is quite common in the textile industry, where it is usual to pack small grey iron castings after fettling in pots, using iron borings or sand to support them. These pots are heated gradually to a temperature of about 800° C. and after soaking a few hours are cooled slowly. The result of this annealing is to obtain a degree of machineability almost similar to that of brass.

Since the tensile strength of the metal depends on the amount of combined carbon it contains it is evident that cast-iron treated in this manner must be much weaker than in the normal cast state. In the first (or low temperature) treatment there is no risk of any serious reduction in tensile strength.

Steel Castings.—Wherever possible steel castings should be annealed, and in England most foundries of any repute anneal their castings before despatching them to the customer.

The annealing operation is particularly important with steel castings because of the high pouring temperatures, the use of chills and the severe internal stresses that are set up during cooling. The crystalline structure of these castings is usually extremely coarse and a refining process is consequently most essential.

Steel castings are amenable to heat treatment in much the same manner as steel forgings, but, owing to their coarse structure and lack of diffusion of the ferrite and carbon areas, it is necessary to resort to prolonged annealing or to high temperatures followed by rapid cooling.

The best form of treatment is to normalise the castings by heating them to a temperature of about 1,000° C., soaking them long enough to obliterate completely the original structure (and to secure diffusion), and to cool them in air. The castings should then be annealed at a temperature about 30° to 50° C. higher than the upper critical range and cooled slowly (large castings may be cooled in the air and so may castings containing a low percentage of carbon, say, less than 0·2 per cent.). The annealing temperatures for this treatment are as follows:—

Carbon.	Annealing temperature.
0·2 per cent.	850° C.
0·3 „	820° C.
0·4 „	800° C.
0·5 „	790° C.

A simpler treatment is plain annealing at temperatures about 50° C. higher than the above figures. Time should be allowed for the breaking up of the ferrite areas and for diffusion. The cooling of the higher carbon steels (above 0·25 per cent.) should be slow to prevent any tendency to harden, but with the low carbon steels it is advantageous to cool the castings in air because this produces a finer grain structure. It is also quite safe to cool all large castings in air.

Treatments involving quenching in oil, and reheating for toughening, can be applied to castings that have been normalised as described above. These treatments are similar to those applied to ordinary plain carbon steel of the same carbon content. It is necessary, however, to remember that extreme variations in the section of the casting call for careful treatment and all except the low carbon castings should be quenched in oil in preference to water.

Heat Treatment of Non-Ferrous Metals and Alloys

Except in those cases where the non-ferrous metals and their alloys are being rolled or drawn into sheet, bar, tubing or wire, it is not usual to heat treat them, and even then the treatment is mainly that of annealing or softening. Of course, when cold pressings are made, involving much work and displacement of the metal, annealing has to be resorted to in order to reduce the hardness and grain distortion. In all such processes the metal is annealed at intervals between the different stages of the reduction, but as this is part of the manufacturer's programme it is only of general interest to the engineer. However, the engineer is often faced with some difficulty in the working of such materials, particularly in press work, or in complicated sheet metal work involving much mechanical work such as hammering, and therefore the process of annealing the principal metals and alloys is dealt with in these pages.

Annealing is mainly a means for assisting the working of metals and alloys, or is carried out to reduce brittleness in the finished part. Heat treatments, however, can be devised for increasing the tensile strength, ductility, and resistance to shock, much in the same way as those employed for steel; many of the alloys are capable of being improved by heat treatment, and this fact should not be lost sight of by the engineer.

The principal metals and their alloys are dealt with here from the point of view of their heat treatment results.

Copper.—This metal when in the hardened condition due to working (rolling, drawing, and pressing, etc.) can be annealed at a temperature as low as 200° C., but owing to the length of time required to secure complete annealing at this temperature it is usual to employ higher temperatures. Thus, hard-drawn copper wire required for electric cables is annealed at temperatures between 400° C. and 600° C., the finer wires being annealed at the lower temperatures.

Higher temperatures still are sometimes used, as in the manufacture of tubing, but it is not usual to exceed 650° C., and 700° C. is about the maximum.

Prolonged annealing of the cold-worked metal produces grain growth which lessens the ductility of the metal.

Brass.—The annealing of brass is an important and delicate operation depending on the composition of the alloy, its impurities and the amount of cold work put into it. Both temperature and time have to be considered carefully because they are interrelated. For these reasons it is not possible to specify any definite temperature or temperatures for this operation.

In general, however, the annealing temperature for any particular alloy (of brass) will come within the range of 550° to 760° C. and is likely to be about 650° C. The annealing action commences at about 300° C. but does not become appreciable until 400° C. is reached. The full effect is obtained at about 600° C. There is a danger of " burning " the metal at 800° C.

The effect of prolonging the annealing operation is to cause crystal grain growth, which is very rapid and which creates weakness in the material. Thus, the time for soaking the alloy at the correct temperature must not exceed that which is found necessary to restore the grain structure from its distorted condition to the normal size and state.

Aluminium.—It is necessary at times to anneal cold-worked aluminium, particularly in the case of press work, stamping or spinning, where cold rolled aluminium sheet is the material employed. When pressings requiring a " deep draw " are made ordinary cold rolled sheet will rupture often, and it is essential that the sheet should be annealed.

Now the recrystallisation of the elongated grain-structure (due to rolling) in aluminium is an extremely slow process unless, perhaps, it is carried out at high temperatures. Recrystallisation in the case of copper or brass is usually very rapid, and these two materials therefore are very different to aluminium in this respect. With aluminium, however, it appears that mechanical softening is not dependent to any considerable extent on the recrystallisation phenomenon and, for commercial purposes, it is not necessary to prolong the annealing treatment which is so essential if recrystallisation is to be completed. For practical purposes a " dead soft " condition simply is required, and complete equilibrium of the crystal grains is not essential. Thus, whatever time may be required to secure the latter condition, it is only necessary to prolong the treatment sufficiently to secure the desired degree of mechanical softness.

The hardness of the cold-rolled sheet, as measured by the Shore scleroscope (using the magnifier hammer), varies from 11 to 15, but, by annealing, this can be reduced to about 4 or 5. The annealing action is most rapid at first and then becomes slower and slower. It is also more rapid at the higher temperatures. Thus, in some tests of R. J. Anderson,* a 12-gauge cold-rolled sheet had a Shore hardness number of 15 as rolled, but after annealing for 30 minutes at 300° C. the hardness was 7·1, and after 60 minutes at the same temperature the hardness was 4·9. Also, in annealing the same metal at 400° C. for 5 minutes the hardness number was 10·6, and after 10 minutes the hardness number was 4·9.

The quality of aluminium sheet from a deep pressing standpoint can be determined by means of the Erichsen testing machine, which by the movement of a ram produces an indentation in the form of a cup. The depth of the depression is measured (in millimetres) at the moment rupture takes place. The Erichsen value, of course, varies according to the thickness of the sheet. This form of test, therefore, is valuable as a measure of the annealing action.

The usual annealing temperature for aluminium is about 400° C. and the time allowed may vary from half an hour to many hours. For cold-rolled sheet, however, it is possible to carry out the annealing in a few minutes. The effect of varying the temperature is shown by some results obtained by Anderson, who annealed a number of sheets of different gauges, giving each one 3 minutes' heating. Some of these results are given in the following table :—

EFFECT OF VARYING THE ANNEALING TEMPERATURE ON COLD-ROLLED ALUMINIUM SHEET.

Gauge.	400° C.		425° C.		450° C.		475° C.		500° C.	
	Shore hardness.	Erichsen value.	Shore hardness.	Erichsen value.	Shore hardness.	Erichsen value.	Shore hardness.	Erichsen value.	Shore hardness.	Erichsen value.
No. 18	11·6	7·78	7·4	8·90	5·0	10·04	5·0	10·0	4·9	9·88
„ 22	5·0	9·01	5·0	8·44	4·6	8·56	4·9	8·41	4·6	8·31
„ 26	4·8	7·90	4·7	7·61	4·6	7·59	4·4	7·70	4·4	7·66

The Shore hardness number of the cold-rolled sheets varied from 13 to 15, and the Erichsen values for the three sizes specified were: No. 18, 6·58 mm.; No. 22, 5·92 mm.; No. 26, 4·57 mm.

Aluminium Alloys.—One of the most important of the aluminium alloys is duralumin. This alloy can be annealed satisfactorily at a temperature between 350° and 400° C. It is not advisable to heat beyond 420° C. The soaking time should be 30 to 60 minutes, after which the alloy can be quenched in water, or else cooled in air, both treatments producing approximately the same results.

Since this alloy tends to harden in course of time, it is advisable to carry out any work, such as machining, etc., immediately after annealing.

In the case of the copper-aluminium alloys an improvement in the tensile strength can be obtained by heat treatment. Thus, castings containing 3 to 4 per cent. of copper when heated to about 500° C. and cooled in air are improved to the extent of about 3 tons per square inch. The tensile strength as cast is about 6 or 7 tons per square inch, and after treatment this is increased to 9 or 10 tons per square inch. The ductility, also, of the alloy is increased considerably.

---

* "Annealing Cold-rolled Aluminium Sheet by Abbreviated Exposures at Various Temperatures," R. J. Anderson, Inst. Metals, Sept. 11, 1918.

Bronzes.—The tin-copper alloys are amenable to heat treatment, but the extent of the improvement depends on the amount of tin contained, and also on the impurities, or other elements present, in the metal. To understand the effects produced it is necessary to consider the constitution of the alloys. With alloys of less than 9 per cent. tin the metal on cooling forms a solid solution (containing not more than 9 per cent. tin). The portions that solidify first consist of almost pure copper while the later portions become richer in tin. Thus the alloy when cold consists of areas of copper surrounded by areas of the solid solution (generally called the alpha constituent). There are no marked change points, and therefore there is no place at which the metal can be arrested with advantage.

When, however, the alloy contains more than 9 per cent. of tin, another constituent appears during cooling. At about 800° C. the complete alloy becomes solid and consists of a mixture of two solid solutions, one the alpha constituent already mentioned and the other the beta constituent. At 500° C. the beta solution becomes unstable and breaks up into alpha solid solution and a compound known as the delta constituent. This compound is brittle and, of course, reduces the ductility of the alloy in proportion to the amount present or (in other words) in proportion to the amount of tin over and above 9 per cent.

On heating such an alloy to a temperature above 500° C. the delta constituent is nearly all absorbed or dissolved in solution (beta solution), and if the metal is quenched in water this constituent to a great extent is prevented from separating out again and the resulting alloy then consists mainly of a solid solution. With the delta constituent absent the metal is much more ductile and at the same time is stronger. The following figures are based on the results obtained by Guillet and are of considerable service :—

Tin per cent.	*Best quenching temperature. Approximate.*	Tensile strength as cast, *tons per sq. in.*	Tensile strength *quenched, tons per sq. in.*
5	500° C.	19	24
9	650° C.	25	26
13	700° C.	24	30
16	600° C.	25	43
21	600° C.	20	37

Advantage may be taken of this important change in the constitution at temperatures above 500° C. for forging the metal, an operation that can be carried out only just below a red heat.

If the alloys are heated to a temperature below 500° C. the separation of the delta constituent is more completely effected and the tensile strength is therefore reduced. This annealing, as it might be termed, has according to Guillet's experiments the following effects :—

Tin per cent.	Tensile strength as cast, tons per sq. in.	Tensile strength quenched at 450° C., tons per sq. in.
5	19	24
9	25	18
13	24	21
16	25	21
21	20	17

Gunmetal.—The alloy considered here is the standard Admiralty metal, containing 88 per cent. copper, 10 per cent. tin, and 2 per cent. zinc. Except for the presence of zinc this alloy is similar to an ordinary bronze and it might be thought that the treatments specified for bronze would be suitable for gunmetal as well. This, however, is not the case, as is shown by the work of H. S. Primrose and J. S. G. Primrose.

The cooling of the alloy after casting is very similar to bronze (copper-tin) the first portions to solidify (or crystallise out) being the copper containing all the zinc together with a small amount of tin, forming the alpha constituent (or solid solution). As the temperature falls the successive portions of the alpha constituent continue to crystallise, each being richer in tin until (at the moment of complete solidification) the beta constituent fills the spaces between the alpha grains. At about 500° C. this beta constituent breaks up into alpha solid solution and the hard brittle delta constituent. Now between these two constituents microscopic crevices are formed, and these may be large enough to allow water or oil to pass through, a condition which is fatal for many purposes such as pumps, steam fittings, etc. The two constituents, being of very different compositions, have different coefficients of contraction and thus the formation of the crevices would appear to be inevitable.

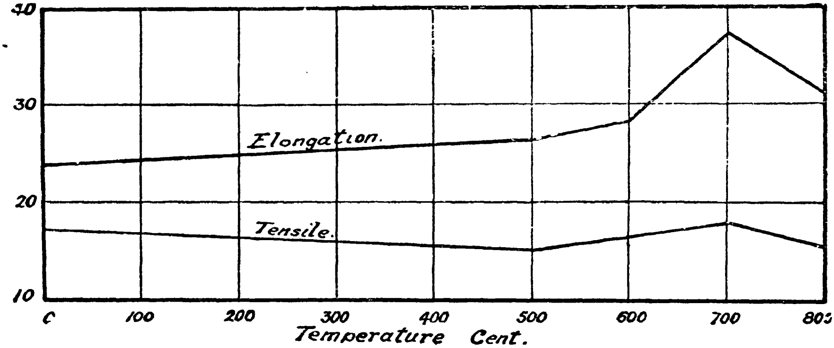


FIG. 151.—Annealing Gunmetal Castings. At 700° C., the ductility is improved considerably without any reduction in the tensile strength. Ordinates represent tons per sq. in. and also percentage elongation.

By rapid cooling in the mould (using chills) the beta constituent can be prevented to some extent from breaking up into these two constituents and the difficulty partially overcome. But in practice it is not possible to control the rate of cooling so effectively as to cause the constituents to arrange themselves in a harmless way. They are not always distributed uniformly, and of such small dimensions as to break any possible path through the metal.

Referring to the work of the Primrose brothers, they found that heating gunmetal and quenching it in water failed to have the good effects obtained with ordinary bronzes. In fact, the strength and ductility of the alloy falls off to a very considerable extent. On the other hand, heating the metal to a temperature of about 700° C., soaking it for 30 minutes and then cooling it at a moderate rate in the furnace, improved the tensile strength and ductility very considerably. At the same time the absorption of the troublesome delta constituent is more or less complete and it does not appear in the structure to the same marked extent.

Thus the porosity of the alloy is reduced and in this way many castings which fail to stand up to the water pressure test can be rectified.

The following results obtained by the Primrose brothers are of service in establishing the value of this annealing treatment. These tests were carried out on inch round bars 10 inches long, cast at a temperature just below 1,100° C. In the first series the bars were cast in dry-sand moulds and then cooled slowly thus representing the usual type of gunmetal casting. Different bars were heated to various temperatures, kept for a period of 30 minutes, and then cooled moderately slowly. The tensile strengths and elongation values are plotted in the graph shown by Fig. 151. The great increase in the elongation value is of immense importance and this, combined with the fact that the tensile strength does not fall off (annealing at 700° C.), places the treatment in the list of those that are of real service commercially.

The effect of annealing chill castings is shown in Fig. 152. The same marked improvement is obtained at 700° C., in fact in these and other tests this temperature appears to be most suitable, and the soaking time of 30 minutes the best. Increasing the soaking tends to reduce the tensile and elongation values.

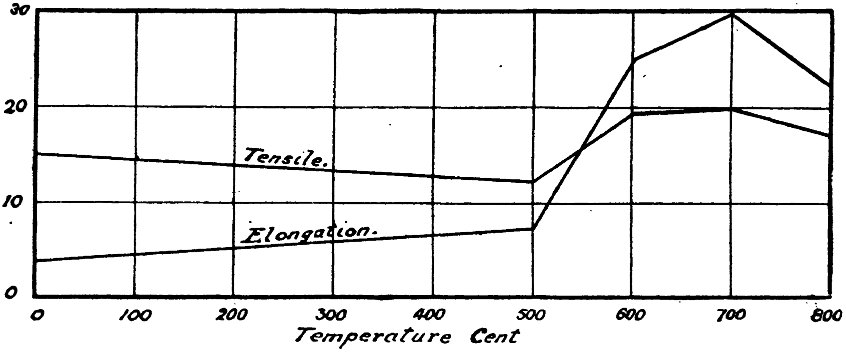


FIG. 152.—Annealing Chilled Gunmetal Castings. Both the ductility and tensile strength are improved by heating to 700° C., and slow cooling. Ordinates represent tons per sq. in. and also percentage elongation.

The heat treatment, therefore, for gunmetal is annealing at 700° C. for 30 minutes and then cooling fairly slowly in a small furnace or in ashes. This improves the ductility by a considerable percentage and tends to raise the tensile strength, while at the same time the porosity of the metal is reduced to a minimum. Heating to higher temperatures is harmful and may even cause incipient fusion (commencing at about 800° C.).

It is important to note that gunmetal heat treated in the manner described does not form a suitable material for bearings. As a bearing alloy it should be used in the cast condition.

Aluminium Bronze.—The aluminium-copper alloys may be divided into two groups: (1) those that respond to heat treatment, and (2) those that are little affected by it. The first group contains from about 7·5 to 11 per cent. of aluminium, while the second group contains less than 7 per cent.

The constitution of these alloys is such that those containing only up to about 7 per cent. (strictly 7·35 per cent.) of aluminium are solid solutions (alpha) and no change takes place in their constituents during heating and cooling. But when the alloy contains more than 7 per cent. of aluminium a new constituent (beta) appears which is hard and dark coloured and is of an unstable character since it is very much altered by heat treatment.

Prolonged heating enables this constituent to attain a stable condition, but the time required for this is very considerable. The effect of slow cooling the whole range of commercial alloys and also the quenching of them is shown in Fig. 153.

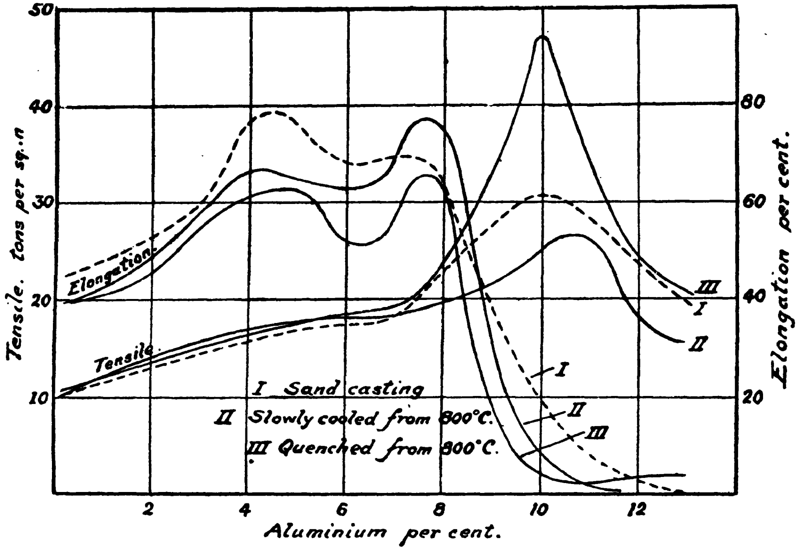


Fig. 153.—Heat Treatment of Aluminium Bronze.

The annealing of aluminium bronze tends to increase the grain size and thus reduces the tensile strength and more particularly the yield point. This is shown in the following table, which represents some of the experiments carried out by Carpenter and Edwards :—

Aluminium, per cent.	Condition.	Yield point, tons per sq. in.	Ultimate tensile, tons per sq. in.	Elongation in 2 in., per cent.	Reduction of area, per cent.
	Rolled :				
0·10	Untreated	6·9	14·50	65·5	90·71
	1 hour at 600° C.	5·0	14·11	65·0	91·60
	1 hour at 900° C.	5·8	13·26	56·0	87·65
2·99	Untreated	11·6	19·79	57·25	86·11
	1 hour at 600° C.	6·9	18·54	66·0	89·84
	1 hour at 900° C.	5·8	19·76	82·5	83 60
5·76	Untreated	11·8	28·40	74·2	76·93
	1 hour at 600° C.	9·4	27·20	77·0	75·00
	1 hour at 900° C.	6·0	23·65	86·0	70·00
7 35	Untreated	10·6	29·68	72·5	74·34
	1 hour at 900° C.	7·1	23·89	92·0	72·00

CHAPTER XI

CARBON STEELS

CARBON Steels are classified under many headings and are sold by steel makers under various names and titles, all of which has a most confusing effect when the necessity arises for the selection of a steel for a given part. Whatever name or description is given to a steel, that steel can be placed in one or other of the following groups, which represent a practical classification according to the tensile strength in the annealed condition.

Classification of Carbon Steels

I. *Mild Steels.*
  (1) Dead soft: tensile 20 tons, carbon 0·05 to 0·15 per cent.
  (2) Ordinary: tensile 25 tons, carbon 0·15 to 0·25 per cent.
II. *Medium Carbon Steels.*
  (1) 30 ton: tensile 30 tons, carbon 0·25 to 0·35 per cent.
  (2) 40 ton: tensile 40 tons, carbon 0·35 to 0·45 per cent.
III. *High Carbon Steels.*
  (1) 50 ton: tensile 50 tons, carbon 0·45 to 0·60 per cent.
  (2) Tool Steel: tensile above 50 tons, carbon 0·60 to 1·4 per cent.

A close examination of the above classification shows that the tensile strength is almost proportional to the carbon content of the steel. In practice this is not strictly true owing to the different conditions in which steel may exist, even though it has been subjected to an annealing treatment. Also the presence of varying proportions of manganese, phosphorus and other impurities affects the relationship. W. E. Dalby * determined the maximum tensile strength of a number of steels (of different carbon content) and as a result plotted a curve showing the relation between this and the pearlite content. This curve is reproduced (Fig. 154) and below the pearlite figures the corresponding carbon content is given.

Point No. 1 is the ultimate strength of good Swedish iron containing 0·04 per cent. carbon (almost the nearest approach to commercially pure iron). The line joining this point and No. 2, corresponding to 0·9 per cent. carbon steel, passes through the origin line at about 16 tons, thus indicating that carbon-free iron which has been worked has an ultimate tensile strength of 16 tons per square inch.

The adoption of the pearlitic content instead of the carbon content results from the fact that the pearlitic state of the carbon constituent represents the

---

* Professor W. E. Dalby, M.A., B.Sc., F.R.S., Paper read before the Institution of Naval Architects, March 28th, 1917.

annealed state of the steel, and it is only in the annealed condition that the relationship referred to above is even approximately true.

From this curve, and also from other data, Dalby arrives at the following equation:

$$\text{Ultimate strength} = 51 \times \text{carbon per cent.} + 16.$$

This equation represents the ultimate strength of good commercial steel of normal quality, after annealing to allow the pearlite to form. Thus taking an average "40 ton" steel containing, say, 0·4 per cent. of carbon, the ultimate tensile strength in the annealed condition will be—

$$(51 \times 0{\cdot}4) + 16$$
$$= 20{\cdot}4 + 16 = 36{\cdot}4 \text{ tons per square inch.}$$

This is, however, in its softest condition, which is not the normal state in which a steel of this character is used in most engineering work. Normalising by cooling in air will generally raise this value by several tons, and suitable heat treatment by still more.

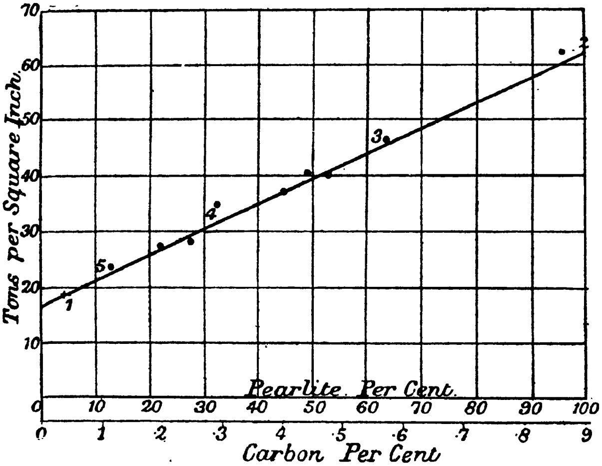


FIG. 154.—Relation between Carbon Content in Steel and the Maximum Tensile Strength. The steel is in the annealed condition (Dalby).

For the purpose of *very rough approximations* it can be assumed, generally, that the ultimate tensile is about 100 times the carbon percentage when the steel is in the normalised state (*i.e.* air cooled). Thus a steel with 0·4 per cent. carbon will give approximately 40 tons tensile strength.

Conversely, according to Dalby the carbon content can be estimated approximately from the ultimate tensile strength :—

$$\text{carbon per cent.} = \frac{(\text{ultimate tensile strength} - 16)}{51}$$

Or the still more approximate method mentioned, gives the carbon percentage as a hundredth of the ultimate strength.

Mass Effects.—All calculations such as the above, and in fact the results produced by all treatments, are considerably affected by the mass of the steel being dealt with. The results obtained by heat treating a test bar of, say, one inch diameter will be very different to those obtained on a large forging like a wheel hub or a heavy axle, even though the treatment is similar. This must be borne in mind and the various test results given in this, and succeeding chapters, must not be taken as directly applicable to all parts requiring treatment. In the main the results are those obtained with standard size test bars or pieces of a diameter less than 1⅛ inches.

As an example of the effect of mass, Bullens * quotes the following figures :—

Diameter of bar in inches.	Ultimate tensile strength. Tons per sq. in.
½	62·7
1	60·0
1½	57·7
2	55·0
2½	50·1
3	47·7
3½	45·4

Classification According to Results.—The different mechanical strengths that can be obtained from a given steel by means of suitable heat treatments, opens up another method for classifying steels, one which is of much importance to the designer. A low carbon steel when suitably "toughened" may be used in place of a more expensive medium carbon steel simply normalised, the cost of the extra heat treatment being no doubt small compared with the difference in cost of the two steels.

This view of the heat treatment question should not be lost sight of, for there is no doubt that some very surprising changes can be made, some which even enable a better steel, such as an alloy steel, to be used in preference to another, simply on account of the simpler heat treatment involved and the lower cost thereof. Generally it means the substitution of a fairly common grade of steel for a more expensively made steel. The table on p. 263 shows the steels described in this chapter arranged in order of the mechanical properties obtainable by suitable treatments.

Acid *versus* Basic Steels.—This is a subject which is open to a good deal of controversy, and opinion on the relative merits of the steels produced by the two processes is very divided. Without going into details of the processes, it should be made clear that these steels take their names from the character of the furnace linings in which they are produced. In the acid process the lining is generally siliceous—containing silica and silicates—and is acid in character, while in the basic process the lining consists of metallic oxides such as lime, magnesia, and alumina, etc., which are basic (*i.e.* have an opposite chemical reaction to that of acids).

In the acid process there is no removal of sulphur and phosphorus, and it is therefore necessary to select carefully the pig iron and scrap, which should be very free from both these impurities. On the other hand, the phosphorus is almost entirely removed, and the sulphur very much reduced, by the basic process and in consequence it is possible to use impure pig iron and all sorts of scrap, a fact which no doubt leads to the abuse of this method. Both methods when suitably controlled produce good material, but among many engineers there is a strong feeling of distrust for basic steel and some will not use it under any consideration whatever. There is no doubt that basic steel is prone

---

* D. K. Bullens, "Steel and its Heat Treatment."

to contain more slag than acid steel and that it appears to give more trouble in drop forging and stamping. It is therefore advisable to inspect such steel carefully, both chemically and with the microscope, before using any quantity for forgings and stampings.

The acid process requires pig-iron and ores of great purity, and as these are becoming more difficult to obtain it is highly probable in the future that the basic process will be employed to a greater extent, and that most of the steel required for constructional work will be produced by this process. There is no doubt, therefore, that basic steel will have to be used more for ordinary engineering purposes, and it is equally certain that the steel makers will produce material free from many of the defects which are so often present in that made to-day.

Form and Finish.—The form in which the steel is ordered has an important influence on its cost, and it is essential, therefore, that this should be specified. The finish is even more important and should receive attention so as to secure the material under the most advantageous terms.

Broadly speaking, steel is supplied either as billets, black rolled bars, bright drawn bars, or blue reeled bars.

The billet material and the black rolled bars are used generally for forgings and drop stampings, and their shape and size are, therefore, controlled by the shape and size of the forging or stamping. For nearly all purposes either a square or a round section is suitable, and special sections are not often necessary, or desirable, because of their increased cost. The square section should not have sharp corners as these cause trouble to both the rolling mill people and to the stamper : the corners should be rounded off. Probably the cheapest section is that known as the " Gothic " shape, in which the steel still retains a squarish shape, but the sides are curved and the corners well rounded. Black rolled bar is generally more costly, but is more serviceable for many forgings and stampings.

In all this rough material there is a possibility of such surface troubles as roaks, fine hair cracks, and sometimes laps. These are often difficult to detect, but they almost invariably show up as cracks or fissures in the forging after only a few blows, and may become so deep as to cause the part to be useless. Most of these surface troubles, however, only penetrate a short distance and if the steel suppliers are instructed to rough machine the steel before finishing the rolling the source of the difficulty is removed. This procedure, as a matter of fact, is adopted by several of the most up-to-date firms and their material will be found quite sound in this respect. As a rule the alloy steels give more trouble during rolling, and the rough billets and bars are defective more often than those of mild or medium carbon steels.

For parts which have to be machined direct from the bar it is usual to employ bright drawn or blue reeled steel. The former is drawn cold and possesses a good smooth finish which in many cases forms part of the final article. The blue reeled bar does not possess so good a finish, but is rolled (or reeled) so well that the bars are all the same diameter (or other section). Both kinds are suitable for automatic machines where the chucking arrangements only permit of a very small variation in the size of the bar.

Hardening Effects due to Drawing and Rolling.—The cold working of steel raises its elastic limit, tensile strength and hardness, but greatly reduces its ductility and dynamic strength. If the steel is worked to an excessive degree it becomes extremely brittle. This is due to the distortion of its structure, *i.e.* the grains of ferrite, pearlite, etc., are elongated in the direction of rolling and sections of the individual grains slip along their cleavage planes, generating amorphous metal at these planes which accounts for the brittleness of the material.

Thus all bar steel, drawn or rolled in the cold or semi-cold state, will give higher tensile figures, and lower figures for ductility (as represented by elongation and reduction), while the dynamic strength as shown by the Izod impact test will often be very poor. If the material is annealed it will return to its normal condition and give test results more in accordance with its composition.

As, however, the object of drawing steel cold is to produce bar of good finish and of accurate dimensions (diameter, etc., and straightness), the ordinary annealing operation, owing to scaling or oxidising troubles, cannot be applied and the steel must be used in the stressed condition produced by cold working. It is necessary that the annealing should be carried out in such a manner as to reduce the oxidation to a minimum, so that the bars will retain their original brightness and finish. This, however, necessitates the packing of the bars in boxes which will exclude the air during the operation, or, alternatively, it means the use of special furnaces which maintain an inert atmosphere during the period of working.

The effect of cold working is usually greatest in small-section bars, and is always worse in the outer layers than at the centre of the bar. This is important in the smaller sizes such as ½ inch or ¾ inch diameter, because the tensile test pieces will embrace very nearly the full section of the bar, and in consequence will give a high yield point and breaking figure, whereas when the material is machined into bolts or screws the thread or stem is machined from the centre and the outer layers are cut away. The centre being less affected by drawing possesses a lower tensile strength and the bolts, etc., do not give test results that agree with the original tests. They are, in fact, often below the requirements, because some steel suppliers evidently take advantage of this drawing effect to supply steel of low carbon content and which, simply by reason of the cold working, gives the tensile results asked for. This also applies to cold-drawn steel tubing.

This has an important influence on the manufacture of studs of small sizes, since these are made often from bright drawn steel of the exact size of the stud, the only machining being that of screwing. Here the thread is cut into the hardest layers of the material and as these are the most brittle it is easy to understand why stripping troubles occur. From this it is evident that the better studs are those which are machined from bar of a larger diameter.

Bright Turned Bars.—Messrs. The Coghlan Iron and Steel Company, Ltd., of Leeds, employ a patented method for turning or machining round bars after the final annealing or normalising process, and thus the effects of drawing are eliminated. This material is turned to within an accuracy of ±0·002 inch, and possesses a beautiful finish due to the burnishing action of the rollers employed in steadying the bar during machining.

This method, however, is not applicable to special section bars such as square or hexagon, etc., and the difficulty with these regarding the impact strength still remains.

Ground Bar.—To overcome this same difficulty other firms are grinding the bar after heat treatment, and one firm quotes an accuracy of 0·00025 inch (plus or minus) and a silvery finish. A rougher finish is also supplied with an accuracy of 0·001 inch (plus or minus). This material has the full properties of the heat treated condition, but the increased cost makes its use prohibitive in many cases.

Mild Steel

(*Dead soft.* 0·05 *to* 0·15 *per cent. carbon.*)

Composition.—The usual composition of these dead soft steels is given in the following table :—

	Locomotive Boiler Tubes.	Common screw Stock.	Acid open-hearth Steel.	Sheet Steel.
Carbon	0·12	0·11	0·14	0·14
Manganese	0·33	0·30	0·46	0·42
Sulphur	0·025	0·03	0·04	0·032
Phosphorus	0·030	0·051	0·032	0·020
Silicon	0·020	0·02	0·030	0·051

The composition of this class of steel for most purposes should come within the following limits :—

Carbon	0·05 to 0·15 per cent.
Manganese	0·30 ,, 0·70 ,,
Sulphur	Not over 0·04 ,,
Phosphorus	,, 0·04 ,,
Silicon	,, 0·20 ,,

Heat Treatment.—Owing to the small amount of carbon these steels contain, the range of results obtainable by heat treatment is very limited; in fact it is usual to leave out altogether the question of heat treatment when considering the possible use of the material.

The following treatments are of use :—

Annealing and Normalising :

Heat rapidly to 840°–870° C., soak a minute or two, cool in air. This will relieve strains set up in cold working, pressing, drawing, etc.

Hardening (*or Toughening*) :

Heat rapidly to 840°–870° C., soak a minute or two, quench in water.

This is the best treatment because it refines the grain and removes any strains caused by previous working. It also improves the machining quality of the material, which, as is well known, is usually poor, having a tendency to tear badly during turning and screwing.

With these low carbon steels the change into austenite, when heating, is very rapid, and as the grain soon coarsens with length of time or increased temperature, both these factors should be controlled carefully. The steel need only be heated through and then cooled or quenched.

The second treatment when applied to parts of intricate shape may set up hardening strains, which should be removed by reheating the parts to about 700° C. and then cooling in air (*i.e.* toughening). This, however, is seldom necessary.

Mechanical Tests.—A few test results are given below showing the effect of the above treatments on test bars of $\frac{3}{8}$ inch diameter of "acid" steel.

Steel and Treatment.	Yield, tons per sq. in.	Ultimate, tons per sq. in.	Elongation per cent. in 8 ins.	Reduction of area per cent.
As rolled	16·1	23·5	34·5	65·3
Annealed	14·4	22·2	37·5	67·5
Water quenched, 860° C. ..	20·7	29·8	22·8	61·2
860° C. water / 700° C. air ..	16·6	24·1	35·4	66·1

The composition of the above steel is C 0·10 per cent., Mn 0·32, S 0·024, P 0·028, Si 0·019.

Applications.—This steel is employed for such work as the following :—

Pressings and cold stampings.
Tubing and piping.
Wire.
Sheet—plain, tinned, and galvanised.

Mild Steel

("*Ordinary.*" 0·15 *to* 0·25 *per cent. carbon.*)

Composition.—The following are typical analyses of this steel :—

	Basic open-hearth Steel.	Acid open-hearth Steel.	Spring Clip used in automobiles.
Carbon	0·18	0·18	0·16
Manganese	0·50	0·50	0·45
Sulphur	0·035	0·028	0·045
Phosphorus	0·035	0·044	0·063
Silicon	0·027	0·021	0·04

The composition of this class of steel for most purposes should come within the following limits :—

Carbon	0·15 to 0·25 per cent.
Manganese	0·40 „ 0·90 „
Sulphur	Not over 0·06 „
Phosphorus	„ 0·06 „
Silicon	„ 0·25 „

Forging and Drop Stamping.—This steel is easily forged or stamped, but like all low or medium carbon steels the temperature at which burning takes place is very high (about 1,400° C.), and in consequence the drop stamper will often take advantage of this, and will work the steel at too high a temperature. The correct forging heat is from 1000° to 1200° C., at which temperature the steel is sufficiently plastic for most purposes.

These low carbon steels easily develop a coarse-grained structure and it is essential that the finishing temperature should be closely watched.

Heat Treatment.—This steel, like the dead soft variety, does not harden appreciably, but such treatments as annealing, normalising, and toughening are of value in refining the structure, particularly after forging and stamping and also after cold working. In the case of forgings and stampings which are so often made at very high temperatures, a normalising treatment is absolutely essential to break down the coarse crystalline structure resulting from high finishing temperatures.

The following treatments are used :—

Annealing and Normalising :

Heat to 810°–840° C., soak 15 to 30 minutes, cool in air.

This is applicable for steel which has been forged or stamped at a low finishing temperature (850°–950° C.) and is in a good condition as regards grain size and diffusion. This treatment will relieve strains set up in the forging operation and equalise the structure.

Double Normalising :

Heat to 840°–870° C., soak 15 to 30 minutes, cool in air to " black heat " (500° C.).

Reheat to 810°–840° C., soak 15 minutes, cool in air.

This treatment is intended for parts which have been finished at a high forging heat (950° to 1,100° C.) and are in consequence very crystalline. The first " heat " enables diffusion of the ferrite to take place more rapidly and more uniformly, although the grain size still remains large, but the second " heat," while still improving the uniformity, breaks down the grain size and improves the dynamic strength of the steel.

Hardening (or Toughening) :

Heat to 810°–840° C., soak 15 to 30 minutes, quench in water (or oil).

Reheat to 450°–500° C., soak 30 minutes, cool in air.

The results obtained are perhaps the best of any obtained by treatment, for not only is the tensile strength increased, but the ductility and dynamic strength are good. Quenching in water may be too drastic in some cases owing to the intricate nature of the part, and quenching in oil will have to be resorted to, although this does not give the same degree of refinement as that obtained by water quenching. In such cases the second heating may not be necessary owing to the " softer " action of the oil, but this depends on the size of the part—the larger this is the less will be the hardening action. With very thin pieces the effect of water quenching is to induce brittleness and the second heating is very necessary. This applies to sections up to about 2½ inches thick, or with oil quenching 1 inch thick. Above these sizes the second heating is not so important, although it is useful in relieving hardening strains.

Mechanical Tests.—

(*Carbon.* 0·25 *per cent.*)

Condition or Heat Treatment.	Yield, tons per sq. in.	Ultimate, tons per sq. in.	Elongation per cent. on 2 ins.	Reduction of area per cent.	Impact (Izod), ft.-lbs.
Bar as received	18·5	27·0	41·0	68·0	79, 81
Annealed 860° C., cooled in furnace	20·8	25·4	41·0	70·4	82, 78
Normalised 840° C., soaked 30 mins.	21·5	26·9	39·2	64·7	86, 82, 84
Hardened 860° C., quenched in oil	25·3	31·4	36·8	63·8	87, 90
860° C. 15 mins. (oil), 760° C. 15 mins. (air)	23·1	26·7	38·5	67·5	88, 89, 89

The above tests were made on some black rolled mild steel of 0·25 per cent. carbon content and are the average of the results obtained with two sets of test pieces 1⅛ inches diameter. The bar was supplied in the annealed or normalised condition and, as will be seen, further annealing and normalising made no improvement, the steel being in a good state already. The effect of hardening in oil from 860° C., however, raised the yield point from about 20 tons to 25 tons per square inch, and the ultimate breaking stress from 27 tons to about 31 tons without reducing the ductility much, while the dynamic strength as revealed by the impact test is even better than in the normalised or annealed state.

The reheating to 760° C. restores the steel to the annealed condition, but as is shown by the impact tests the structure is in a better state because of this treatment.

Machining Qualities.—The dead soft steel is often troublesome during machining in so far that it tears badly and the finish is rough. This is improved by heat treatment. With ordinary mild steel the same trouble is experienced sometimes, but as a rule the material machines well and rapidly, in fact it may be taken as the best of all steels for rapid machining. It is common practice in America to increase the percentage of sulphur and sometimes phosphorus so as to improve the cutting properties, but this is a very doubtful procedure where a high dynamic strength is required ; phosphorus inducing brittleness to a very high degree.

Applications.—This steel is used very extensively for machine work, shafting, frames for motor chassis, large engine forgings such as crank shafts, connecting rods, levers.

Medium Carbon Steel

(" *30-ton.*" 0·25 *to* 0·35 *per cent. carbon.*)

Composition.—The following are typical analyses of this steel :—

	Black Rolled Bar Acid Steel.	Black Rolled Bar Acid Steel.	Billet Steel for Stamping.
Carbon	0·34	0·28	0·31
Manganese	0·49	0·74	0·59
Sulphur	0·049	0·035	0·036
Phosphorus	0·053	0·027	0·025
Silicon	0·25	0·11	0·12

The composition should come within the following limits :—

Carbon	0·25 to 0·35	per cent.
Manganese	0·50 „ 0·85	„
Sulphur	Not over 0·06	„
Phosphorus	„ 0·06	„
Silicon	„ 0·25	„

Forging and Drop Stamping.—This is an easy steel to forge or stamp, but again it is common to find that stampings are made at high temperatures, and that the resulting material is coarse-grained. The correct forging temperature is from 850° to 1,150° C., while burning commences at about 1,350° C. Its welding properties are good.

Heat Treatment.—A wide range of results can be obtained by heat treatment, and if these are considered, this steel can be put to a great variety of uses. The following are typical treatments :—

Annealing :

Heat to 800°–830° C., soak 15 to 30 minutes, cool in furnace or boxes, etc.

The treatment reduces the steel to its softest state and removes all forging strains, etc. In this state it is easily machined.

Normalising :

Heat to 800°–830° C., soak 15 to 30 minutes, cool in air.

The treatment removes forging strains and refines the structure. There is a tendency for the steel to harden on the surface and this renders machining a little more difficult than in the fully annealed condition. This, however, is generally only slight and the treatment is more commercial than annealing ; the difference in the tensile strength not being great. Small sections, of course, harden most, and in some cases full annealing may be essential.

Double Normalising :

Heat to 870°–900° C., soak 15 minutes, cool in air.

Re-heat to 800°–830° C., soak 15 to 30 minutes, cool in air.

This treatment is useful for stamping and forgings finished at too high a temperature and is intended for breaking up the coarse crystalline structure that usually results from high finishing temperatures.

Hardening (and Toughening).

Heat to 800°–830° C., soak 15 minutes, quench in water (or oil).

Re-heat to temperature that gives desired results, cool in air (do not quench).

The first heat gives the steel its maximum hardness especially if water quenching is adopted. With intricate pieces or parts with sharp corners, or with holes close to the edge, water quenching may be too drastic and cracks may develop. In such cases oil quenching should be resorted to. This effect is very pronounced in thin sections, when oil should always be used.

The reheating is always necessary after water quenching, even if it is desired to retain the maximum hardness obtained by the first heat. Thus reheating to 150°–180° C. will ease the hardening strains considerably without reducing the hardness. This is shown by the curve in Fig. 155, where it will be seen that the steel when hardened has an impact strength of 23 ft.-lbs., but when reheated to 180° C. the impact value is 38 ft.-lbs.

With oil quenching there is not the same necessity for reheating when maximum hardness is desired, but it is always advisable.

To obtain greater dynamic strength the reheating should be carried out at a temperature which will give the desired impact value and tensile strength. The effect of reheating is to reduce the tensile strength and to increase the impact value. This is also shown in Fig. 155.

Usually the reheating temperature is 700° C., which, as this curve shows, gives a tensile strength of about 36 tons per square inch and an impact value as high as 90 ft.-lbs.

Mechanical Tests.—The tensile strength of this steel in the annealed and normalised states will range as follows :—

	Annealed.	Normalised.
Ultimate breaking strength ..	25 to 35 tons	27 to 38 tons
Yield ratio	50 „ 80 per cent.	50 „ 80 per cent.
Elongation in 2 ins.	40 „ 25 „	35 „ 25 „
Reduction of area	60 „ 50 „	60 „ 45 „
Impact (Izod), not less than ..	10 ft.-lbs.	15 ft.-lbs.

The impact values are most variable, but the figures given should be obtained quite easily. In fact, for specification purposes a value of 20 ft.-lbs. is quite practicable. With careful forging heats and good heat treatment (*i.e.* correct temperatures and soaking times), values as high as 40 and 50 ft.-lbs. can be obtained. Much, however, depends on the size and shape of the part and on the direction of flow of the steel during working; large masses giving low values (in normalising particularly), and the flow, if across the test piece (in the direction of the axis of the notch), reducing the value very considerably.

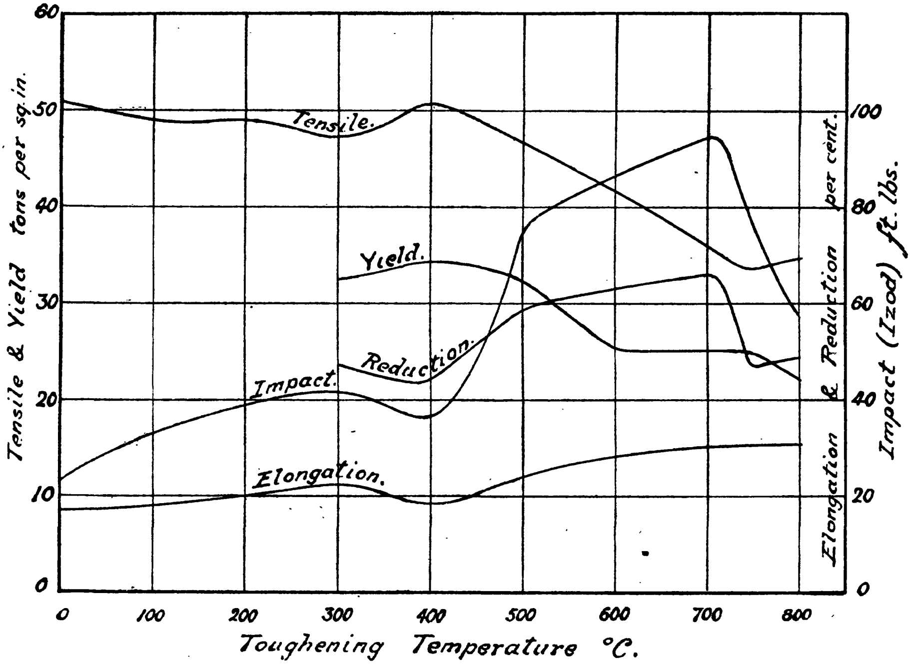


FIG. 155.—Heat Treatment of 0·3 per cent. Carbon Steel. All test bars hardened and then reheated to the temperatures specified and cooled in air. Test results plotted against reheating or toughening temperatures.

The effect of the double heat treatment, *i.e.* hardening and then reheating, is shown in Fig. 155, which shows graphically the results of a series of tests made on bars 1⅛ inches diameter, which were hardened by quenching in water and then reheated to the temperatures indicated in the graph. The steel when hardened has a tensile strength of about 51 tons, but by reheating this falls off until at 700° C. it is about 36 tons. The dynamic strength, which is about 23 ft.-lbs. when the steel is in the hardened condition, increases as the reheating temperature is raised, until at 700° C. it reaches about 95 ft.-lbs.

The best results are obtained by reheating to between 600° and 700° C.; the ductility and dynamic strength are at their highest while combined with a tensile strength equal to that usually required from the steel.

Machining Qualities.—This steel is capable of being machined rapidly, especially in the heat-treated state (*i.e.* double treatment). It does not, however, machine so rapidly as ordinary mild steel

Applications.—This is a useful steel for parts such as crankshafts, spindles, shafting, piston rods, and forgings for axles and other parts intended to run in bearings such as bronze. It is a much better material than mild steel for wearing, although it cannot be considered so good as "40-ton" steel.

Medium Carbon Steel

(*"40-ton." 0·35 to 0·45 per cent. carbon.*)

Composition.—The usual composition of this class of steel is shown by the following table :—

	Acid Steel for Aero-engine Cylinders.	Automobile Engine Crankshaft.	Black rolled Bar.
Carbon	0·45	0·40	0·35
Manganese	0·73	0·78	0·80
Sulphur	0·04	0·039	0·044
Phosphorus	0·026	0·029	0·042
Silicon	0·16	0·19	0·13

The composition should come within the following limits :—

Carbon	0·35 to 0·45 per cent.
Manganese	0·50 „ 0·80 „
Sulphur	Not over 0·06 „
Phosphorus	„ 0·06 „
Silicon	„ 0·25 „

Forging and Drop Stamping.—The lower carbon steels of this group forge well, while the higher carbons (0·45 per cent.) are only a little more difficult. The forging range should not exceed 1,300° C. owing to risk of "burning." The steel also welds with fair ease although not so readily as the "30-ton" steels.

Heat Treatment.—This steel, like the 30-ton steel, is capable of being heat treated to give a wide range of results and is valuable for a large variety of purposes, because of this. The treatments are very similar to those given to the 30-ton steels.

Annealing :

Heat to 790°-810° C., soak 15 to 30 minutes, cool in furnace or boxes.

The steel is reduced to its softest state for machining, all forging strains are removed, and the structure refined.

Normalising :

Heat to 790°–810° C., soak 15 to 30 minutes, cool in air.

This treatment removes forging strains and refines the structure. Like the 30-ton steel there is a tendency to harden on the surface and difficulty in machining may result. But this only causes trouble in thin-section parts (under 1 inch diameter) and need not be considered seriously with large pieces. Commercially this treatment is preferable to full annealing for most parts, but with small parts full annealing may be absolutely necessary. The effect of normalising a steel of 0·44 per cent. carbon content is shown in Fig. 156, which is a graph of the results obtained by normalising a number of bars 1⅛ inches diameter at different temperatures. From this it will be seen that the best result is obtained at a temperature of about 800° to 820° C., where the impact test value reaching a maximum shows that the steel is in its most refined state. This curve also shows how little the tensile test figures vary and how misleading they would be without the Izod impact test.

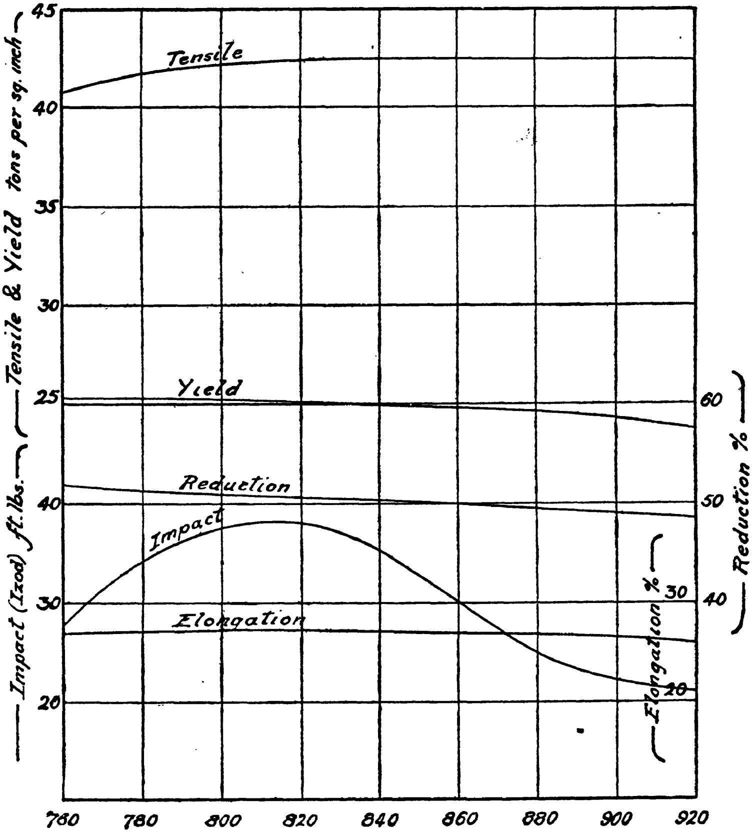


Fig. 156.—Effect of Varying the Normalising Temperature on a Medium Carbon (0·44 per cent. C). Soaking time 30 mins.

Hardening (and Toughening):

Heat to 780°–800° C., soak 15 minutes, quench in oil.

Reheat to temperature that gives desired results, cool in air (do not quench).

The first heat hardens the steel. Oil quenching is the safer, but water quenching gives the maximum tensile strength. The usual precautions regarding intricacy, sharp corners, and holes should be taken, and only oil used for delicate parts. Water should be used whenever possible, however, because of the increased dynamic strength that results.

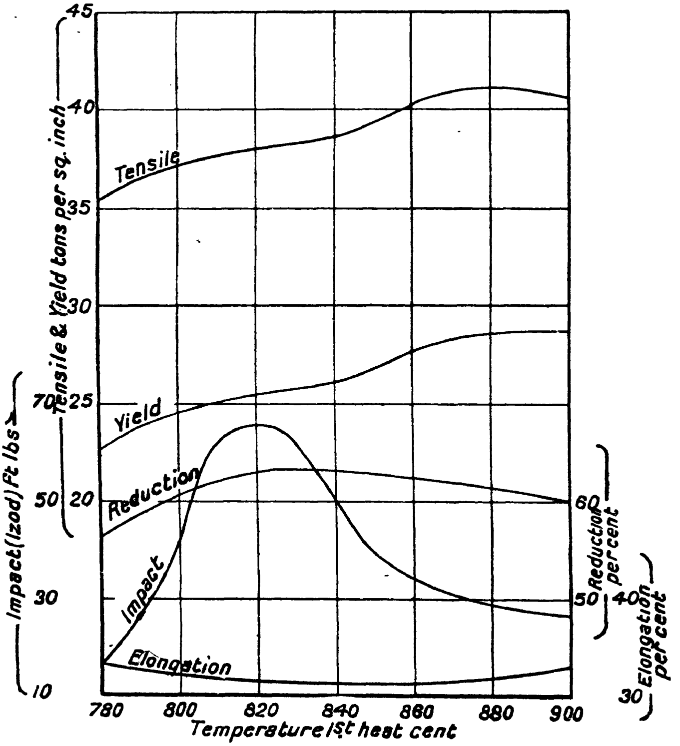


FIG. 157.—Effect of Hardening Medium Carbon Steel (0·44 per cent. C) by quenching in Oil at Different Temperatures and then Reheating to 700° C., and Cooling in Air.

The results obtained by quenching in oil and water respectively are shown in Figs. 157 and 158, which are graphs obtained by heating test bars ($1\frac{1}{8}$ ins. diameter) to different temperatures, soaking 30 minutes, and then quenching. It will be noticed in both that the dynamic strength, as represented by the Izod impact test, reaches a maximum and then falls off again. This maximum point in the case of oil quenching is obtained at 820° C., and that given by water quenching is at 790° C. to 800° C. (See Fig. 158.) Thus for water quenching it is advisable to quench at a lower temperature than for oil quenching, a fact that is important when the best results are required. These curves also show that the dynamic strength is greater with water quenching than with oil quenching.

The tensile strength is greater with water quenching, and increases as the hardening temperature is raised, but if the best temperatures are selected the results are as follow :—

	Yield. Tons per sq. in.	Ultimate. Tons per sq. in.	Elongation in 2 ins. Per cent.	Reduction Area. Per cent.	Impact, ft.-lbs.
Oil quenching at 820° C.	25·5	38·0	31·5	63·0	66
Water quenching at 795° C.	31·2	44·8	27·0	62·4	95

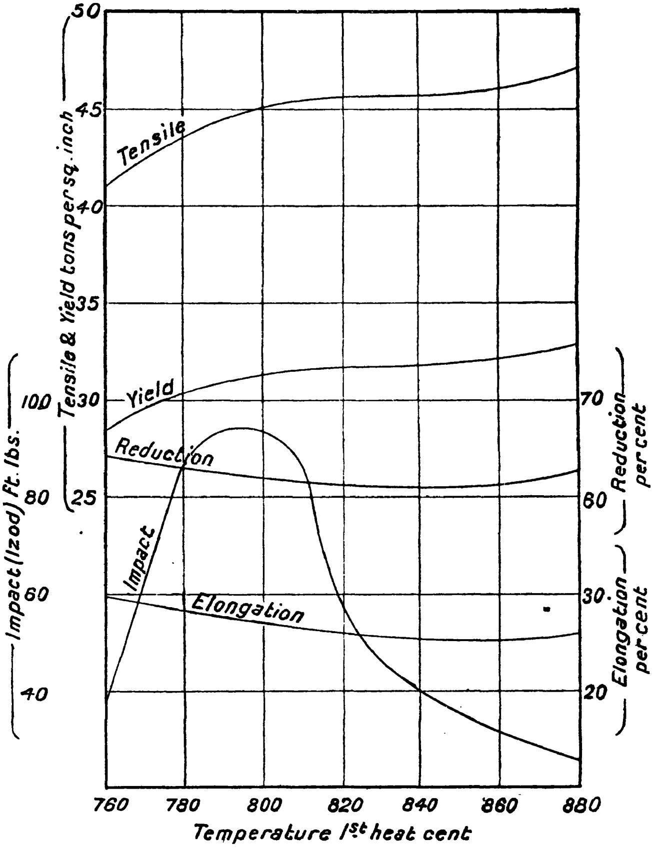


FIG. 158.—Effect of Hardening Medium Carbon Steel (same as Fig. 157) by quenching in water at different temperatures and then reheating (toughening) to 700° C., and cooling in air.

In the above tests the bars were all forged down to 1¼ inches square from billets 6¼ inches square and then normalised at 800° C. (30 minutes' soaking), afterwards machined to 1⅛ inches diameter and then hardened as specified and all reheated to 700° C. for 30 minutes and cooled on the floor. The composition of the steel was :—

Carbon	0·44 per cent.
Manganese	0·75 ,,
Sulphur	0·035 ,,
Phosphorus	0·027 ,,
Silicon	0 20 ,,

Reheating is most essential, even if it is desired to obtain the maximum

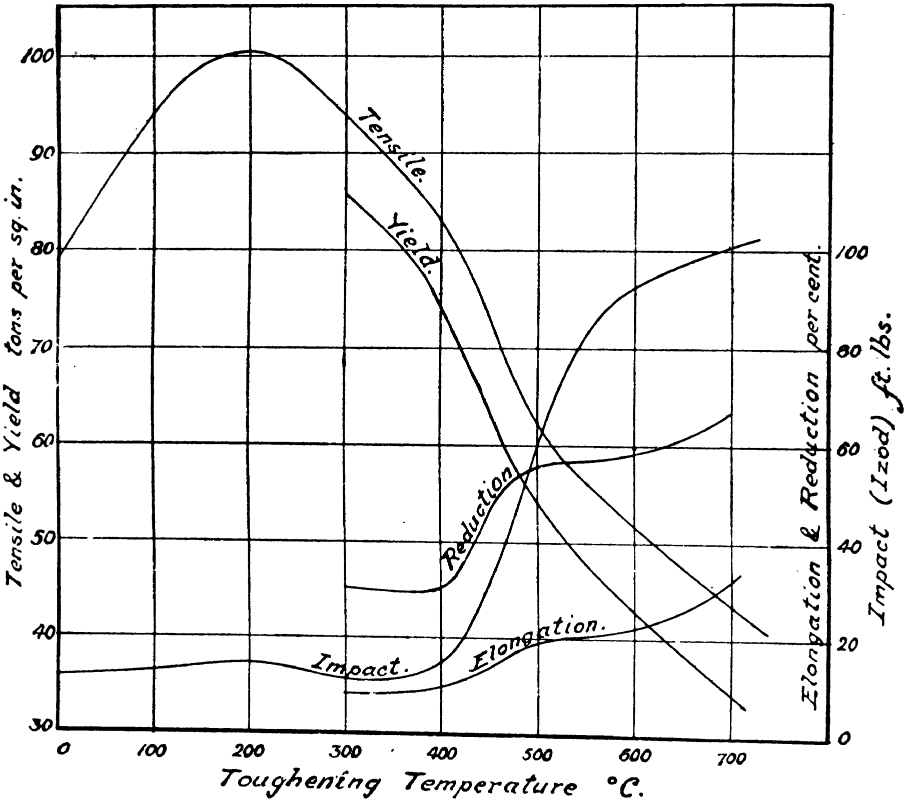


FIG. 159.—Complete Heat Treatment of 0·44 per cent. Carbon Steel. All test bars were normalised at 800° C., hardened at 800° C. in water and reheated (toughened) to the temperature specified and cooled in air.

hardness as in the case of gears, which should be reheated to 150°–180° C. to relieve the hardening stresses set up. The full effects of reheating are shown in Figs. 159 and 160. Test bars of the same steel as that employed in the above tests were used, each being hardened at 800° C. by quenching in water or oil. The bars were then reheated to different temperatures, soaked for 30 minutes, and allowed to cool in still air. The most useful range is between 500° C. and 700° C., high tensile strengths and good impact test figures being obtained. Hardening in water produces better results than oil hardening.

Mechanical Tests.—The results obtained with a steel of the composition quoted above are given in Figs. 156, 157, 158, 159, and 160. Steel containing less, or more, carbon will tend to give lower or higher values for the tensile strength and higher or lower values for the dynamic strength, respectively. These medium carbon steels, however, will be found very variable and inconsistent in practice and the results obtained from the same cast or consignment of steel treated in the same manner will cover a wide range. This is particularly the case with drop stampings made from such steel. The figures given in the table on p. 260 are intended to serve only as a guide and must not be taken as representing the results that will actually be obtained. The impact values will be found to vary most, but the figures given are just a little above the minimum values obtained under normal conditions.

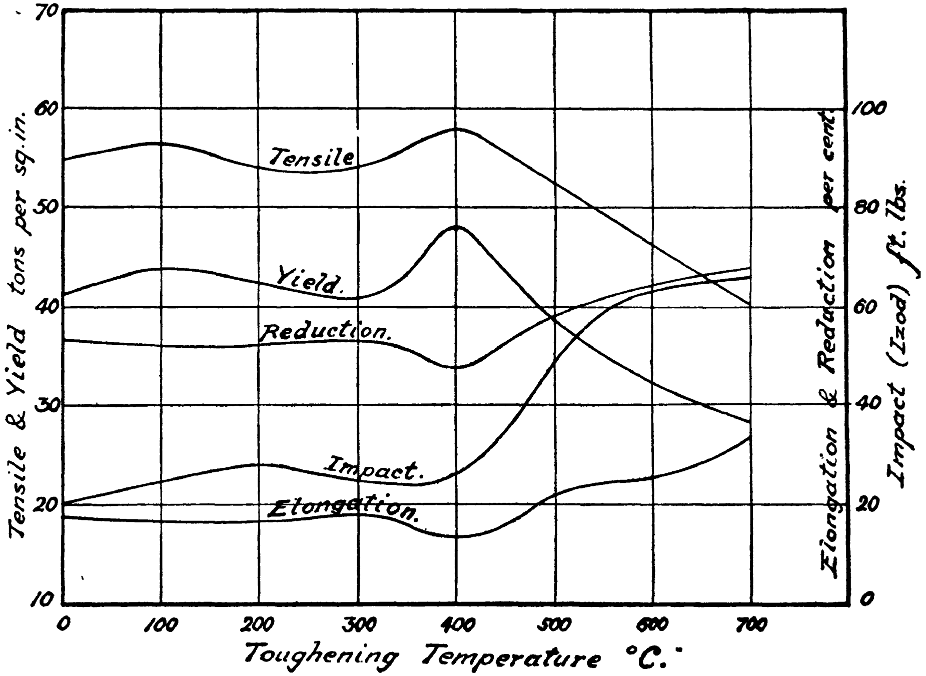


FIG. 160.—Same Steel as Fig. 159, but hardened in oil at 800° C. and toughened at different temperatures.

Applications.—This steel should be used in place of 30-ton steel for parts which are liable to crack or develop severe hardening stresses due to water quenching. The oil quenching gives results equal to, and better than, those obtained by water quenching 30-ton steel, while distortion is reduced considerably.

It is useful for axles, crankshafts and other driving shafts because it wears the least of the carbon steels, 0·4 carbon offering the greatest resistance to abrasive action.* It is used very much by locomotive builders for axles,

---

* According to J. Robin, *Inst. Journ. II.*, 1910.

crankpins, and other forgings and also to a great extent by automobile builders for axles, swivel axles, hubs, connecting rods, while aero engine makers use it for air-cooled cylinders.

	Tons per sq. in.		Elongation in 2 ins. per cent.	Reduction of Area. per cent.	Impact (Izod), ft.-lbs.
	Yield.	Ultimate.			
Normalised only, 800° C.					
0·35 per cent. C	22·0	36·0	33·0	58·0	35
0·40 „	24·0	38·0	31·0	56·0	30
0·45 „	25·0	40·0	30·0	53·0	25
Heat treated at 800° C. (Water) 700° C. (Floor)					
0·35 per cent. C	25·0	39·0	32·0	55·0	60
0·40 „	27·0	41·0	30·0	52·0	55
0·45 „	30·0	45·0	27·0	50·0	50
800° C. (Oil) 700° C. (Floor)					
0·35 per cent. C	24·0	36·0	34·0	64·0	45
0·40 „	26·0	39·0	32·0	62·0	40
0·45 „	28·0	41·0	30·0	60·0	35

Medium High and High Carbon Steels

(“ 50-*ton.*” 0·45 *to* 0·60 *per cent. carbon. Tool Steel.* 0·60 *to* 1·4 *per cent. carbon.*)

The principal feature of steels containing higher carbon contents than 0·45 per cent. is their brittleness, and it is mainly on account of this that they find so little use in practice. The alloy steels, which possess a much larger dynamic strength, are used almost entirely in mechanical constructional work to the exclusion of the higher carbon steels.

One fairly common application is in the making of keys and cotters, and for this purpose it is usual to employ a steel containing from 0·6 to 0·8 per cent. of carbon. The specification for such a steel should be :—

Carbon	0·60 to 0·80 per cent.
Manganese	0·4 „ 0·50 „
Sulphur	0·05 per cent. maximum
Phosphorus	0·05 „ „
Silicon	0·15 „ „

The heat treatment for such parts should be approximately :—

(1) Heat to 760° C., soak 10 minutes, quench in oil.
(2) Re-heat to 400°-500° C., soak 15 minutes, cool on floor.

This hardening and toughening treatment should give the following mechanical tests :—

Yield. Tons per sq. in.	Ultimate. Tons per sq. in.	Elongation in 2 ins.	Reduction of Area.	Impact, ft.-lbs.
55	65	8 per cent.	15 per cent.	5

Some firms supply steel containing up to 0·55 per cent. carbon as a 40-ton steel, a practice which is exceedingly bad on account of the low dynamic strength of the material. While such steel in the annealed or normalised state will give a tensile strength of about 40 to 54 tons per square inch the impact value will only be about 5 to 10 ft.-lbs. Hardening and toughening will tend to raise this latter value, but the risk of cracking (even during oil quenching) is so serious that such steels should be condemned for work of any but the simplest character.

The forging and drop stamping also becomes very difficult as the carbon increases and the risk of cracking during cooling is quite considerable.

The remarks about manganese on p. 121 should be noted, and if it is necessary to employ these steels this element should be carefully watched.

Railway tyres are made from steels containing 0·5 to 0·7 per cent. carbon, and these are heat treated to obtain a sorbitic structure in order to withstand severe shocks. The test applied is a falling weight, generally 1 ton. This is allowed to fall freely on to the tyre from gradually increasing heights until a certain minimum deflection is obtained without fracture. The amount of this deflection depends on the dimensions of the tyre and the class of steel used.

Springs are made from high carbon steel. For laminated springs such as are used for railway stock and for road vehicles, steel containing from 0·5 to 0·8 per cent. of carbon is used, but for coiled springs a higher percentage of carbon is required, the range being 0·8 to 1·0 per cent. If more carbon is used there is a risk of free cementite forming and this, owing to its brittleness, might start cracks.

The heat treatment of springs as carried out by many manufacturers is a somewhat crude and, in view of the increasing performance expected from springs, a very unsatisfactory process. The steel is heated (often to a high temperature) and, after forming, is hardened by quenching in whale oil. This practice of forming and hardening with a single heating is unsound because of the time taken in forming (during which the steel cools) and the uncertain temperature at the moment of quenching. If the maximum of quality and service is required the steel should be heated to a temperature just high enough to enable the spring to be formed, and then it should be reheated to correct hardening temperature and quenched. This reheating ensures the removal of any internal stresses and, what is particularly important, it ensures a uniform temperature throughout the entire spring at the moment of quenching. With the older method of working uneven temperatures are common.

The tempering operation (with laminated springs) is one which gives surprising results, considering that it consists of heating the hardened springs in a furnace operating at a temperature higher than that required for tempering and then removing them at the correct moment, which is judged by the charring action on a twig of hazel that the operator applies to the heated metal.

These methods, however, are giving way to ones that are under definite control, and now the best springs are made by heating the metal in furnaces having separate chambers for the hardening and tempering operations. The hardening temperature is usually high enough for the forming operation, and consequently the same chamber is used for both operations, the formed spring being returned for reheating previous to quenching. The tempering chamber is maintained at the correct temperature and the spring is allowed to remain in it until thoroughly and uniformly heated.

Coil springs are generally tempered in a lead bath which, it is claimed, ensures a higher degree of temperature uniformity, a claim which is losing value in view of the recent improvements in furnace design.

Wire ropes are now made from steel containing a large percentage of carbon, ranging from 0·4 to 0·85 per cent. In the manufacture of this wire an operation known as "patenting" is applied and this imparts to the metal the qualities of toughness and freedom from brittleness. The wire is passed continuously through a heated tube (the furnace contains many of these tubes), and is raised to a temperature above the critical range. On leaving the tube the air cools the wire with sufficient rapidity to ensure a sorbitic structure being retained in the steel, and this corresponds to the conditions of quality already mentioned. The wire after this treatment is drawn to its final size, and the combination of the cold drawing and this process produces a wire of great strength and toughness.

Strength of Steel at Different Temperatures.—The effect of high temperatures on the strength of steel is frequently an important consideration and it is unfortunate that so little work has been carried out in determining the relationship between temperature and the physical properties of steel.

A series of measurements were made by J. E. Howard, of the Watertown Arsenal, U.S.A., on four steels of different carbon content, and the results obtained are valuable. The following table is a brief summary of these results, which for convenience have been taken from a graph, round figures being given for the tensile strengths corresponding to the temperature in Centigrade units:

EFFECT OF TEMPERATURE ON TENSILE STRENGTH OF CARBON STEEL.

Carbon .. .. Manganese ..	0·20 per cent. 0·45 ,,	0·37 per cent. 0·70 ,,	0·57 per cent. 0·93 ,,	0·97 per cent. 0·80 ,,
Temperature, degs. Cent.	Tons per sq. in.	Tons per sq. in.	Tons per sq. in.	Tons per sq. in.
20	31	38	53	69
100	30	36	49	66
200	33	42	56	74
300	36	44	58	72
400	30	40	50	59
500	24	32	41	48
600	15	22	28	36
700	10	13	17	25
800	8	9	12	15

From the above table it will be seen that the tensile strength of all four steels diminishes a little as the temperature is raised to 100° C. and then increases as the temperature is raised further, until at about 300° C. it reaches a maximum. The amount of carbon in the steel has some influence on the position of these minima and maxima in the scale of temperature, the lowest carbon steel having a minimum strength at about 95° C. and the highest carbon steel a minimum strength at about 130° C. The corresponding maximum strength points occur between 220° C. and 330° C. After passing these temperatures the steels diminish rapidly in strength.

The results obtained by other observers confirm the existence of the minimum and maximum strength points mentioned above and also show that the strength of steel increases as the temperature falls.

General Summary

As explained on p. 245, carbon steels can also be classified according to the mechanical strength they will give under different treatments. The following table is drawn up in this manner, the yield point being taken as the controlling property of the material, and as this increases the different steels are given together with their heat treatments and approximate carbon contents :—

Yield.	Ult.	E.	R.	I.	Steel.	C, per cent.	Treatment.
14	22	35	65	40	Dead soft mild	0·1	Annealed slowly.
16	24	35	65	100	,, ,,	0·1	860° C. water, 760° C. air.
20	25	40	70	60	Ordinary mild	0·25	Annealed 860° C.
20	29	20	60	50	Dead soft mild	0·1	860° C., quenched water only.
20	28	35	55	25	30-ton	0·30	Annealed 820° C.
21	26	38	63	50	Ordinary mild	0·25	Normalised 840° C.
22	32	33	53	35	30-ton	0·30	,, 820° C.
23	36	33	56	35	40 ,,	0·35	,, 800° C.
23	29	35	65	80	Ordinary mild	0·25	860° C. oil, 760° C. air.
24	38	31	56	30	40-ton	0·40	Normalised 800° C.
24	36	30	65	65	30 ,,	0·30	800° C. water, 700° C. air.
24	36	34	64	45	40 ,,	0·35	800° C. oil, 700° C. air.
25	39	32	55	60	40 ,,	0·35	800° C. water, 700° C. air.
25	40	30	53	25	40 ,,	0·45	Normalised 800° C.
25	31	35	60	60	Ordinary mild	0·25	860° C. quenched water only.
26	39	32	62	40	40-ton	0·40	800° C. oil, 700° C. air.
27	40	28	62	60	30 ,,	0·30	800° C. water, 600° C. air.
27	40	32	60	40	40 ,,	0·35	800° C. oil, 600° C. air.
27	41	30	52	55	40 ,,	0·40	800° C. water, 700° C. air.
28	41	30	60	35	40 ,,	0·45	800° C. oil, 700° C. air.
29	44	28	52	35	40 ,,	0·35	800° C. water, 600° C. air.
30	45	25	58	50	30 ,,	0·30	800° C. water, 500° C. air.
30	44	29	55	35	40 ,,	0·35	800° C. water, 500° C. air.
30	44	28	55	35	40 ,,	0·40	800° C. oil, 600° C. air.
30	45	27	50	50	40 ,,	0·45	800° C. water, 700° C. air.
31	46	25	50	50	40 ,,	0·40	800° C. water, 600° C. air.
33	49	24	50	45	40 ,,	0·35	800° C. water, 500° C. air.
34	48	24	55	30	40 ,,	0·45	800° C. oil, 600° C. air.
35	50	22	52	30	40 ,,	0·40	800° C. oil, 500° C. air.
36	52	20	48	40	40 ,,	0·40	800° C. water, 500° C. air.
36	52	20	48	40	40 ,,	0·45	800° C. water, 600° C. air.
41	55	20	51	25	40 ,,	0·45	800° C. oil, 500° C. air.
44	60	18	45	30	40 ,,	0·45	800° C. water, 500° C. air.

The treatments that are abbreviated, such as " 800° C. water, 700° C. air," should read as : harden from 800° C. by quenching in water and reheat to 700° C. and then cool in air (on the floor). The soaking time depends on the section of the piece.

When consulting the above table it is necessary to bear in mind that the figures given are only approximate, and that the results obtained by the treatments specified will vary to an extent dependent on the size of the part and also the conditions under which the treatment is carried out. Thus, the order in which the several steels are given in the table must not be taken as rigidly correct.

CHAPTER XII

ALLOY STEELS

The principal alloy steels are Nickel, Chromium, Nickel Chrome, Vanadium, and Manganese steels. There are many more special steels, but the greater number of them are used for tools (high-speed steels), while the remainder have not achieved any marked success in general engineering, or are used only to a very limited extent. A few of these latter steels are dealt with briefly at the end of his chapter.

Alloy *versus* Carbon Steel.—The superiority of alloy steels over carbon steels is well known, but there is still a tendency to employ carbon steel for parts where an alloy steel would not only give a high factor of safety but would render the manufacture of the parts a simpler operation, the reduced cost of manufacture counterbalancing the increased cost of material. This appears to be due to lack of knowledge or appreciation of the simple heat treatments some of the alloy steels require as compared with the carbon steels. For example, a swivel axle, such as is used for the front wheels (steering) of a car or motor lorry, could with advantage be made from a low nickel steel instead of a medium carbon steel. The nickel steel can be forged with almost the same ease as a medium carbon steel, but when the heat treatment is considered the nickel steel requires less treatment, which means less fuel, labour, plant, and upkeep. Two such steels are considered side by side herewith :—

	Carbon Steel.	Nickel Steel.
Composition, approx. ..	0·4 per cent. Carbon	0·3 per cent. Carbon, 3 per cent. Nickel
Forging qualities	Good	Good
Heat treatment I.	Normalising 800° C.	Normalising only, 800° C.
,, ,, II.	Hardening 800° C. Quenched in oil	
,, ,, III.	Toughening 700° C.	

MECHANICAL TESTS

Yield	30 tons per square inch	30 tons per square inch
Ultimate	43 ,, ,, ,,	44 ,, ,, ,,
Elongation	29 per cent.	25 per cent.
Impact	33 ft.-lbs.	35 ft.-lbs.

From the above it will be seen that two heatings and one quenching are saved by the use of the nickel steel, and as each separate heating can be reckoned at 6*s*. to 7*s*. per cwt. (inclusive cost), a saving of 12*s*. to 14*s*. is easily effected and this covers the difference in cost between the two steels. Apart from any possible saving of a direct nature such as this, there is that all-important factor "time" to be considered; clearly the parts will "pass through " the hardening shop in less time and will be available for machining long before the carbon steel axles are ready.*

A more important factor still is the certainty that the dynamic strength is better. The high forging and stamping temperatures so prevalent do not have so serious an effect on the structure of nickel steel as on that of carbon steel, and in consequence the forged parts are generally in a better condition before heat treatment than those made from carbon steel. This in the case of mass production is no little matter, especially when lives depend on the strength of the parts concerned.

Although the above case is cited, in which the heat treatment of the nickel steel is given as a simple normalising operation, it must not be assumed that this is the best treatment for such a steel. The full advantages of alloy steels are only obtained by the full heat treatment of hardening and reheating (tempering or toughening). A steel with less than 3 per cent. nickel, if heat treated, would answer quite well and would scarcely be more costly than the 40-ton carbon steel, while the advantages of a refined structure and greater certainty of results would be obtained.

Although alloy steels are sometimes very greatly superior to carbon steel, it should be remembered that the addition of a given alloying metal does not always improve all the properties found in carbon steel, nor does it remove all the faults in such steel. Again, important commercial considerations such as heat treatment may be more difficult in the case of alloy steels, and the adoption of carbon steel may, as a result, be a better proposition.

The principal effects produced by the addition of the alloying metals are described in Chapter VIII. These are summarised in a very general way in the table on next page. When comparing one steel with another it must be remembered that the composition should be taken into account; a steel containing, say, much nickel may offer more difficulties in forging than one containing only a little chromium. This table only serves to give a general impression of the relative qualities of the alloy steels.

Nickel Steels

The nickel steels used commercially are mainly what are known as pearlitic steels, *i.e.* their structure on slow cooling contains pearlite and they are machinable. The nickel content seldom exceeds 7 per cent. and the carbon 0·5 per cent.

There is one important exception, and this is the high nickel steel used for internal-combustion engine valves, ignition tubes, magneto spindles (being non-magnetic). This class of steel contains 20 to 25 or 30 to 35 per cent. of nickel and 0·3 to 0·5 per cent. of carbon, and on slow cooling retains an austenitic or martensitic structure and is therefore too hard for machining.

Those steels containing up to 5 per cent. of nickel are much superior to

---

* A further important factor is the amount of " scrap " produced in the two cases. In a record of drop forging steels extending over a period of 12 months, the total rejections on medium carbon steel billets and drop forgings was about 30 per cent., while for the corresponding period that on 3 per cent. nickel steel was about 0·5 per cent. The former percentage is admittedly unduly great, but after making allowance for this the difference is considerable, and neutralises the difference in first cost in the two cases.

EFFECT OF ALLOY METALS ON THE PROPERTIES OF CARBON STEEL.

Alloy Metal.	Constituents affected.	Form taken in Steel.	Physical Properties after Suitable Treatment.				Commercial Defects.	Forging Qualities.	Heat Treatment.	Machining Qualities.
			Tensile.	Ductility.	Dynamic.	Hardness.				
Nickel	Ferrite only	Solid solution in ferrite	Increased	Increased	Increased	In proportion to tensile. Wearing surface not improved	Tendency to pipe with consequent segregation. Rolls worse than carbon steel. Seamy	Slightly less plastic. Will withstand overheating better	Less affected by prolonged heating. Treatment is a simpler operation. Oil quenching, less distortion	Good in annealed or normal state. Tougher than carbon steel in the heat treated state
Chromium	Carbon areas	Double carbides	Increased	No increase	Slight increase	Considerable increase. Wearing qualities improved very much	Same as carbon steel	More difficult than carbon or nickel steels	Much affected by prolonged heating. Treatment is difficult, requires higher temperatures. Oil quenching necessary	Tough in annealed state—very hard in normalised state
Nickel and Chromium	Nickel affects ferrite; chromium affects carbon areas	Nickel forms solid solution in ferrite. Chromium forms double carbide	Increase due to both Ni and Cr	Increase due to Nickel	Increased by both Ni and Cr	Increased by Chromium. Wearing qualities improved considerably	Similar to nickel steel. Seamy. Rolls worse than carbon steel	Less plastic than carbon or nickel, but better than chrome steel	More difficult than nickel steel, but less difficult than carbon or chrome steel. Oil quenching. Less affected by prolonged heating, but not so good as nickel steel	Fair in annealed or normal state; tougher than carbon steel or nickel steel, but not so tough as chrome steel
Chromium and Vanadium	Chromium affects carbon areas; vanadium partly the ferrite and partly the carbon areas	Chromium forms double carbide. Vanadium forms partly solid solution and partly a double carbide	Increased	Increased	Increased	Above 0·25 % Va hardness is increased, giving good wearing surface	Same as carbon steel	Like carbon steels. Is easiest of all alloy steels	Treatment similar to nickel chrome steels. Not easily affected by prolonged heating, but not so good as nickel. Oil quenching—less distortion	Good in annealed or normal state; tougher than carbon steel or nickel steel, but not so tough as chrome steel

carbon steels and their adoption should be more general. Even with only low percentages of nickel (1 or 2 per cent.) the improvement of the steel is considerable, particularly in regard to the dynamic strength and consistency of results.

Seams and Laminations.—The principal defects in nickel steel are seams and laminations which are due to difficulties in manufacture. There is a strong tendency for piping and segregation to take place, and unless a large portion (containing these faults) of the original ingot has been cut away the effect of subsequent rolling is to develop a laminated or banded structure. An example of this is shown by the micrograph Fig. 103, Chapter IX, which represents a piece of 4 per cent. nickel steel. Billets of this steel intended for stamping purposes will often show surface cracks or roaks, which if not machined away will open out during the forging operation and spoil the part machined. The steel should, if possible, be rough machined before rolling to final size, when this trouble will disappear.

Forging and Machining Properties.—Those steels with less than 5 per cent. nickel and 0·5 per cent. carbon can be forged with almost the same ease as carbon steels of approximately the same carbon content. The higher nickel values from, say, 4 to 7 per cent. increase the toughness of the metal and render the forging a little more difficult, but as a rule those parts which can be made from a medium carbon steel of 0·5 per cent. carbon can also be made from these steels.

Nickel steel has an advantage over carbon steel in that there is not the same tendency to form a coarse crystalline structure and therefore, provided the billet material is in a fairly good condition, the forgings and stampings will not be influenced to the same extent by high finishing temperatures and will, as a rule, be in much better condition than carbon steel stampings. This is a most important feature of this steel and will outweigh many disadvantages such as initial cost of material, etc.

The machining properties of nickel steel are good, in fact it is the best of the alloy steels in this respect.

Presence of Chromium.—Many nickel steels contain small percentages (up to 0·2 per cent.) of chromium. This element in such small amounts does not interfere appreciably with the behaviour and treatment of the steel; it has, if anything, a beneficial effect in so far that it tends to increase the hardness without reducing the ductility.

This chromium is probably introduced through the use of steel scrap, which may often contain nickel chrome steel.

Influence of Nickel.—The influence of nickel on the tensile strength and ductility of a steel (in the annealed state) containing about 0·25 per cent. of carbon is shown in Fig. 161. This curve shows that the tensile strength is increased by 2 to 2½ tons per square inch for each 1 per cent. addition of nickel up to about 5 per cent. The dynamic strength in the annealed state is a maximum with a nickel content of about 2 per cent.

With increasing percentages of carbon the influence of nickel grows stronger.

This influence on the strength and ductility is mainly due to the fact that nickel dissolves in the iron forming a solid solution. In this respect it is quite different to chromium or manganese, which associate with the carbide (or cementite) and increases the hardness of the steel.

Although the addition of nickel improves the qualities of steel in the annealed or normalised state, the use of such steel in this soft condition does not always justify the increased expense over carbon steel. The full value of the nickel addition is only secured by heat treating the steel, because then the qualities of the steel are developed to their greatest extent. For this reason a nickel steel should be selected for a given purpose with the intention of obtaining the desired mechanical strength by proper heat treatment. At the same time, however, a nickel steel may, with advantage in production costs, often be used in place of a carbon steel, even though the material cost is higher. This is a point which should not be lost sight of when dealing with parts which must have a tensile strength in the region of 30 to 50 tons per square inch. Then the lengthy and sometimes risky heat treatment required for the carbon steel can be superseded by a simple normalising treatment.

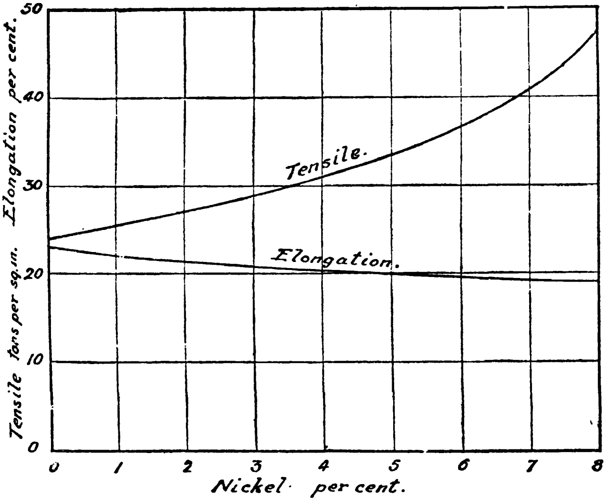


FIG. 161.—Effect of Nickel on the Tensile Strength and Ductility of 0·25 per cent. Carbon Steel. Nickel increases the former without seriously influencing the latter.

When the steel is fully heat treated it is even advantageous to use it instead of carbon steel, especially for parts having only a small working margin or factor of safety. Strength for strength a nickel steel requires less carbon, and with the reduction of this embrittling element the heat treatment is a much safer operation and the development of cracks and flaws is made almost impossible since most of the quenching can be done in oil instead of water. Further, the effects of prolonged heating or of overheating are not so serious as with carbon steels, and because of this, fine-grained structures are more easily obtained. This, in fact, is the greatest feature of nickel steels, and advantage should always be taken of it when dealing with difficult and intricate parts.

Again, the use of oil-quenching methods means that the distortion of the parts is reduced to a minimum.

Classification.—Nickel steels intended for case-hardening purposes are dealt with in Chapter XIII. Those which are simply heat treated can be classified into three groups as follows :—

Group.	Nickel Content.	Carbon Content.
I.	1 to 4 per cent.	0·20 to 0·35 per cent. 0·35 ,, 0·5 ,,
II.	5 ,, 6 ,,	0·3 ,, 0·4 ,,
III.	20 ,, 35 ,,	0·3 ,, 0·5 ,,

Of these the first group is the one mostly used, particularly the 3 per cent. nickel steel with 0·3 per cent. carbon. The higher nickel steels of Group II. are not used much, while those of Group III. have only certain very limited applications.

Nickel Steels Group I.—The compositions of some of the more common 1 to 4 per cent. nickel steels are shown by the following typical analyses :—

	50-ton Nickel Steel.	Aero-engine Crankshaft.	Inlet Valves for Car Engine.	Armour Plate to resist Rifle Fire.	Gun Steel.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Carbon	0·20	0·31	0·30	0·31	0·40
Nickel	3·59	3·61	3·10	4:05	3·81
Manganese ..	0·69	0·68	0·50	0·99	0·56
Sulphur	0·013	0·022	0·038	0·046	0·020
Phosphorus ..	0·007	0·029	0·032	0·021	0·029
Silicon	0·18	0·12	0·12	0·14	0·25
Chromium ..	Nil	Nil	Nil	Nil	Nil

Specifications for some of the most useful steels are given below :—

1 Per Cent. Nickel Steel (Medium Carbon)

Chemical Composition

Carbon	0·30 to 0·35 per cent.
Nickel	0·9 ,, 1·5 ,,
Manganese	0·7 ,, 1·0 ,,
Sulphur	Not over 0·05 ,,
Phosphorus	,, 0·05 ,,
Silicon	,, 0·30 ,,

Mechanical Tests

	Normalised.	Heat Treated.
Yield, tons per square inch	18 to 22	32 to 37
Ultimate ,, ,, ,, ...	35 ,, 39	42 ,, 48
Elongation per cent.	40 ,, 30	40 ,, 30
Reduction of area per cent.	65 ,, 55	65 ,, 55
Impact (Izod), ft.-lbs.	40 ,, 30	70 ,, 50

2 Per Cent. Nickel Steel (Medium Carbon)

CHEMICAL COMPOSITION

Carbon	0·25 to 0·35	per cent.
Nickel	1·75 „ 2·50	„
Manganese	0·60 „ 0·90	„
Sulphur	Not over 0·05	„
Phosphorus	„ 0·05	„
Silicon	„ 0·30	„

MECHANICAL TESTS

	Normalised.	Heat Treated.
Yield, tons per square inch	20 to 25	35 to 40
Ultimate, „ „ „	35 „ 40	46 „ 50
Elongation per cent.	45 „ 35	45 „ 35
Reduction of area per cent.	65 „ 55	65 „ 55
Impact (Izod), ft.-lbs.	40 „ 30	80 „ 60

2½ Per Cent. Nickel Steel (Low Carbon)

CHEMICAL COMPOSITION

Carbon	0·20 to 0·30	per cent.
Nickel	2·0 „ 3·0	„
Manganese	0·4 „ 0·85	„
Sulphur	Not over 0·05	„
Phosphorus	„ 0·05	„
Silicon	„ 0·30	„

MECHANICAL TESTS

	Normalised.	Heat Treated.
Yield, tons per square inch	18 to 22	27 to 33
Ultimate, „ „ „	32 „ 37	38 „ 46
Elongation per cent.	35 „ 25	40 „ 30
Reduction of area per cent.	55 „ 45	60 „ 50
Impact (Izod), ft.-lbs.	40 „ 30	70 „ 50

3 Per Cent. Nickel Steel (Medium Carbon)

CHEMICAL COMPOSITION

Carbon	0·25 to 0·35	per cent
Nickel	2·7 „ 3·50	„
Manganese	0·3 „ 0·75	„
Sulphur	Not over 0·04	„
Phosphorus	„ 0·04	„
Silicon	„ 0·25	„

MECHANICAL TESTS

	Normalised.	Heat Treated.
Yield, tons per square inch	20 to 25	43 to 50
Ultimate, ,, ,, ,, ...	38 ,, 44	50 ,, 60
Elongation per cent.	30 ,, 20	25 ,, 20
Reduction of area per cent.	50 ,, 40	65 ,, 55
Impact (Izod), ft.-lbs.	35 ,, 45	80 ,, 60

3½ Per Cent. Nickel Steel (Medium Carbon)

CHEMICAL COMPOSITION

Carbon	0·3 to 0·4	per cent.
Nickel	3·0 ,, 4·0	,,
Manganese	0·3 ,, 0·65	,,
Sulphur	Not over 0·04	,,
Phosphorus	,, 0·04	,,
Silicon	,, 0 25	,,

MECHANICAL TESTS

	Normalised.	Heat Treated.
Yield, tons per square inch	25 to 30	45 to 55
Ultimate, ,, ,, ,, ...	42 ,, 50	55 ,, 65
Elongation per cent.	25 ,, 18	25 ,, 15
Reduction of area per cent.	50 ,, 40	65 ,, 55
Impact (Izod), ft.-lbs.	35 ,, 25	80 ,, 60

Heat Treatment.—Compared with plain carbon steel the heat treatment of nickel steel is simpler and does not require the same care and accuracy. This steel is much less affected by prolonged heating or by heating to high temperatures. This is due to the slowness with which crystal grain growth takes place.

The slowness in the growth of the crystal grains also applies to the rate of diffusion or equalisation of the constituents, necessitating longer periods of heating or higher temperatures to secure uniformity in the steel. Thus in the case of forgings or stampings which have suffered on account of very prolonged heating or have been finished at too low temperatures it will be necessary to normalise or anneal them at temperatures much in excess of the critical range in order to accelerate the diffusion of the constituents. Thus, because of this sluggishness in diffusion in nickel steel, the heat treatment temperatures are usually considerably above the upper critical range, instead of only 20° to 30° C. as in the case of carbon steels. Fortunately the critical ranges of nickel steel are much lower than the corresponding carbon steels, and these working temperatures are really not much higher than those for carbon steels, and the tendency to warp and crack, always associated with high quenching temperatures, is therefore not more serious. Further, the use of the higher quenching temperatures is made safer by reason of the important fact that quenching in oil generally gives the desired results, and the risky and drastic quenching in water is eliminated.

The upper critical ranges for the steels in general use are tabulated below. The temperatures given are very approximate and it should be clearly understood that considerable variations will be found between different batches of steel.

The lower critical ranges are also tabulated and the figures given are subject to the reservation just quoted.

Upper Critical Points of Nickel Steels

1 to 4 per cent. Nickel, 0·2 to 0·5 per cent. Carbon

(Approximate only.)

Carbon per cent.	Ac3 Range. Temperature, Cent.						
	Nickel 1 per cent.	Nickel 1·5 per cent.	Nickel 2 per cent.	Nickel 2·5 per cent.	Nickel 3 per cent.	Nickel 3·5 per cent.	Nickel 4 per cent.
0·20	797	792	787	782	777	772	767
0·25	784	779	774	769	764	759	754
0·30	770	765	760	755	750	745	739
0·35	764	759	754	749	744	738	733
0·40	758	753	748	743	738	732	726
0·45	752	747	742	737	732	726	718
0·50	746	741	736	731	726	719	710

Lower Critical Points of Nickel Steels.
Same composition as above.

Nickel per cent.	Heating. Ac1. Degs. C.	Cooling. Ar1. Degs. C.
1·0	715	670
1·5	710	660
2·0	704	649
2·5	699	638
3·0	693	627
3·5	688	616
4·0	682	604

Owing to the wide range of critical temperatures nickel steels cover, the heat-treatment temperatures are not given, but the following general rules will enable the reader to arrive at the approximate figures.

For annealing and normalising a safe working temperature can be obtained by simply adding 100° C. to the Ac3 temperature of the steel. Should the material be in a very poor condition, *i.e.* due to high forging or stamping temperatures, etc., then two heats may be necessary, one at about 150° C. above the Ac3 point and the other at about 70° C. The soaking time for pieces 1 to 2 inches thickness of cross section should be about one hour or longer.

For hardening (previous to toughening or tempering) the poor material should be normalised first so that the structure is fairly uniform before this important treatment is commenced. The temperature then should be about 80 to 100° C. above the Ac3 range, and those steels containing $2\frac{1}{2}$ per cent. or more nickel with 0·25 per cent. or more carbon should be quenched in oil. Those steels containing less may be quenched in water.

The tempering and toughening temperatures depend on the requirements and will have to be determined by trial or from a curve similar to that shown in Fig. 162. Usually the steel is toughened to obtain the maximum dynamic strength, and the toughening temperature is about 600° C.

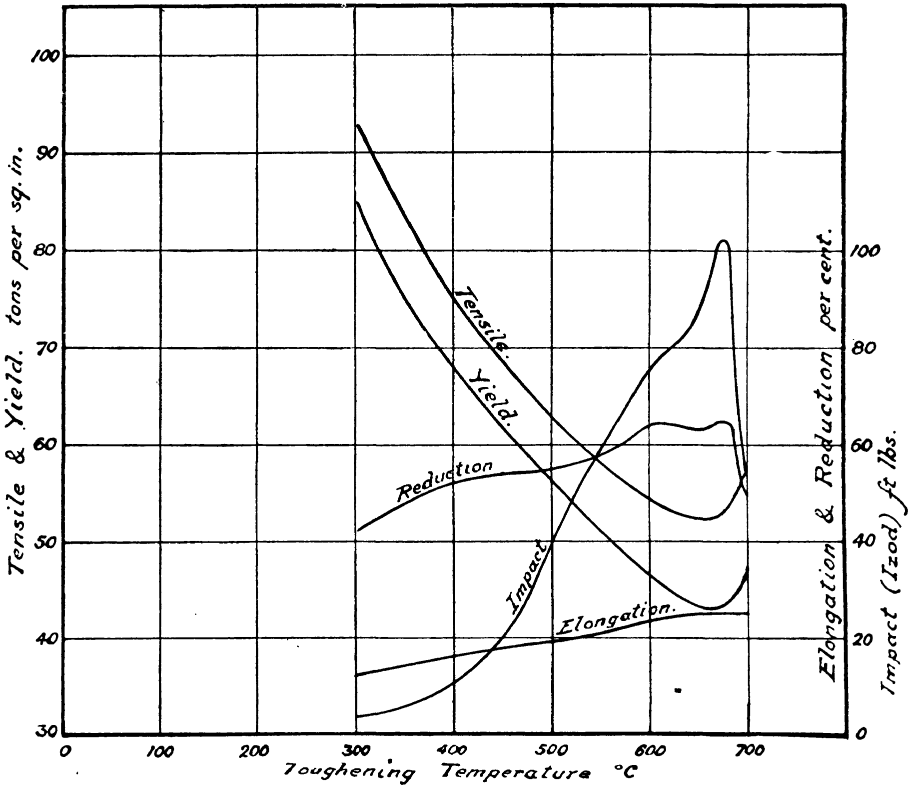


FIG. 162.—Heat Treatment of 3 per cent. Nickel, 0·3 per cent. Carbon Steel. Hardened in oil at 830° C. and toughened at the temperatures shown, and quenched in water.

The steel, after heating to the toughening temperature, should be quenched in oil or water.

For gears, however, the hardened steel should only be tempered at a temperature of about 150° to 180° C. to relieve the hardening stresses, etc.

As examples the usual forms of heat treatment for a typical nickel steel are quoted below. The steel contains 3 per cent. of nickel and 0·3 per cent. of carbon, and is one in common use.

Annealing.—Heat to 850° C., soak 45 to 60 minutes, cool in furnace or in boxes.

This treatment reduces the steel to its softest state for machining, removes all forging stresses, and refines the structure.

Normalising.—Heat to 850° C., soak 45 to 60 minutes, cool in air.

This treatment removes forging stresses and refines the structure. There is a tendency for the surface of the parts to harden, and with thin sections below an inch diameter this difficulty may be serious, particularly if the steel contains more than 0·4 per cent. carbon. In such cases it is advisable to allow the steel to cool in the furnace and only remove it when the red heat has disappeared (about 550° C.). Commercially, full annealing should only be resorted to when machining becomes difficult.

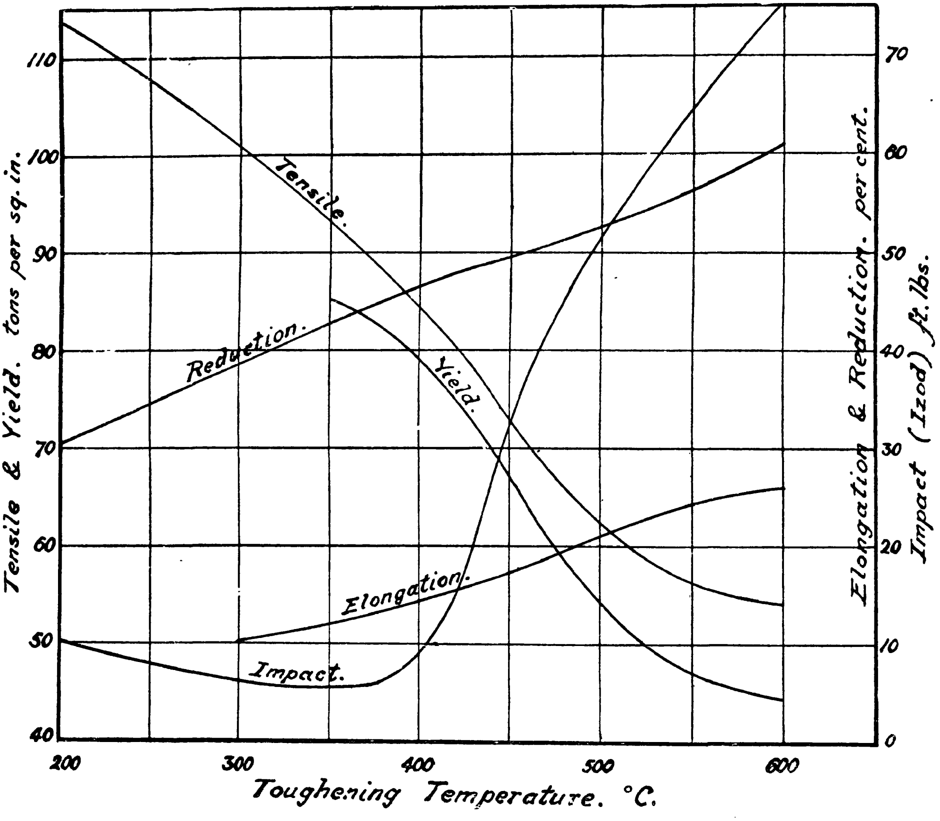


FIG. 163.—Heat Treatment of 4 per cent. Nickel, 0·4 per cent. Carbon Steel. Hardened in oil at 820° C. and toughened at the temperatures shown, and quenched in water.

Hardening (and Toughening).—Heat to 830° C., soak 45 to 60 minutes, quench in oil. Reheat to 600° C., soak 30 to 45 minutes, quench in oil or water.

The first heat hardens the steel and it is then in its weakest state dynamically, but the second heat reduces the hardness and produces a tough material which is exceedingly good as regards dynamic strength. The effect of this second heat is demonstrated by Fig. 162, which is a curve * showing the results obtained by reheating oil-hardened bars $1\frac{1}{8}$ inches diameter at different temperatures. The tremendous increase in the impact strength will be noted, and also the improvement in the ductility as shown by the elongation and reduction of area. The tensile strength, of course, falls, but at 600° C. it is still very high and this, combined with the high ductility and dynamic strength, makes the steel a valuable one.

A similar curve is shown in Fig. 163 for a steel containing 4 per cent. nickel and 0·4 per cent. of carbon.

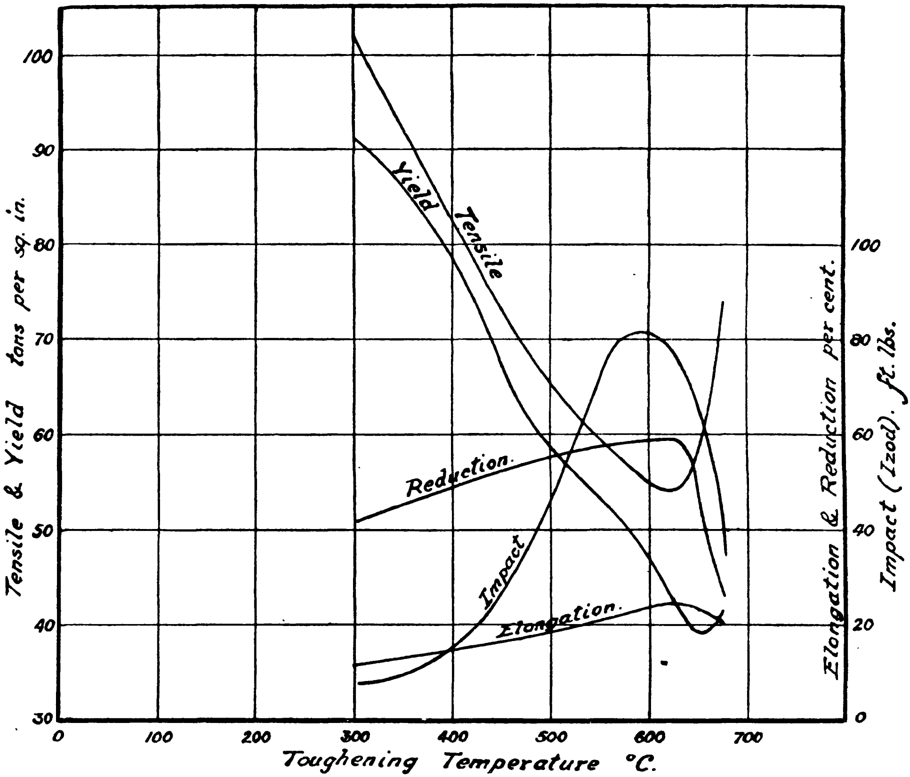


FIG. 164.—Heat Treatment of 4·87 per cent. Nickel, 0·36 per cent. Carbon Steel. Hardened in oil at 820° C. and toughened at the temperatures shown, and quenched in oil.

Applications.—The steels in this range are used for parts such as the following :

Axles generally.
Crankshafts for car and aero engines.
Gears.
Inlet valves for internal combustion engines.

---

* Taken from leaflet, "Nickel Steel," published by Messrs. Brown Bayley's Steel Works, Ltd., Sheffield.

Nickel Steels, Group II.—Those steels containing about 5 to 6 per cent. of nickel are not often used, it being more usual to employ a nickel chrome steel for the higher strengths. Steels containing 5 and 6 per cent. of nickel are in common use as case-hardening steels, and as such are described in the next chapter.

The properties of a steel * containing 4·87 per cent. of nickel and 0·36 per cent. of carbon are shown in Fig. 164.

Such a steel requires careful treatment, but is simpler than nickel chrome steel and offers less risk of cracking during hardening where intricate parts are concerned.

Nickel Steels, Group III.—The composition of the very high nickel steels (20 to 35 per cent. nickel) is generally one or other of the following :—

	I.	II.
Carbon	0·3 to 0·45 per cent.	0·3 to 0·4 per cent.
Nickel	24 ,, 28 ,, ,,	30 ,, 35 ,, ,,

These steels cannot be heat treated like other steels, and even with slow cooling remain austenitic in character. It is possible, however, to anneal them slightly by heating up to 780° C. and cooling in air, when they can be machined with more success.

In the natural state they give the following test results :—

	I.	II.
Yield, tons per square inch ..	20	22
Ultimate tensile ,, ,, ..	40	43
Elongation per cent. (2 inches) ..	35	40
Reduction of area per cent. ..	50	55

The high nickel content does not, as will be seen, confer extreme strength on the steels, which in fact are no better than a 5 per cent. nickel steel, but they are very dense and resist shocks exceedingly well. They are also very inert chemically and resist corrosion, while, compared with most other metals, they have a low coefficient of expansion. They are also non-magnetic.

For these reasons a high nickel steel is used for gas-engine valves and sometimes for boiler tubes and other similar purposes where corrosion is of consequence. It has also found an application in spindles for magnetos because of its non-magnetic qualities.

Chromium Steel

Chromium steel has only a small field of usefulness compared with nickel and nickel chrome steels. Its greatest use is in connection with armour-piercing shells and with high carbon steels for tools requiring a keen cutting edge. As an addition to case-hardening steels it is valuable because of the extreme hardness it confers upon the case, but in so far as the core is concerned no great improvement is obtained. With higher carbon steels (0·3 to 0·5 per cent. carbon) good hard surfaces are obtained which are valuable in the case of gears, crushers, cold rolls, drawing dies, etc., where wearing qualities are important.

Thus the great qualities secured by the addition of chromium are hardness

---

* Taken from leaflet, "Nickel Steel," published by Messrs. Brown Bayley's Steel Works, Ltd., Sheffield.

and resistance to abrasion (or wear). Chromium should not be added if only tensile strength is required.

Forging and Machining Properties.—The low chromium (less than 0·5 per cent.), low carbon (less than 0·3 per cent.) steels do not offer any special difficulties in forging or stamping, but the higher chrome steels require very careful working and must be heated to at least 1,050° to 1,100° C. and forged with heavy or powerful blows.

The machining properties are good with the low carbon steel (0·25 per cent.), but as the carbon content increases or the chromium is increased the material becomes difficult to machine efficiently.

Influence of Chromium.—Chromium differs from nickel in its influence on steel in so far that it mainly associates with the carbon, forming double carbides which, although extremely hard, are not so brittle as the iron carbide alone (cementite). Nickel, on the other hand, associates with the iron (ferrite) only, and simply affects its tensile and dynamic strengths.

Thus the addition of chromium does not raise the tensile strength greatly, in fact with low carbon steels (0·3 per cent.) the increase is practically negligible. But as the carbon content is increased the influence of chromium becomes much more marked owing to the increasing amounts of double carbide, which while increasing the tensile strength, have a much greater hardening effect.

The hardening effect is, of course, obtained at the expense of the dynamic strength, but the falling off is not so great when the hardness is due to chromium as when it is due to carbon alone. Chromium steel when heat treated is less brittle than carbon steel of the same hardness. Thus it is usually better to obtain the desired hardness by increasing the chromium instead of adding more carbon.

Chromium steel in the annealed or normalised state is no stronger than plain carbon steel of the same carbon content. The full properties of the steel are only obtained by hardening treatments. Such treatments require greater care than in the case of nickel or even plain carbon steel, because of the tendency to develop a coarse-grained structure on prolonged heating, or at high temperatures. The addition of chromium raises the critical ranges Ac (heating) and lowers the *Ar* ranges (cooling). From this it is easy to infer that the change into austenite on heating or its decomposition on cooling only takes place with slowness, which partly accounts for the hardness obtained by fairly slow cooling such as quenching in oil (or, with high carbon steels, in air), the steel being easily retained in the austenitic or the martensitic condition. With suitable treatment a very fine-grained structure is obtained, which gives toughness or increased tensile strength without any serious loss of ductility. This fine structure is in fact an important characteristic of these steels.

Chromium increases the resistance to corrosion, and for this reason is especially valuable in marine work and for parts such as valves for internal combustion engines.

Stainless steel, which has become so popular for table cutlery, owes its stainless qualities to the presence of chromium in large amount.

Chromium steels, because of their high resistance to abrasion and corrosion, are suitable for steam turbine blades.

Classification.—Steels intended for case-hardening purposes are dealt with in the next chapter. Those which are simply heat treated are classified as follows :—

Group.	Chromium Content.	Carbon Content.
I.	0·5 to 1·0 per cent.	0·35 to 0·5 per cent.
II.	0·5 „ 1·0 „	Over 0·5 „
III.	1·0 „ 2·5 „	„ 0·25 „
IV.	Over 2·5 „	„ 0·20 „

Only the first three groups are used to any extent; Group IV. is mainly associated with tool steels.*

Chromium Steel, Group I.—The compositions of two typical chrome steels belonging to this group are given herewith :—

	Small Gear Wheel.	Valve Steel.
	per cent.	per cent.
Carbon	0·37	0·44
Chromium	0·56	0·77
Manganese	0·40	0·80
Sulphur	0·025	0·018
Phosphorus	0·010	0·017
Silicon	0·055	0·43

Heat Treatment.—Chromium steel differs from nickel steel in so far that its heat treatment requires much greater care and accuracy in temperature and heating time. It is more difficult than carbon steel to treat, but owing to its tendency to resist changes in constitution the quenching may be performed in oil, with the result that there is less risk of distortion while the desired degree of hardness is still obtained.

Generally, the correct temperatures for treatment are the same as for plain carbon steels of the same carbon content. The addition of each 0·1 per cent. of chromium raises the critical range (on heating) by about 1·5° C., which, however, when added to the critical ranges of carbon steel gives a temperature still within the usual limit of 30° C. allowed for carbon steels. These temperatures should not be exceeded, otherwise the structure will coarsen rapidly and low impact tests will result. This is shown by the three tests given below :—

CHROMIUM STEEL—Cr 0·75, C 0·45

Quenching Temperatures, quenched in Oil and reheated to 425° C.	Impact (Izod), ft.-lbs.	Ultimate tensile, tons per sq. in.
760° C.	42	91
925° C.	36	93
1,040° C.	26	91

---

* The demand for steels suitable for valves for internal combustion engines and capable of withstanding high temperatures without distortion, has brought into being several high chromium steels, some of which contain as much as 12 or 13 per cent. chromium. Such steels are described on pp. 281 and 311, along with others for the same purpose. Reference should also be made to Chapter XIX, under "Valves for Internal Combustion Engines."

The soaking time will have to be regulated carefully. It should not exceed that required for carbon steel, *i.e.* about 30 minutes for each inch thickness of section. Longer periods coarsen the structure, having the same effect as high temperatures.

Annealing and normalising are only necessary to produce a refined structure and to render the material machinable ; these treatments usually are not final, since no advantage is obtained by using chromium steel in the soft condition.

The hardening and toughening operations are similar to those adopted for plain carbon steels, but the results obtained are, of course, very different. For particulars of typical treatments reference should be made to those given under plain carbon steels, Chapter XI.

Mechanical Tests.—The addition of 1 per cent. chromium to a carbon steel of less than 0·5 per cent. carbon increases the tensile strength by 15 to 20 per cent. without any change in the ductility. The following figures represent average results obtained with this class of steel :—

Carbon per cent.	Chromium per cent.	Yield, tons per sq. in.	Ultimate, tons per sq. in.	Elongation in 2 ins.	Reduction of Area.	Impact (Izod), ft.-lbs.
0·35	0·5	26	42	34	60	55
0·35	1·0	28	47	33	60	50
0·50	0·5	35	55	28	55	45

The above values represent the steel in the hardened and toughened condition. The increase in hardness is not shown by these tests nor is it shown by the Brinell machine or scleroscope, but as soon as the material is machined it will be found that it is more difficult to cut than nickel or nickel chrome steels of the same strength. Thus it is the quality of wearing (or resistance to abrasion) that is conferred on the steel ; the actual tensile and ductility values are no better than those obtained from nickel or nickel chrome steels.

Applications.—This group of chromium steels is employed in making such parts as small gears, worms, swivel pins, and other parts subjected to wear.

Chromium Steels, Group II.—These steels all contain more than 0·5 per cent. carbon, and in consequence the hardening qualities of the chromium become very marked. The principal uses of these high carbon 0·5 to 1 per cent. chromium steels is in the manufacture of small tools such as chipping chisels, punches, drills, saw blades, and razors. Such parts as shears, clippers, cutlery, and scissors are also made from chromium steel. The special virtue of the steel is the keen cutting edge which can be produced.

The addition of manganese to the steel emphasises the hardening qualities, but at the same time makes the heat treatment a more delicate operation.

In heat treatment the temperatures used should be the minimum for carbon steels of the same carbon content. The treatments then are those which should be given to good quality tool steels.

Bullens * quotes a series of tests for a steel containing :—

Carbon	0·70 per cent.	approx
Chromium	0·50 ,,	
Manganese	0·60 ,,	

---

* D. K. Bullens, "Steel and Its Heat Treatment."

These tests for convenience are shown graphically in Fig. 165. Unfortunately no particulars are given regarding the dynamic strength, but this would certainly be much higher than for plain carbon steel of the same hardness.

Chromium Steel, Group III.—Those steels containing from 1 to $2\frac{1}{2}$ per cent. chromium, with carbon ranging from 0·25 per cent. upwards, are mainly used for parts requiring an extremely hard surface and yet capable of withstanding very heavy crushing loads. For this reason, balls and ball races, roller bearings, stone-crushing machinery, and other crushers are often made from this steel.

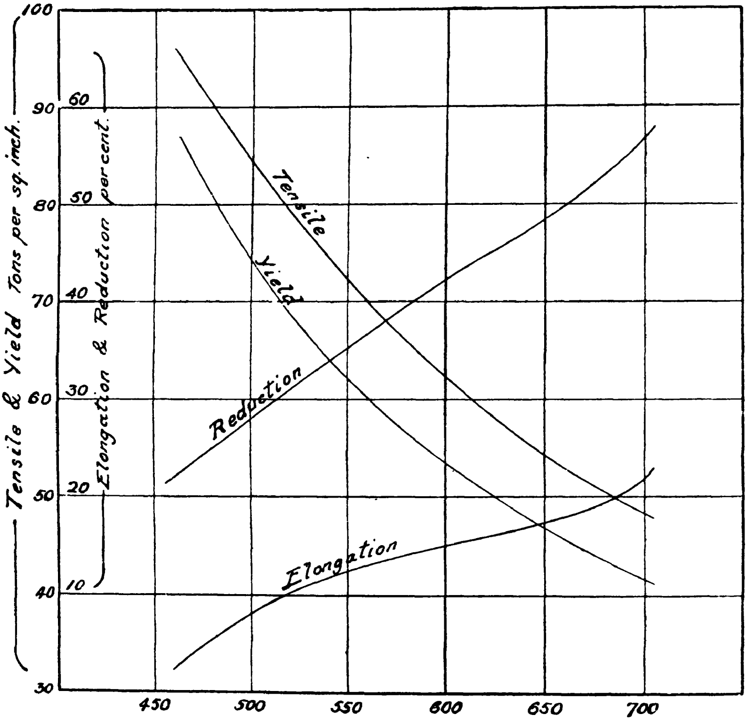


FIG. 165.—Heat Treatment of Chrome Steel (C 0·70, Cr 0·50, Mn 0·60). Hardened in oil at 770° C., toughened at the temperatures shown, and quenched in oil (Bullens).

The usual composition is about 1·0 per cent. carbon with 1·5 to 2·0 per cent. chromium, when the maximum of hardness is obtained consistent with toughness. Such a steel is capable of being forged although it will be necessary to heat to 1,000° to 1,100° C., and to use powerful or very heavy blows in order to overcome the tough structure which the steel possesses even at these temperatures.

Small amounts of nickel are sometimes added with the object of assisting in the forging and heat treatment. Thus a roller bearing taken from an aero engine was found to have the following composition :—

Carbon	0·96	per cent.
Chromium	1·81	,,
Nickel	0·32	,,
Manganese	0·35	,,
Sulphur	0·039	,,
Phosphorus	0·043	,,
Silicon	0·187	,,

This steel when heated to 830° C. and quenched in oil gave the requisite hardness and toughness.

The preparation of these steels for machining is not so simple an operation as with the lower chromium steels. Such a steel as that quoted above will require prolonged heating for several days and then will have to be cooled at an exceedingly slow rate. The temperature for this annealing operation should be about 810° C. The hardness in this state should then be about Brinell No. 179 (4·5 mm. impression).

A more rapid method of annealing is to normalise the steel at a temperature of about 950° C., and then while it is cooling in the air to take it as soon as the red heat has disappeared and reheat at once to about 830° C. and allow it to cool in the furnace.

Chromium Steel, Group IV.—The steels in this group are noted for their resistance to corrosion and abrasion,* and for this reason they are receiving much attention. One of the best known is the so-called "stainless steel," which is now used extensively in the manufacture of cutlery. The fact that it is finding applications in general engineering is sufficient to justify the study of its properties.

Stainless steel usually contains from 12 to 14 per cent. of chromium and from 0·15 to 0·40 per cent. of carbon. A typical analysis is given below :—

Carbon	0·35	per cent.
Chromium	12·2	,,
Nickel	0·46	,,
Manganese	0·16	,,
Silicon	0·18	,,

The stainless properties are affected by the carbon content, and if the steel contains much carbon it is more apt to rust. For cutlery the percentage of carbon is about 0·3 or a little higher, but steels are made containing about 0·2 per cent. of carbon, and these appear to possess the stainless property to a higher degree.

The tensile strength (or hardness) depends on the percentage of carbon and is little affected by variations in the chromium content.

The forging qualities of stainless steel are fairly good, but it is necessary to work at higher temperatures than with other alloy steels. The working range is 950° C. to 1,100° C., and on no account should the steel be worked at temperatures below 850° C. because of the risk of "cold working." The higher carbon steels (0·25 to 0·40) are more difficult to work than those containing 0·1 to 0·2 per cent. of carbon. The latter can be rolled or drawn with comparative ease and, under the name of "stainless iron," are now on the market in the form of sheet, strip, and wire.

---

* "Chromium Steels and Iron," Aitchison, *Proc. I.A.E.*, Nov. 1921. "Some Engineering Uses of Stainless Steel," *Engineering*, Oct. 28th, 1921. "Stainless Steel," *Automobile Engineer*, Nov. 1921. "Turbine Blading," *Metal Industry*, Oct. 28th, 1921.

The heat treatment of this steel offers no special difficulty, in fact it can be handled in the same manner as an air-hardening steel, except that higher temperatures are required. Forgings should be normalised by heating them to a temperature of 950° C., soaking for 30 mins., and cooling in air. In this state they are too hard for machining and it is necessary to reheat them to a temperature of 750° C.

Heat Treatment of Stainless Steel and Iron.—Mechanical Properties

Composition.	Heat Treatment.		Mechanical Properties.				
	Hardening, °C.	Toughening, °C	Yield, tons/sq. in.	Ultimate, tons/sq. in.	Elongation per cent.	Reduction of area per cent.	Impact (Izod), ft.-lbs.
		—	66·8	73·2	13·5	41·9	28
		200	68·4	73·0	12·0	37·8	33
Carbon 0·07		300	68·8	72·4	12·5	36·4	39
Chromium 11·7	930° C.	400	68·8	72·3	15·5	51·0	39
Nickel 0·57	Oil	500	58·8	72·4	18·0	52·2	36
Manganese 0·12	quenched	600	38·0	49·1	20·0	59·3	28
Silicon 0·08		700	30·6	40·4	26·5	65·8	79
		750	27·9	36·7	31·0	68·8	87
		800	33·6	53·6	13·5	44·6	51
Carbon 0·07		—	58·8	69·6	18·5	51·0	12
Chromium 13·3	930° C.	500	56·4	68·0	21·5	61·5	12
Nickel 0·40	Oil	600	35·2	45·6	25·5	71·8	92
Manganese 0·29	quenched	750	36·6	38·6	34·0	68·8	110
Silicon 0·32							
Carbon 0·15		500	—	89·5	10·0	36·0	16
Chromium 11·8	930° C.	600	42·0	56·4	20·0	52·2	35
Nickel 0·77	Oil	700	38·0	46·8	26·0	58·1	60
Manganese 0·16	quenched	750	31·2	43·9	28·0	61·5	68
Silicon 0·09							
Carbon 0·37							
Chromium 12·0	900° C.	500	—	105·0	8·6	24·0	8
Nickel 0·55	Oil	600	57·1	64·1	14·8	41·8	15
Manganese 0·15	quenched	700	47·1	54·0	21·0	52·2	30
Silicon 0·19							
Carbon 1·01							
Chromium 11·8	900° C.	650	46·1	59·6	19·0	40·6	12
Nickel —	Air	700	44·4	53·2	21·0	55·9	20
Manganese 0·28	cooled	750	36·8	50·0	24·0	47·2	23
Silicon 0·06							

Owing to the high percentage of chromium the critical range is much higher than that of carbon steels and, because of this, the hardening temperature is high. The usual temperature for air hardening is 950° C., but if oil quenching is resorted to, the hardening temperature may be 920° C.

After hardening the steel should be reheated (*i.e.* tempered or toughened) in the same manner as other steels in order to obtain the requisite mechanical properties.

The table on p. 282 gives the results obtained by Aitchison * by heat treating a number of stainless steels and irons containing different percentages of carbon. In the hardened state this steel possesses a tensile strength of about 100 tons per sq. in., but by reheating, tensile strengths as low as 40 tons can be obtained. Thus, the range of results is much greater than those obtained from other alloy steels.

The resistance to corrosion to some extent is controlled by the smoothness of the surface and the absence of strained portions. If the steel has been finely machined so that the tearing (or distortion) of the surface is only slight there will be little risk of it rusting, but heavy cuts or scratches are likely to be the cause of rusting because of the stressed condition that exists at these points. To obtain the maximum resistance to corrosion the steel should be polished, but not necessarily to the same degree as electro-plate, etc.

The properties of other chromium steels are described at the end of this chapter under "the effects of high temperatures on the strength of steel." The reader is advised also to consult the papers referred to in the footnotes.

Nickel Chrome Steel

Nickel chrome steels are without doubt the best of the alloy steels. Nickel steels are noted for their high tenacity and ductility together with high dynamic strength, while chromium steels are valuable for their hardness and good wearing qualities together with a fair dynamic strength. Other alloy steels such as vanadium or chrome vanadium have not yet come into great prominence, and although the latter steel is very similar to nickel chrome, it cannot be regarded as superior. The combination of nickel and chromium in one steel gives to it both the qualities of toughness and hardness associated with these metals respectively and yet appears to eliminate the disadvantages each possess. Thus such a steel will serve a wider range of uses than either of the plain nickel or chromium steels.

Dynamic Strength.—These steels are remarkable for the wide range of strengths that can be obtained with heat treatment, and a study of the tensile results obtained from series of test bars differently heat treated would at first lead to the belief that a steel of one composition only would answer the requirements of several specifications differing perhaps as much as 50 to 60 tons per square inch. Thus Fig. 166 shows the variation in the tensile strength that can be obtained with a steel containing 0·36 per cent. carbon, 1·10 per cent. nickel, and 0·92 per cent. chromium after hardening and then tempering or toughening at different temperatures.

But, as will be seen, the dynamic strength as represented by the impact curve does not vary in the same consistent manner that the static strength does ; there is a region in which it falls off to a very dangerous value. Moreover, this region, even where the tensile strength is concerned, is not so satisfactory owing to the sensitiveness of the steel to variations in the treatment temperature.

---

* "Chromium Steels and Iron," by Leslie Aitchison, D.Met., B.Sc., A.I.E.

It is important, therefore, that the selection of a nickel chrome steel should be made with regard to its heat treatment quite as much as with reference to the actual requirements for strength, etc. Unless this is done, and a steel is used which, giving the correct tensile strength after heat treatment, requires treating at a temperature where the impact values obtained are low, the result will be disaster which will be difficult to account for. Yet the same steel when toughened to give a lower tensile strength, or even one which is higher, will behave well and will possess a high dynamic strength. This is simply due to the relation between the dynamic strength and the temperatures used in reheating the steel after hardening, a relationship which must be watched in each particular group of nickel chrome steels.

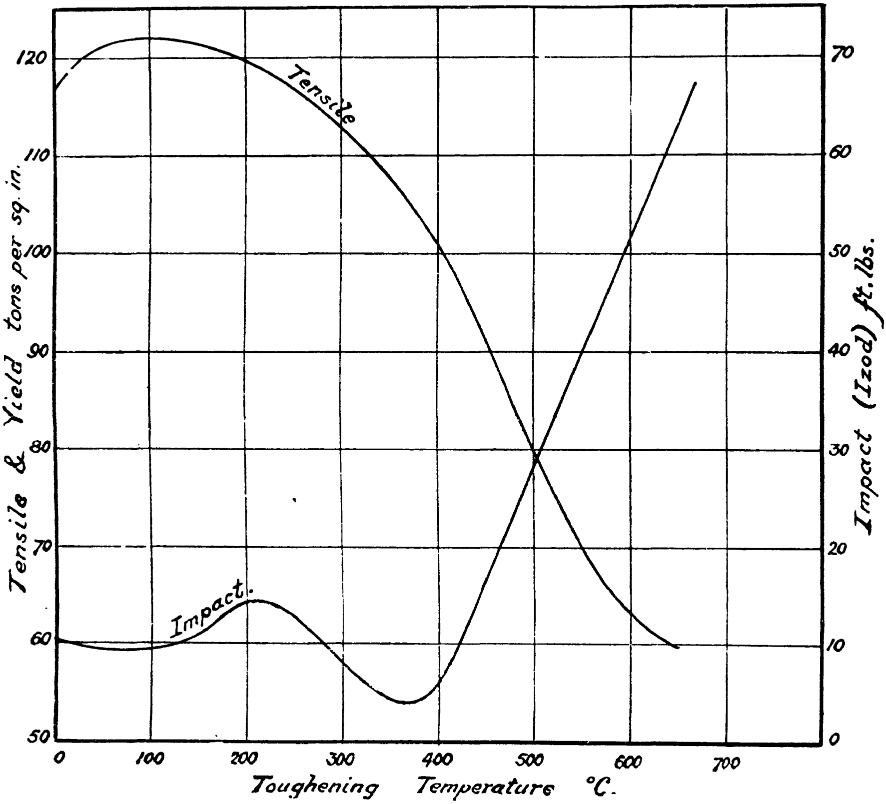


Fig. 166.—Effect of varying the Heat Treatment of a Nickel Chrome Steel. Note the wide range of results obtainable but at the same time the very variable impact test results, especially over the range 300° C. to 350° C.

Referring again to Fig. 166, it will be seen that this particular steel in the fully hardened state (*i.e.* not tempered) has a tensile strength of 117 tons and impact value of 10 ft.-lbs. When tempered at 200° C. the tensile strength is increased by 2 tons while the impact value is raised to a maximum for this region. In such a condition the steel is eminently suitable for the clash gears in a gear box of an automobile. Further heating, however, reduces the impact value considerably, and in fact the steel is worse dynamically than when fully hardened. Thus although the tensile curve indicates that the steel would meet a specification calling for, say, 90 to 110 tons, the dynamic strength might be exceedingly poor and in some instances so low that only 2 ft.-lbs. would be required to break a test specimen. The region from 250° C. to 400° C. may be regarded as unsafe on this account. At a toughening temperature of 400° C., however, the dynamic strength commences to improve rapidly, and at about 500° C. the steel is in a safe region and can be used to meet any requirements coming within the limits obtained by heat treatment.

A safe rule in selecting a nickel chrome steel is to choose one which will give the required strength when toughened (after hardening, of course) at a temperature below 250° C. or else above 500° C. Any steel which requires toughening at temperatures between 250° C. and 500° C. to give the desired results should not be employed.

Quenching after Toughening.—In connection with this peculiar variation in the dynamic strength, it is very important to quench the steel after heating for toughening. The maximum impact value is then obtained. In this respect nickel chrome steel differs from plain carbon steel, which should be cooled slowly from the toughening heat to secure the best results.

If the toughening temperature is above 500° C. and the steel is allowed to cool slowly the impact value may be low, due to the slow cooling through the danger region. Quenching in oil or water eliminates this difficulty.

The limits of this danger zone and the falling off in the dynamic strength are found to vary with each particular group of steels, and also in different casts of the same composition. In no case, however, have the authors found a steel in which this erratic behaviour * is entirely absent, and it should therefore be always guarded against by applying the rule mentioned above. This same effect is found in other alloy steels such as nickel and chrome vanadium steels, but in lesser degree.

Seams and Laminations.—Seams and laminations are found in nickel chrome steel just as in the case of nickel steel, but not to the same extent. When due care has been taken in the manufacture of the steel and a good portion of the upper part of the original ingot has been cut away, piping troubles are eliminated and the rolled metal possesses a uniform structure without much banding or other troubles of a laminated character. It is good practice to have the billets rough machined before rolling, as this eliminates surface defects which "open out" during forging and drop stamping. In this respect these steels give more trouble than nickel steels.

Forging Properties.—The addition of chromium reduces the plastic qualities of the steel and in consequence the forging and drop stamping

---

* This peculiarity in alloy steels is known under the name of "Krupp Krankheit," or, more commonly, "temper brittleness." So far no adequate explanation has been found for the phenomenon, but it is quite evident that it has an important bearing on the use of these steels for parts subjected to severe shocks or continuous vibration. The dynamic strength (as measured by the impact test) is the only property affected and for this reason the ordinary run of tests such as ultimate tensile stress, yield point, elongation and reduction per cent. do not give the slightest indication of a defect which might lead to extremely disastrous results in practice. It is essential that quenching should always follow tempering and that the rule specified for selecting a steel should be observed.

operations are more difficult than with carbon or nickel steels. This difficulty increases rapidly with increase in chromium and also in a lesser degree with increase in nickel. Greater care in preheating must be taken and, in fact, it is necessary with some steels to preheat them in one furnace up to 600° C. and then to transfer to the second furnace for the forging heat. The rate of heating should be slow and uniform, while the actual forging heat should not exceed 1,100° C. in most cases.

The sensitiveness of these steels to bad treatment during forging, etc., not only grows with the chromium content but appears to be dependent to some extent on the ratio of nickel to chromium in the steel. Thus with three steels having approximately the following compositions the third steel was the most difficult to handle, and stampings made from it very often developed cracks while cooling.

	Steel No. 1. Per cent.	Steel No. 2. Per cent.	Steel No. 3. Per cent.
Carbon	0·35	0·35	0·35
Nickel	1·0	2·0	3·0
Chromium	1·0	1·0	1·0

This particular steel (No. 3) had a nickel to chrome ratio of 3 to 1, and although a splendid steel in many other respects it was not so suitable for stamping as No. 2 steel, having a ratio of 2 to 1, while No. 1 steel, having a ratio of 1 to 1, although much better than No. 3, was not so good as No. 2. The chromium, it should be noticed, is 1 per cent. in each case.

When the chromium is raised to 1·5 per cent. and above, the stamping of intricate parts is exceedingly difficult and the wear on the dies is very great. Thus a 4·5 per cent. nickel, 1·5 per cent. chromium, 0·35 per cent. carbon steel can only be used for comparatively simple shaped parts.

The cooling after stamping requires just as much care as the preheating and heating for stamping. The presence of chromium, particularly when it amounts to 1 per cent. and above, tends to cause the steel to self-harden, and careless cooling on the floor in the presence of draughts will soon cause cracks to develop. This is very pronounced when the steel also contains 3 per cent. of nickel and above. The stampings or forgings should be placed on ashes and protected with metal shields from draughts. The subsequent normalising operation should then follow as soon as possible owing to the tendency for cracks to develop on standing.

The tendency of most drop stampers (who have in the past handled carbon steels only) is to overheat these steels to increase their plasticity, with the result that a coarse-grained structure is very often produced. Prolonged heat treatment is then required to restore the steel to a good state, which means that it is cheaper to control the forging temperature and, if necessary, to reheat more than once to complete the stamping.

Machining Properties.—The machining properties of these steels depend, of course, on the composition and on the heat treatment given. It should be made a general rule that all stampings and forgings be normalised before machining in order to eliminate hard spots, which are common in the raw stampings. In the low chromium steels containing less than 1 per cent. chromium and 2 per cent. nickel the machining is then fairly efficient. But with steels containing 1 per cent. chromium or more, and above 2 per cent. nickel, with 0·3 to 0·4 per cent. carbon, the ordinary normalising operation does not put the steel into a good machinable condition. There will be found hard patches which will make such operations as milling, profiling, and gear cutting difficult and inefficient both as to time and wear of cutters. For these steels, and in fact for all, it is advisable to reheat, after normalising, to a temperature of about 650° C. and then cool slowly, a treatment which puts the steel in almost its softest condition. All such troubles as hard spots then disappear and the machining operation is satisfactory.

In the case of stampings and forgings which are to be machined after heat treatment, it is advisable to rough them over after normalising—an operation which is helpful in two ways : (1) because the bulk of the machining is done while the steel is soft, and (2) the removal of the scale and surplus metal (particularly the former) greatly facilitates the heat treatment, producing more uniform results. The deciding points as to whether a part should be heat treated before or after machining are as follows :—

(1) Hardness of steel in the treated state.
(2) Nature of machining operations.
(3) Distortion produced by heat treatment.

A list is given on p. 206 showing the approximate relationship between the hardness of steel and its cutting properties. This should be referred to and a decision arrived at as to what hardness is permissible under the conditions ruling. The tensile strength is also given, and thus the designer can decide whether to take the part under consideration as one to be heat treated beforehand (thus limiting the tensile strength) or else to be treated after machining (thus increasing the tensile strength). It should be remembered that the addition of chromium makes the steel less easy to machine, and although the Brinell hardness may appear low enough for machining this is not always a true guide. Large percentages of chromium make machining very difficult and, in fact, it is almost impossible to deal commercially with such steels in even the normalised state ; it is necessary to anneal them in the manner already described.

The heat treatment of parts after machining is not advisable on account of the risk of distortion, but when this is necessary a steel should be chosen which will give the required tests when quenched in oil or air. Allowance should, of course, be made for grinding afterwards to correct for any change in size or shape.

Heat Treated Bars.—For many parts such as can be made direct from bar material on automatic or semi-automatic machines, it is usual to obtain bars which have been heat treated already. For such work it is practicable to use material having a tensile strength up to 60 tons per square inch. Above this value the machining becomes difficult. The advantages of this practice are obvious ; the production of accurately machined parts with a finish unmarred by any oxidation or other blemishes due to heat treatment is a most important feature.

This bar material can be obtained either in the common black rolled condition or, for close chucking machines, in the reeled state having an accuracy good enough for the collets, and a fairly good (although not bright) finish.

The usual specification for such material is as follows :—

Yield, tons per square inch	45 to 50
Ultimate, ,, ,, ,, ...	55 ,, 60
Elongation per cent.	Not less than 16
Reduction of area per cent.	,, ,, 50
Impact (Izod), ft.-lbs.	,, ,, 40

The tensile strength often exceeds 60 tons per square inch, but this should not be encouraged owing to the increasing difficulty in machining. To check such material rapidly the bars should be "Brinelled" and should come within the following range of hardness: Nos. 233 to 277 (impressions 4 to 3·65 mm.).

Influence of Nickel and Chromium.—The influence of nickel and chromium when added alone have been described. Each confers certain good qualities on the steel, but these qualities are of different characters due to the fact that nickel affects the ferrite constituent and chromium the cementite (carbon) constituent of the steel. The combination, therefore, is likely to produce both classes of improvement in the steel, and as a matter of fact it does. Not only are the toughness and ductility increased (due to nickel) and the hardness raised (due to chromium), but the disadvantages connected with the addition of nickel and chromium alone are to a great extent eliminated. Further the combination appears to intensify the good qualities given by each.

Thus, while chromium makes the steel sensitive to prolonged heating, producing a coarse and brittle structure, nickel has the opposite effect and therefore neutralises this tendency. From this fact alone it will be clear that to secure the best results the proportions of the two alloying metals will have to bear a certain relation to each other. This relationship is usually referred to as the "Nickel-chrome ratio," and is of some importance although steels are made commercially having very different ratios of nickel to chromium.

Since the two alloying metals exert their influence independently it will be understood that while nickel lowers the critical ranges (on heating) chromium will tend to counteract this, since it raises the critical ranges (on heating). Thus while each 0·1 per cent. of nickel lowers the critical range by 1° C., chromium raises it by about 1·5° C. for each 0·1 per cent., and therefore a steel having 0·3 per cent. carbon with an $Ac3$ point of 790° C. as plain carbon steel, is changed by 3 per cent. nickel, so that the $Ac3$ point is 30° C. lower, and still further changed by 1 per cent. chromium which raises the $Ac3$ point 15° C., giving a final critical temperature of 775° C. approximately. Unfortunately, in practice it is not possible to calculate in this manner owing to the influence of manganese, and also because of the influence of the nickel and chromium upon each other varies as their proportions change. Still as an approximate method such a simple calculation is sometimes helpful.

The critical ranges on cooling may also be calculated although only very approximately. Like chromium steels nickel chrome steels are sluggish over the changes from one state to another, and in consequence they are easily hardened in oil or air, a good martensitic or martensite-austenitic structure being obtained. This, of course, means that distortional troubles and cracks are avoided to a great extent.

The tendency of both metals to give a fine-grained structure with heat treatment is very pronounced in these steels, and in many cases it is almost impossible to detect the grains even at 800 to 1000 magnifications. This characteristic accounts for the high dynamic strength of these steels. At the same time the good wearing properties due to the presence of the double carbide of chromium and iron (and manganese if in sufficient quantity) are retained. Thus a steel which has the highest combination of strength, ductility, dynamic strength, and wearing properties is obtained.

Ratio of Nickel to Chromium.—Bearing in mind the different behaviour of nickel and chromium when added to steel, it will be readily understood that the presence of varying quantities of each will give the steel characteristics that will vary in the same manner. Thus the addition of chromium in increasing quantities will increase the mineralogical hardness of the steel and also make it more sensitive to prolonged heating. Increasing the nickel will improve the strength and ductility and improve the steel from the heat treatment point of view. Thus considering steels of the same carbon content (0·30 to 0·35 per cent.), the effect of varying the ratio of nickel to chromium may be generalised as follows :—

The addition of chromium to a nickel steel has the important effect of giving it air-hardening properties which increase rapidly in intensity as the chromium is raised. Nickel certainly intensifies this, and of three steels each containing 1 per cent. of chromium, that which contains 3 per cent. of nickel will exhibit a very strong tendency to harden in air as compared with the others containing 1 and 2 per cent. of nickel respectively. The latter are almost free from this tendency. This property of air hardening, however, must not be confused with intrinsic hardness. The steel containing 3 per cent. of nickel and 1 per cent. of chromium is no harder when suitably heat treated than that containing 1 per cent. of nickel and 1 per cent. of chromium. In fact, the latter steel has proved to be better for gears than the 3 Ni, 1 Cr steel, and certainly better than the 2 Ni, 1 Cr steel.

The wearing properties of the steel appear to be proportional to the chromium present, but they fall off slightly with increasing quantities of nickel, the effect of nickel being very much weaker than the hardening influence of chromium. Thus for wearing surfaces the chromium should be high and the nickel low, *e.g.* a steel such as that mentioned above with a 1 to 1 ratio should be used.

The dynamic strength is raised by both nickel and chromium, but nickel has the greater influence in so far that it counteracts the tendency of chromium to develop a coarse structure during prolonged heat treatment, especially during forging and drop stamping (if carried out at high temperatures), and for this reason the nickel content should be high for a given chromium content.

The tensile strength is raised by both nickel and chromium, but no doubt to the greater extent by chromium, since the values obtained from steels containing nickel in varying percentages from one to three, but with 1 per cent. of chromium, are almost identical after the same heat treatment, but those obtained with a slightly higher chromium content are at once higher. Thus chromium may be regarded as the deciding factor in strength, although, of course, nickel still controls it in some measure.

Uniformity in heat treatment is dependent on the nickel content and the most consistent results are obtained with high ratio nickel to chrome steels, a fact which is of great importance commercially.

Therefore, taking all these points into account, it would appear commercially that the high ratio nickel chrome steels are best for most purposes and that to secure good wearing qualities the chromium should be raised and the nickel content readjusted to secure the same ratio again. This will be clearly seen by studying the compositions of the steels recommended by different makers, and these are therefore dealt with next.

Classification.—It would appear that nickel chrome steels could be classified according to the ratio of the two alloy metals. This, however, is not so useful as a classification based on tensile and dynamic strengths. The question of wearing does not fit in with this scheme, but this is more or less a special quality to be dealt with separately.

The steels at present used may be placed under one or other of the following typical compositions :—

Class No.	Carbon.	Nickel.	Chromium.	Ni-Cr Ratio.
1	0·35	1·0	0·5	2 to 1
2	0·35	1·2	1·2	1 ,, 1
3	0·34	2·0	1·0	2 ,, 1
4	0·30	3·0	1·0	3 ,, 1
5	0·35	3·5	0·7	5 ,, 1
6	0·32	3·5	1·0	3·5 ,, 1
7	0·30	4·5	1·5	3 ,, 1
8	0·35	4·0	1·25	3 ,, 1

The tensile strength increases in almost the same order as the steels are given. The two last classes (Nos. 7 and 8) are air-hardening steels.

These steels are more fully described below under their respective class numbers.

Class No. 1

CHEMICAL COMPOSITION

Carbon	0·30 to 0·40 per cent.
Manganese	0·50 ,, 0·80 ,,
Nickel	0·90 ,, 1·20 ,,
Chromium	0·50 ,, 0·70 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·20 ,,

MECHANICAL TESTS

	Normalised.	Heat treated.
Yield, tons per square inch	35 to 40	40 to 50
Ultimate, ,, ,, ,, ...	45 ,, 50	50 ,, 60
Elongation per cent.	25 ,, 15	25 ,, 18
Reduction of area per cent.	55 ,, 45	60 ,, 50
Impact (Izod), ft.-lbs.	20 ,, 10	45 ,, 35

HEAT TREATMENT.

Normalising.—880° to 900° C., 30 minutes soaking, cool in air.
Treatment.—(1) 850° C., 30 minutes soaking, quench in oil.
(2) Reheat to 650° to 680° C., soak 30 minutes, quench in oil.

APPLICATIONS.

Crankshafts, connecting rods, axles, valve guides.

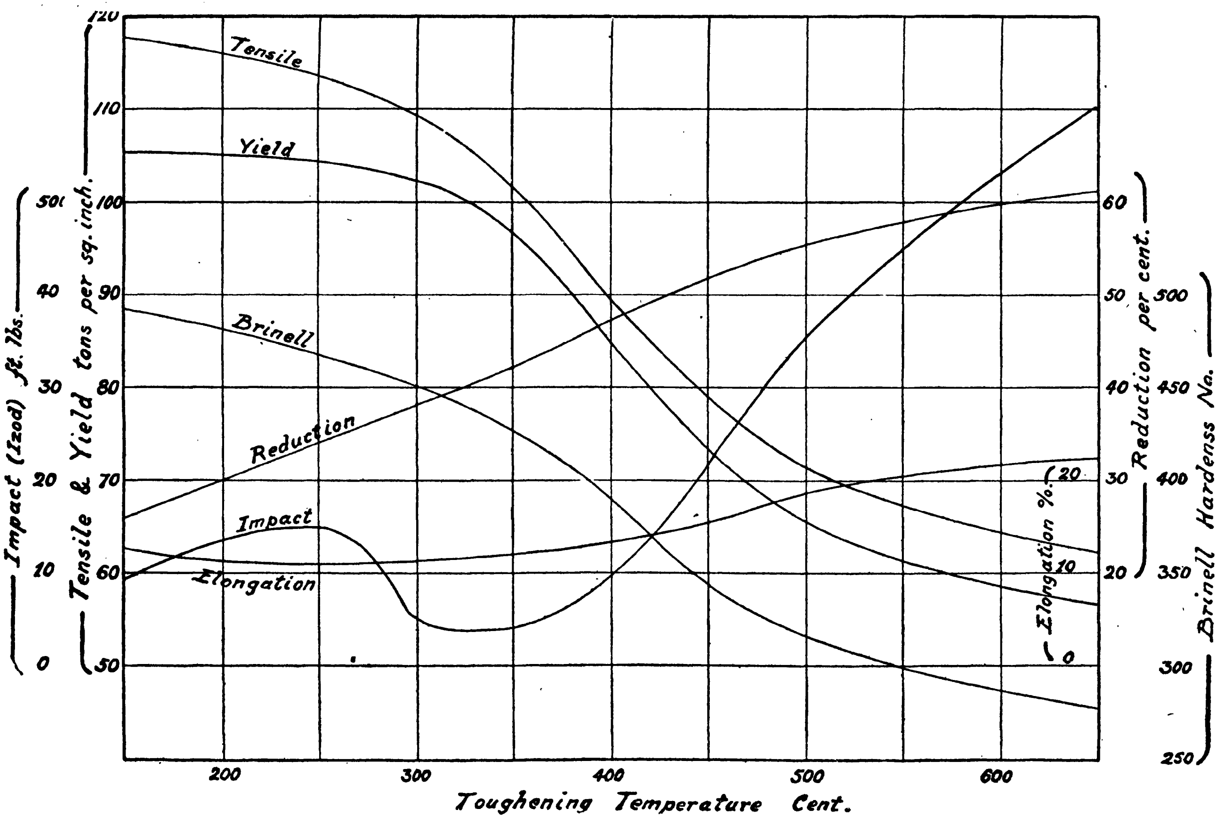


FIG. 167.—Heat Treatment of Nickel Chrome Steel Class No. 2 (C 0·34, Ni 1·24, Cr 1·17, Mn 0·44, S 0·29, P 0·31, Si 0·09). All test pieces were normalised at 830° C., heated to 825° C., quenched in oil, and then reheated to the toughening temperatures specified and quenched in oil.

Class No. 2

CHEMICAL COMPOSITION

Carbon	0·30 to 0·40 per cent.
Manganese	0·30 „ 0·70 „
Nickel	1·10 „ 1·50 „
Chromium	1·00 „ 1·40 „
Sulphur	Not more than 0·040 „
Phosphorus	„ „ 0·040 „
Silicon	„ „ 0·20 „

MECHANICAL TESTS

	Normalised.	Treatment I.	Treatment II.	Treatment III.
Yield, tons per square inch	40 to 50	45 to 55	55 to 65	95 to 110
Ultimate, „ „ „	45 „ 55	55 „ 65	60 „ 70	105 „ 125
Elongation per cent ..	20 „ 15	25 „ 16	23 „ 16	12 „ 8
Reduction of area per cent.	55 „ 45	60 „ 50	60 „ 50	35 „ 25
Impact (Izod), ft.-lbs. ..	20 „ 10	60 „ 40	55 „ 35	20 „ 8

HEAT TREATMENT

Normalising.—830° to 850° C., 45 minutes soaking, cool in air.

Treatment I.—825° C., soak 30 minutes, quench in oil. Reheat to 650° C., soak 30 minutes, quench in oil.

Treatment II.—825° C., soak 30 minutes, quench in oil. Reheat to 600° C., soak 30 minutes, quench in oil.

Treatment III.—825° C., soak 30 minutes, quench in oil. Reheat to 220° to 250° C. in oil bath, soak 45 minutes, cool in air.

A typical treatment curve for this class of steel is shown in Fig. 167. The test bars after normalising were machined to $\frac{5}{8}$ inch diameter, hardened in oil at 825° C., and then reheated to the temperature indicated, afterwards being quenched in oil.

APPLICATIONS

Bar for machining purposes (ready treated to I.), such as bolts, studs, and tie bars. Also connecting rods and crankshafts (Treatments I. and II.). Gears for hard wear (Treatment III.).

Class No. 3

CHEMICAL COMPOSITION

Carbon	0·28 to 0·38 per cent.
Manganese	0·40 „ 0·70 „
Nickel	2·0 „ 2·40 „
Chromium	0·9 „ 1·20 „
Sulphur	Not more than 0·04 „
Phosphorus	„ „ 0·04 „
Silicon	„ „ 0·18 „

MECHANICAL TESTS

	Normalised.	Treatment I.	Treatment II.	Treatment III.
Yield, tons per square inch	40 to 50	45 to 50	55 to 65	60 to 70
Ultimate, „ „ „	45 „ 55	55 „ 60	60 „ 70	70 „ 80
Elongation, per cent. ..	25 „ 15	25 „ 16	23 „ 16	15 „ 10
Reduction of area, per cent.	68 „ 60	65 „ 55	65 „ 55	60 „ 50
Impact (Izod), ft.-lbs. ..	20 „ 10	70 „ 50	65 „ 45	40 „ 30

HEAT TREATMENTS

Normalising.—830° to 850° C., soak 30 minutes, cool in air.

Treatment I.—825° C., soak 30 minutes, quench in oil. Reheat to 650° C., soak 30 minutes, quench in oil.

Treatment II.—825° C., soak 30 minutes, quench in oil. Reheat to 600° C., soak 30 minutes, quench in oil.

Treatment III.—825° C., soak 30 minutes, quench in oil. Reheat to 500° C., soak 30 minutes, quench in oil.

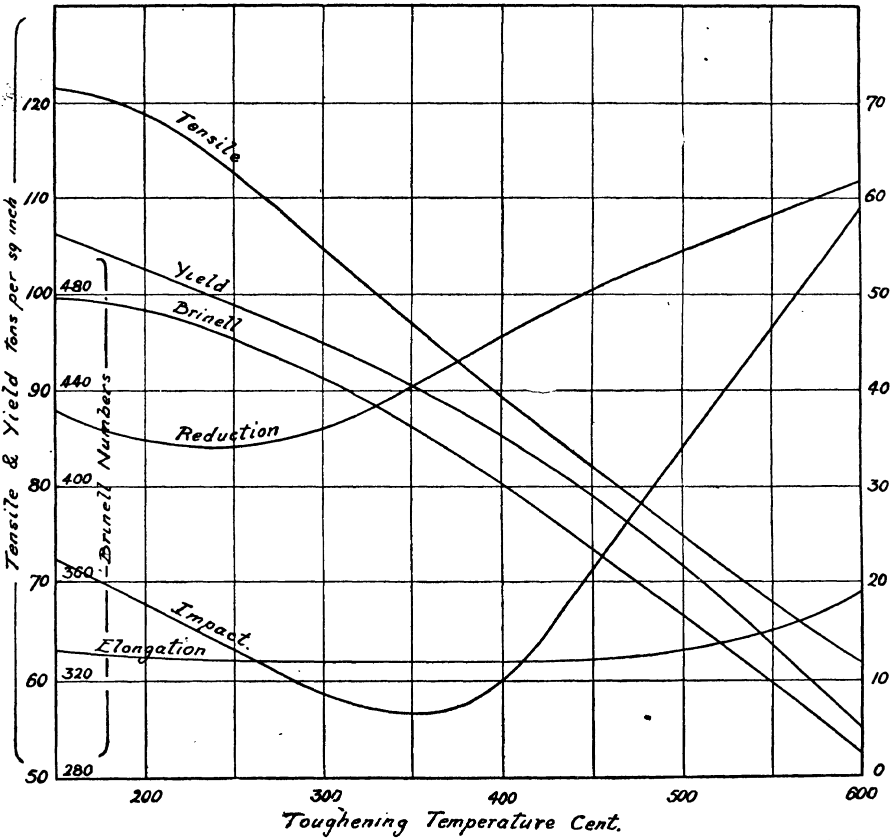


FIG. 168.—Heat Treatment of Nickel Chrome Steel Class No. 3 (C 0·31, Ni 2·31, Cr 1·14, Mn 0·49, S 0·03, P 0·032, Si 0·13). All test pieces were normalised at 820° C., heated to 830° C., quenched in oil and then reheated to the toughening temperatures specified and quenched in oil.

A typical treatment curve for this class of steel is shown in Fig. 168. The method of treatment for the test pieces was similar to that in the case of Fig. 167.

APPLICATIONS

Bar for machining purposes (ready treated to I.), such as bolts, studs, and tie bars. Also connecting rods, crankshafts, and axles (Treatments I., II., and III.). This steel is not suitable for gears for hard wear

Class No. 4

CHEMICAL COMPOSITION

Carbon	0·26 to 0·34	per cent.
Manganese	0·40 ,, 0·80	,,
Nickel	3·00 ,, 3·40	,,
Chromium	0·90 ,, 1·30	,,
Sulphur	Not more than 0·04	,,
Phosphorus	,, ,, 0·04	,,
Silicon	,, ,, 0·20	,,

MECHANICAL TESTS

	Annealed.	Treatment I.	Treatment II.	Treatment III.
Yield, tons per square inch ..	50 to 60	45 to 55	55 to 65	100 to 110
Ultimate, ,, ,, ,, ..	55 ,, 65	55 ,, 65	60 ,, 70	110 ,, 120
Elongation per cent.	20 ,, 15	25 ,, 16	22 ,, 13	10 ,, 5
Reduction of area per cent. ..	60 ,, 50	65 ,, 55	60 ,, 50	45 ,, 35
Impact (Izod), ft.-lbs.	20 ,, 10	65 ,, 45	55 ,, 40	20 ,, 10

HEAT TREATMENTS

Normalising.—810° to 830° C., soak 45 minutes, cool in air. (In this state the steel is too hard for machining.)

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, and cool in air.

Treatment I.—810° C., soak 30 minutes, quench in oil. Reheat to 650° C., soak 45 minutes, quench in oil.

Treatment II.—810° C., soak 30 minutes, quench in oil. Reheat to 600° C., soak 45 minutes, quench in oil.

Treatment III.—810° C., soak 30 minutes, quench in oil. Reheat to 220° to 250° C. in oil bath, soak 45 minutes, cool in air.

APPLICATIONS

Bar for machining purposes (ready treated to I.), such as bolts, studs, and tie bars. Also connecting rods, crankshafts and axles (Treatments I. and II.). Gears for hard wear (Treatment III.).

Class No. 5

CHEMICAL COMPOSITION

Carbon	0·30 to 0·38	per cent.
Manganese	0·40 ,, 0·70	,,
Nickel	3·50 ,, 4·0	,,
Chromium	0·60 ,, 0·90	,,
Sulphur	Not more than 0·04	,,
Phosphorus	,, ,, 0·04	,,
Silicon	,, ,, 0·15	,,

MECHANICAL TESTS

	Annealed.	Treatment I.	Treatment II.
Yield, tons per square inch ..	50 to 60	45 to 55	55 to 65
Ultimate, ,, ,, ,, ..	55 ,, 65	55 ,, 65	60 ,, 70
Elongation per cent.	20 ,, 15	25 ,, 16	22 ,, 13
Reduction of area per cent. ..	60 ,, 50	60 ,, 50	60 ,, 50
Impact (Izod), ft.-lbs.	20 ,, 10	70 ,, 50	55 ,, 35

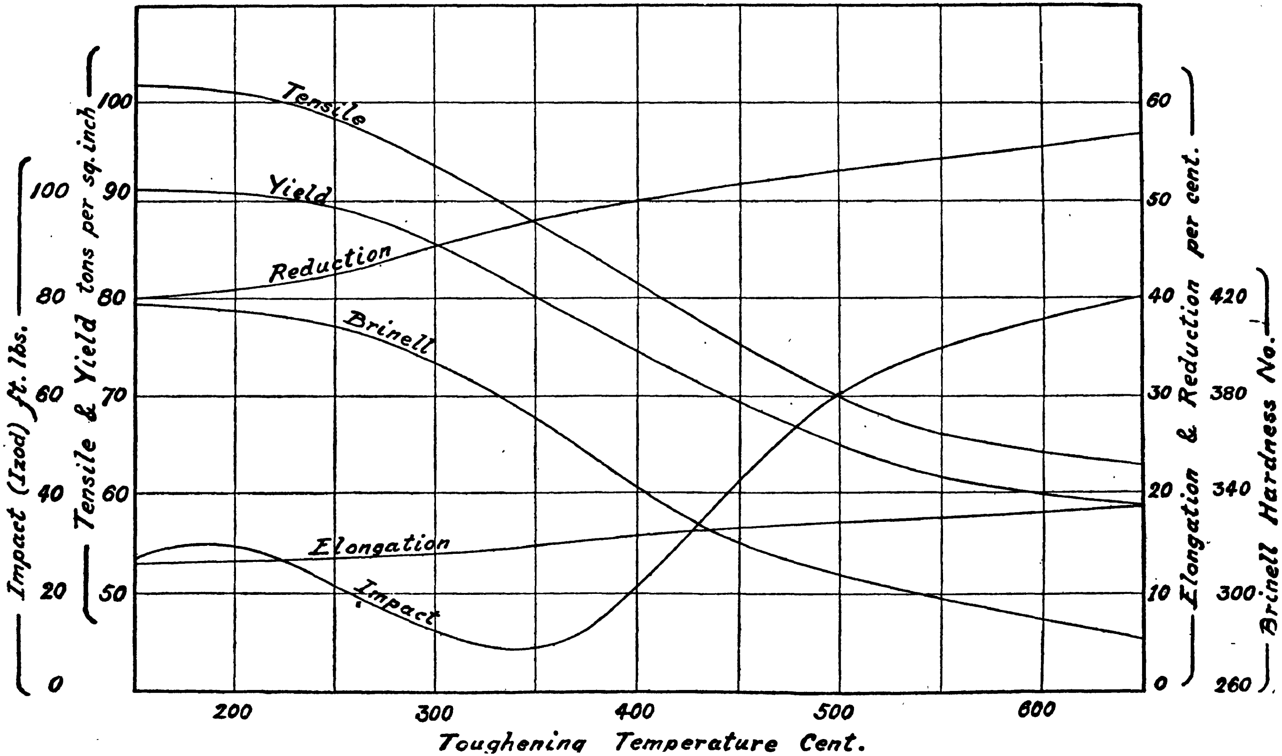


FIG. 169.—Heat Treatment of Nickel Chrome Steel Class No. 5 (C 0·30, Ni 3·75, Cr 0·60, Mn 0·39, S 0·02, P 0·037, Si 0·11). All test pieces were normalised at 825° C., heated to 825° C., quenched in oil and then reheated to the toughening temperatures specified and quenched in oil.

HEAT TREATMENTS

Normalising.—820° to 840° C., soak 30 minutes, cool in air. (In this state the steel is too hard for machining.)

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, and cool in air.

Treatment I.—820° C., soak 30 minutes, quench in oil. Reheat to 650° C., soak 45 minutes, quench in oil.

Treatment II.—820° C., soak 30 minutes, quench in oil. Reheat to 600° C., soak 45 minutes, quench in oil.

The heat treatment curve shown in Fig. 169 is typical for this class of steel. The size of the test pieces and method of treatment were similar to those which gave the results shown in Fig. 167.

APPLICATIONS

Bar for machining purposes (ready treated to I.) such as bolts, studs, and tie bars. Particularly useful for crankshafts and axles, also for connecting rods (Treatments I. and II.); not very serviceable for gears required for hard wear.

Class No. 6

CHEMICAL COMPOSITION

Carbon	0·28 to 0·36 per cent.
Manganese	0·40 „ 0·70 „
Nickel	3·50 „ 4·0 „
Chromium	0·90 „ 1·20 „
Sulphur	Not more than 0·04 „
Phosphorus	„ „ 0·04 „
Silicon	„ „ 0·25 „

MECHANICAL TESTS

	Annealed.	Treatment I.	Treatment II.	Treatment III.
Yield, tons per square inch ..	50 to 60	50 to 60	55 to 65	65 to 75
Ultimate, „ „ „ ..	55 „ 65	55 „ 65	60 „ 70	70 „ 80
Elongation per cent.	20 „ 15	25 „ 16	25 „ 16	20 „ 12
Reduction of area per cent. ..	60 „ 50	60 „ 50	60 „ 50	55 „ 45
Impact (Izod), ft.-lbs.	20 „ 10	65 „ 45	55 „ 35	45 „ 25

HEAT TREATMENTS

Normalising.—820° to 840° C., soak 45 minutes, cool in air. (In this state the steel is too hard for machining.)

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, cool in air.

Treatment I.—820° C , soak 30 minutes, quench in oil. Reheat to 650° C., soak 45 minutes, quench in oil.

Treatment II.—820° C., soak 30 minutes, quench in oil. Reheat to 600° C., soak 45 minutes, quench in oil.

Treatment III.—820° C., soak 30 minutes, quench in oil. Reheat to 500° C., soak 45 minutes, quench in oil.

APPLICATIONS

Bar for machining purposes (ready treated to I.) such as bolts, studs, and tie bars. Also suitable for crankshafts and axles (Treatments I. and II.) and for connecting rods (Treatments II. and III.).

Class No. 7 (Air Hardening)

CHEMICAL COMPOSITION

Carbon	0·26 to 0·34 per cent.
Manganese	0·40 „ 0·60 „
Nickel	4·20 „ 4·70 „
Chromium	1·20 „ 1·60 „
Sulphur	Not more than 0·40 „
Phosphorus	„ „ 0·40 „
Silicon	„ „ 0·20 „

MECHANICAL TESTS

	Annealed.	Treatment I.	Treatment II.	Treatment III.	Treatment IV.
Yield, tons per square in.	50 to 60	55 to 65	65 to 75	95 to 105	90 to 110
Ultimate, „ „ „	55 „ 65	60 „ 70	70 „ 80	110 „ 130	100 „ 120
Elongation per cent.	15 „ 10	25 „ 16	20 „ 12	14 „ 8	15 „ 10
Reduction of area per cent.	55 „ 45	60 „ 50	60 „ 50	35 „ 20	40 „ 20
Impact (Izod), ft.-lbs.	20 „ 10	50 „ 30	40 „ 20	20 „ 8	15 „ 10

HEAT TREATMENT

Normalising.—820° to 850° C., soak 45 minutes, cool in air. (In this state the steel is too hard for machining.)

Annealing.—After normalising as above, reheat to 650° C., soak 60 to 90 minutes, cool in air.

Treatment I.—830° C., soak 45 minutes, quench in oil or air. Reheat to 650° C., soak 60 minutes, quench in oil.

Treatment II.—830° C., soak 45 minutes, quench in oil or air. Reheat to 550° C., soak 60 minutes, quench in oil.

Treatment III.—830° C., soak 45 minutes, cool in still air, no reheating necessary although heating to 150° C. in oil is advantageous.

Treatment IV.—830° C., soak 45 minutes, quench in oil or air. Reheat to 220° to 250° C. in oil bath, soak 60 minutes, cool in air.

APPLICATIONS

Gears for hard wear (Treatments III. or IV.) also pins and small shafts for hard wear. Connecting rods for aero-engines (Treatments I. or II.), also all parts of great strength and hard wear.

Class No. 8 (Air Hardening)

CHEMICAL COMPOSITION

Carbon	0·32 to 0·37 per cent.
Manganese	0·50 „ 0·70 „
Nickel	3·80 „ 4·30 „
Chromium	1·15 „ 1·40 „
Sulphur	Not more than 0·40 „
Phosphorus	„ „ 0·40 „
Silicon	„ „ 0·20 „

MECHANICAL TESTS

	Annealed.	Treatment I.	Treatment II.	Treatment III.
Yield, tons per square inch ..	50 to 60	95 to 110	90 to 105	50 to 60
Ultimate, „ „ „ ..	55 „ 65	110 „ 120	105 „ 115	55 „ 65
Elongation per cent... ..	18 „ 15	15 „ 9	16 „ 10	30 „ 20
Reduction of area per cent...	55 „ 45	40 „ 20	45 „ 25	60 „ 50
Impact (Izod), ft.-lbs. ..	30 „ 20	20 „ 10	22 „ 12	55 „ 40

HEAT TREATMENTS

Normalising.—820° to 850° C., soak 45 minutes, cool in air. (In this state the steel is too hard for machining.)

Annealing.—After normalising as above, reheat to 650° C., soak 60 to 90 minutes, cool in air. The steel is then machinable.

Treatment I.—830° C., soak 45 minutes, cool in still air. Reheat to 100° C. (boiling water) or 150° C. (oil bath), soak 60 minutes, cool in air.

Treatment II.—830° C., soak 45 minutes, cool in still air. Reheat to 220° to 250° C., in oil bath, soak 60 minutes, cool in air.

Treatment III.—830° C., soak 45 minutes, cool in still air. Reheat to 650° C., soak 60 minutes, quench in oil.

APPLICATIONS

Gears for hard wear (Treatments I. and II.), also other parts subjected to great stress or wear.

Air Hardening.—The steels described under classes 7 and 8 will harden by cooling in air from the hardening temperature and need not be quenched in oil. This is an important feature of these steels, because the slower cooling by air reduces the risk of cracking and distortion to a minimum.

A true air-hardening steel will not harden to any greater extent when quenched in oil or water, and therefore such a proceeding is useless; in fact, it is dangerous because of the intense expansion and contraction stresses set up during the cooling. Even an air blast is unnecessary.

Air-hardening steels require tempering or toughening after hardening just in the same manner as those steels that are hardened by quenching in oil or water. Thus, although a very high tensile strength is obtained in the hardened condition, lower values can be obtained by reheating and, of course, the dynamic strength is improved. Since, however, these steels are most suitable for parts requiring great hardness (or high tensile strength) it is usual to employ them for such parts only, and to use other steels for parts requiring a lower tensile strength. Thus gear wheels and other parts subjected to considerable wear are made often out of air-hardening steel which after being hardened is simply reheated to a temperature of 100° C. (by boiling in water), or perhaps to a slightly higher temperature (in oil), in order to relieve the hardening stresses. The reheating increases the dynamic strength (as shown by the impact test), but if the temperature is raised above 170° C. or 180° C. the hardness begins to fall off, otherwise it is unaffected.

The fact that these steels harden in air is one that has to be considered in connection with machining. Clearly all forgings and drop stampings will be too hard for machining, and all that can be done is to reheat the parts to a temperature of 650° C. just as though they were intended to be toughened. This treatment gives the maximum degree of softness to the steel.

The machining should be carried out to within close limits, leaving only a small grinding allowance to be removed after hardening. This is quite practicable because the distortion caused by cooling the part in air is very little.

Chrome Vanadium Steel

Plain vanadium steels are seldom used commercially. This alloying metal when added to a carbon steel does not appear to exert its full influence until chromium is also added. Thus the useful steels generally contain chromium as well as vanadium.

This class of steel is finding favour against nickel chrome steels among engineers on account of its superior forging qualities, simpler and less delicate heat treatment and, generally speaking, its supposed greater dynamic strength. It has not found a practical use as a case-hardening steel, but is rapidly coming into service for such parts as axles, crankshafts, propeller shafts, piston rods, and connecting rods.

Influence of Vanadium in Conjunction with Chromium.

—Vanadium itself, like the other alloying metals, tends to give a fine and dense structure to steel. It appears to increase the ductility, and to some extent the dynamic strength, and when chromium is also present the improvement becomes very great, the latter apparently acting as an "intensifier." Under these conditions vanadium is a very powerful agent, and comparatively small amounts only are required to effect any change. Thus, in the most commonly used steel the vanadium content only amounts to about 0·20 per cent. (chromium about 1·0 per cent.).

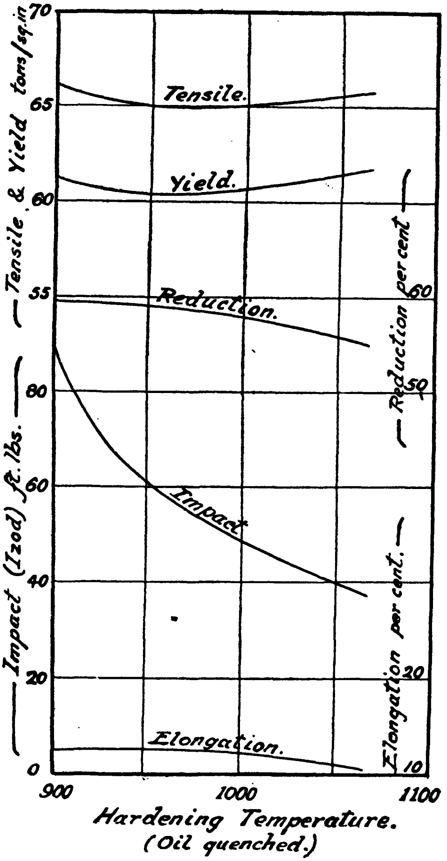


FIG. 170.—Effect of varying the Hardening Temperature on Chrome Vanadium Steel (note the small variation in tensile strength, etc.).

In small amounts like this, it enters into solution in the ferrite, which accounts for the improved ductility and dynamic strength, but in larger amounts it also forms double carbides in a manner similar to chromium. Unlike chromium, however, it does not possess a tendency to coarsen the structure with prolonged heating, and because of this feature the steel is easy and safe to forge and to heat treat.

Forging.—Compared with nickel chrome steels for the same class of work this steel is somewhat more plastic when hot, and therefore forges more easily, and flows more readily in the dies during drop stamping. It has the advantage also in regard to crystal growth in that it is very sluggish (like nickel steels), and can therefore be heated to a high temperature without the risk of a coarse structure resulting.

Heat Treatment.—Like chromium, vanadium raises the critical range temperatures, and therefore the temperatures for heat treatment are generally higher than those for nickel chrome steels. The steel has the same sluggish nature as nickel steel, and therefore requires high temperatures and prolonged heating to effect diffusion throughout the mass. At the same time these higher temperatures and longer soaking times do not produce a large crystal grain structure, an important feature from the commercial standpoint.

There is not the same need for accuracy in heat treatment. This is clearly seen in Fig. 170, which shows the effect of quenching a vanadium steel at various temperatures between 900° C. and 1,100° C. The impact curve, of course, shows the greatest change, but even this is less than with most steels.

Machining Properties.—When properly treated the machining qualities are about the same as nickel steels or low chromium nickel chrome steels, of the same strength.

Classification.—In the usual commercial steels the vanadium content is nearly always the same (tool steels excepted), being about 0·16 to 0·22 per cent., while the chromium varies from 0·75 to 1·40 per cent. The real controlling factor is the carbon content and upon this the different steels can be classified. Thus the groups are as follows :—

Class No.	Carbon.	Chromium.	Vanadium.
1	0·25	0·9	0·18
2	0·35	1·0	0·18
3	0·50	1·0	0·20

Of these the second one is the most common ; the first being a mild type, and the third being intended for springs or hardened gears up to 120 tons per square inch. These steels are dealt with more fully below.

Class No. 1

CHEMICAL COMPOSITION

Carbon	0·22 to 0·30 per cent.
Manganese	0·50 „ 0·80 „
Chromium	0·80 „ 1·10 „
Vanadium	0·16 „ 0·20 „
Sulphur	Not more than 0·05 „
Phosphorus	„ „ 0·05 „
Silicon	„ „ 0·30 „

MECHANICAL TESTS

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch ..	40 to 50	40 to 50	45 to 55
Ultimate, „ „ „ ..	50 „ 60	50 „ 60	55 „ 65
Elongation per cent.	20 „ 10	25 „ 15	22 „ 13
Reduction of area per cent. ..	55 „ 50	65 „ 55	60 „ 50
Impact (Izod), ft.-lbs.	25 „ 15	100 „ 70	80 „ 60

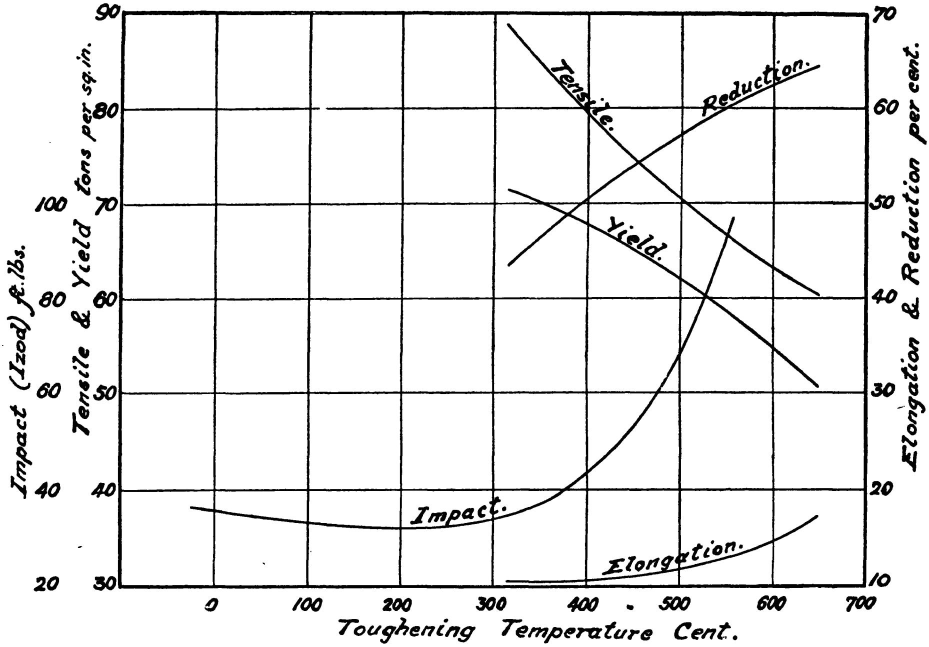


FIG. 171.—Heat Treatment of Chrome Vanadium Steel Class No. 1 (C 0·28, Cr 0·93, V 0·19, Mn 0·73). Hardened in oil at 900° C., and reheated to the toughening temperatures specified and quenched in oil.

HEAT TREATMENTS

Annealing.—Dead soft, 760° to 800° C., soak two hours, cool in boxes or in furnace.

Normalising.—820° to 840° C., soak 45 minutes, cool in air.

Treatment I.—850° C., soak 30 minutes, quench in oil. Reheat to 650° C., soak 45 minutes, quench in oil.

Treatment II.—850° C., soak 30 minutes, quench in oil. Reheat to 550° C., soak 45 minutes, quench in oil.

The curves in Fig. 171 show the effect of varying the toughening or reheating temperature after hardening at 900° C. in oil. Like other alloy steels,

the impact values are very low until the temperature reaches 400° C., although they are higher than in the case of nickel chrome steels.

The composition of this particular sample of steel was :—

Carbon	0·28 per cent.
Manganese	0·73 ,,
Chromium	0·93 ,,
Vanadium	0·19 ,,
Sulphur	0·011 ,,
Phosphorus	0·015 ,,
Silicon	0·28 ,,

Class No. 2

CHEMICAL COMPOSITION

Carbon	0·35 to 0·42 per cent.
Manganese	0·50 ,, 0·80 ,,
Chromium	0·90 ,, 1·20 ,,
Vanadium	0·17 ,, 0·20 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·30 ,,

MECHANICAL TESTS

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch ..	45 to 55	50 to 60	55 to 65
Ultimate, ,, ,, ,, ..	55 ,, 65	60 ,, 70	65 ,, 75
Elongation per cent.	18 ,, 10	20 ,, 14	18 ,, 12
Reduction of area per cent. ..	55 ,, 50	65 ,, 55	60 ,, 50
Impact (Izod), ft.-lbs.	25 ,, 15	90 ,, 70	70 ,, 40

HEAT TREATMENTS

Normalising.—840° to 870° C., soak one hour, cool in air. To improve machinability, reheat to 650° C., soak 45 minutes, quench in water or oil.

Treatment I.—860° C., soak 45 minutes, quench in oil. Reheat to 650°, soak 60 minutes, quench in water or oil.

Treatment II.—860° C., soak 45 minutes, quench in oil. Reheat to 550° C., soak 60 minutes, quench in water or oil.

Class No. 3

CHEMICAL COMPOSITION

Carbon	0·45 to 0·52 per cent.
Manganese	0·50 ,, 0·80 ,,
Chromium	1·0 ,, 1·40 ,,
Vanadium	0·17 ,, 0·22 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·25 ,,

MECHANICAL TESTS

	Annealed.	Treatment I.	Treatment II.
Yield, tons per square inch	50 to 60	60 to 70	70 to 80
Ultimate, ,, ,, ,, ..	60 ,, 70	70 ,, 80	80 ,, 90
Elongation per cent.	18 ,, 14	16 ,, 13	13 ,, 11
Reduction of area per cent. ..	65 ,, 55	60 ,, 50	55 ,, 45
Impact (Izod) ft.-lbs.	60 ,, 40	90 ,, 60	50 ,, 30

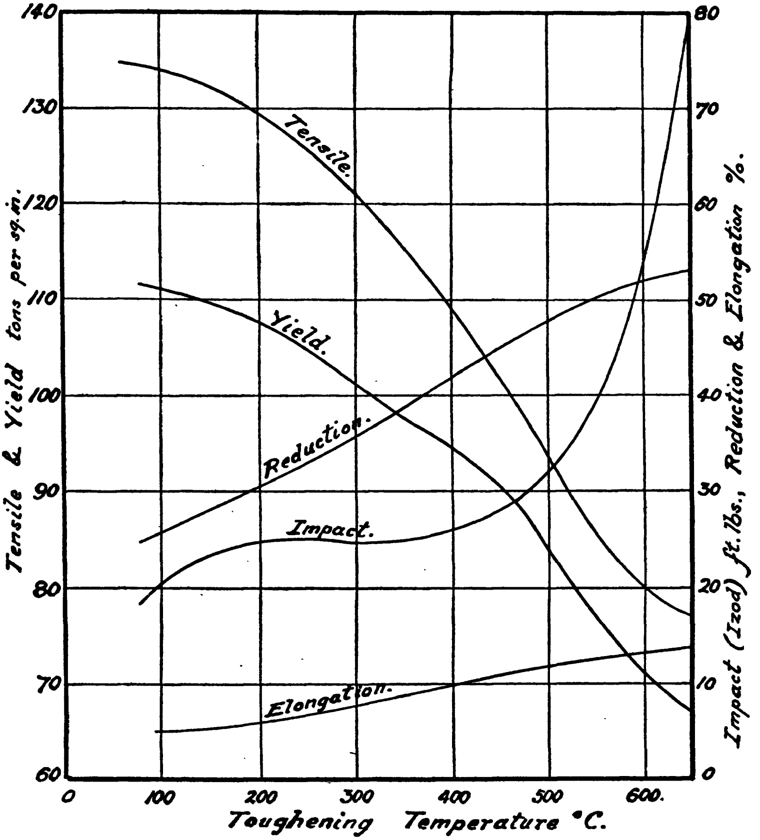


FIG. 172.—Heat Treatment of Chrome Vanadium Steel Class No. 3 (C 0·48, Cr 1·26, V 0·1, Mn 0·85). Test pieces hardened in oil from 900° C., and then reheated to the toughening temperatures specified and quenched in oil.

HEAT TREATMENTS

Annealing.—800° to 840° C., soak two to three hours, cool slowly in boxes or in furnace.

Normalising.—850° to 880° C., soak one hour, cool in air. To improve machinability reheat to 650° to 680° C., soak 45 minutes, quench in water or oil.

Treatment I.—880° C., soak 45 minutes, quench in oil. Reheat to 650° C., soak 60 minutes, quench in water.

Treatment II.—880° C., soak 45 minutes, quench in oil. Reheat to 550° C., soak 60 minutes, quench in water.

The graph, Fig. 172, shows the effect of varying the toughening or reheating temperature on this class of steel. Fig. 173 is given to confirm Fig. 170,

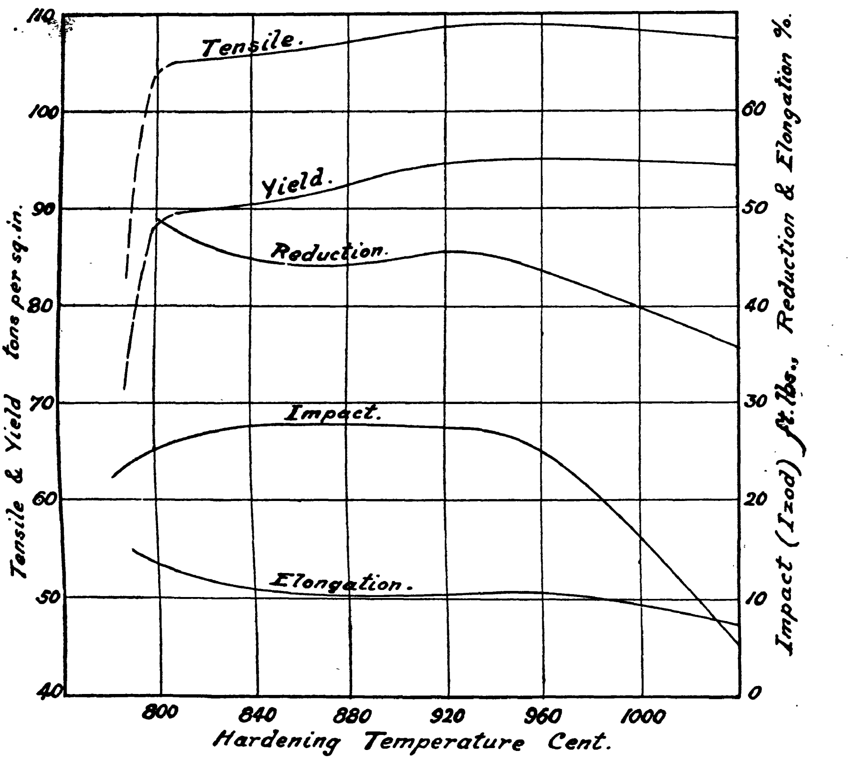


Fig. 173.—Effect of varying the Hardening Temperature on Chrome Vanadium Steel (same composition as Fig. 172). Test pieces hardened at the temperatures specified, quenched in oil, and then reheated to 430° C. and quenched in oil.

and shows how small is the effect of varying the hardening temperature. It will be noticed that the impact value is nearly constant over the range 800° to 950° C.

Special Alloy Steels

There are a few alloy steels which, owing to their high cost, are used only occasionally in constructional work. Such steels generally have a definite application, as, for example, tungsten steel, which is used for permanent magnets in electrical apparatus and for valves in internal combustion engines (aero engines particularly). Other uses, however, are being found, and for this reason a few notes on some of these special steels are given below.

Tungsten Steel.—The addition of tungsten to carbon steel raises the tempering or toughening range of temperatures. A steel in the hardened condition, containing tungsten, must be reheated to a higher temperature than is necessary in the case of a plain carbon steel, in order to convert the martensite into troostite. Thus such a steel when used as a cutting tool will maintain its cutting edge at temperatures much higher than a plain carbon tool steel will do. This, of course, is the basic principle of the high-speed tool steels.

In some instances a small percentage of tungsten is added to a steel in order to increase its tensile strength without reducing its resistance to shock. Thus a small number of springs are made from steel which contains approximately 0·5 per cent. carbon and 0·60 to 0·80 per cent. of tungsten. The heat treatment for such steels is to harden at 850° C. by quenching in oil and then to reheat to 500° C. or 550° C. The tensile strength is then about 80 to 85 tons per sq. in. and the yield point about 58 to 60 tons per sq. in.

Tungsten is added in larger quantities to form various kinds of tool steel, and as much as 18 per cent. is found in some valve steels. In such quantities it confers upon the steel a high tensile strength at high working temperatures (see para. dealing with "Strength of Alloy Steels at Different Temperatures"), and for this reason it is particularly suitable for exhaust valves for internal-combustion engines. The following is a typical specification * for this class of steel :—

CHEMICAL COMPOSITION

Carbon	0·55 to 0·70	per cent.
Silicon	Not more than 0·25	„
Manganese	„ „ 0·25	„
Sulphur	„ „ 0·06	„
Phosphorus	„ „ 0·025	„
Tungsten	15 to 18	„
Chromium	3 to 4	„
Vanadium	Not more than 1·0	„

HEAT TREATMENT

Heat to 950° C., soak for 15 minutes, cool in still air, then reheat carefully to 800° C., soak 30 minutes and cool in air. This treatment will give a tensile strength of 53 to 62 tons per square inch.

According to some test results given by Dr. Leslie Aitchison † the strength of these high tungsten steels at high temperatures is very dependent upon the carbon content (see para. "Strength of Alloy Steels at Different Temperatures").

These steels resist corrosion to a remarkable degree and when made up as valves scale very much less than other steels, with the exception of the nickel chrome steel known as stainless steel.

The forging of the high tungsten steels is a difficult operation and the risk of cracking is considerable. The heat treatment is comparatively simple and the machining properties of the correctly heat-treated steel are good.

Molybdenum Steel.—Apart from the high-speed tool steels molybdenum steels have not found much application in England. In the United States, however, it is produced in comparatively large quantities, and because of its superior qualities there is no doubt but that this steel will find favour here.

---

* Air Board Specification, K. 8, Jan. 1918.

† "Valve Failures and Valve Steels in Internal-combustion Engines," Dr. Leslie Aitchison, *The Automobile Engineer*, Nov. 1919.

Commercially it is not usual to add more than 1·0 per cent. of molybdenum to structural steels. Besides the plain carbon molybdenum steels there are combinations with chromium or nickel and also more complex steels such as chrome nickel molybdenum steel or chrome vanadium molybdenum steel.

With low carbon steels containing molybdenum as the only addition this metal mainly enters into solid solution in the ferrite and adds both strength and ductility to the steel. When more carbon is present and chromium is added, molybdenum probably combines partly with the chromium and carbon forming complex carbides, and the remainder enters into the ferrite.

According to A. H. Hunter,* molybdenum steels, as a class, when compared with other alloy steels having the same tensile strength, give a slightly higher elastic limit, a higher elongation figure, and a much greater reduction of area. Thus these steels are more ductile and tougher than the more common alloy steels. This improvement also shows up under the impact test (Izod), and as a result of comparative tests with some alloy steels the resistance to impact was found to be 34 per cent. greater than the nearest alloy steel. The action of molybdenum is demonstrated by the results shown in the following table :—

MECHANICAL TESTS ON STEEL CONTAINING VARYING PERCENTAGES OF MOLYBDENUM

	Mo 0·20.	Mo 0·40.	Mo 0·76.
Elastic limit, tons per square inch ..	74	73	72
Elongation (in 2-inch), per cent.	13·5	16·6	19·5
Reduction of area, per cent...	52·0	58·4	61·0

The test-pieces contained from 0·28 to 0·36 per cent. carbon, 0·44 to 0·64 per cent. manganese, and 0·70 to 1·04 per cent. chromium. The improvement in ductility is quite pronounced.

For pressed steel parts such as motor frames and shovels, etc., a low carbon steel appears to be the most adaptable. Tests made on such a steel are given herewith.

CHEMICAL COMPOSITION

Carbon	0·164 per cent.
Manganese	0·45 ,,
Molybdenum	0·226 ,,

MECHANICAL TESTS

Thickness of sheet.	Condition.	Elastic Limit, tons per sq. in.	Elongation per cent. (2 inches).
$\frac{5}{32}$ inch	As rolled	24	44·5
$\frac{5}{32}$ inch	Heated to 875° C., quenched in water, reheated to 480° C.	55·5	7·5

Size of test piece, 9 ins. long, 1·5 ins. wide.

The fact that such a steel possesses a high degree of ductility makes it useful

---

* "Molybdenum," paper read before the American Iron and Steel Inst. Summary published in *Metal Industry,* Aug. 26, 1921.

for extremely difficult pressing and forming operations. Also the possibilities of heat treatment, giving the steel a high degree of strength consistent with other desirable qualities, opens the way to a wider application of sheet metal parts.

Of the more complex steels the following have found definite applications :—

CHEMICAL COMPOSITION

	Chrome Nickel Molybdenum.	Chrome Vanadium Molybdenum.
Carbon	0·44	0·38
Manganese	0·42	0·60
Chromium	0·99	1·00
Nickel	2·04	—
Vanadium	—	0·18
Molybdenum	0·36	0·80

The steel containing nickel has been found particularly suitable for gears (oil-hardened) and for other parts requiring great strength. The vanadium steel is more suitable for parts requiring less strength and toughened at the higher temperatures. After hardening and reheating (toughening) to about 540° C., both steels possess a tensile strength greater than 90 tons per sq. in.

Another steel, containing approximately carbon 0·3, nickel 3·0, chromium 0·8, molybdenum 0·4, gave the following test results after a heat treatment consisting of, quenching in oil from 800° C. and then reheating to the temperatures specified.

MECHANICAL TESTS ON CHROME NICKEL MOLYBDENUM STEEL.

Toughening Temperature, °C.	Yield, tons per sq. in.	Ultimate tons per sq. in.	Elongation per cent. in 2 in.	Reduction of area per cent.	Brinell Hardness.
260	104	111	14·0	46·8	455
480	76	84·5	16·0	51·6	363
540	71·5	80	18·5	58·3	344
600	66·5	74	18·5	60·0	328

Molybdenum steels forge quite readily and are not so susceptible to temperature effect as medium carbon and chrome steels.

The heat treatment of these steels is very simple and much less delicate than that of most other steels. A series of test bars * which were hardened at various temperatures between 800° C. and 1,100° C., and all reheated to the same temperature, gave the same yield point, tensile strength, and elongation, the only variation observable being in the reduction of area, which was 62·7 per cent. at 800° C. and 59 per cent. at 1100° C. No figures are quoted for the dynamic strength, and as this is a most important property it is unfortunate that this test was omitted.

Manganese Steels.—This type of alloy steel is noted for its wear-resisting properties, and although its behaviour under heat treatment has been perplexing, this difficulty is disappearing in face of a more perfect knowledge of

---

* "Molybdenum and its Properties," *Metal Industry*, July 15, 1921.

the metallurgical factors and in consequence manganese steel is now finding an extending field of application.

The steels in use may be divided into two groups : those containing up to 2 per cent. manganese and those containing from about 10 per cent. up to 15 per cent. manganese. These two groups are distinctly different and the qualities of the one must not be confused with those of the other. For convenience these steels will be referred to as Low manganese steel and High manganese steel respectively.

Low Manganese Steel.—Manganese steels containing up to 2 per cent. of manganese may be regarded as possible substitutes for nickel and nickel chrome alloy steels in mechanical constructional work. So far they have not come into general favour for such work, a fact that is probably due to a widespread impression that such steels are brittle. If the steel is made properly and heat treated correctly very good results are obtained, there being no brittleness.

The addition of manganese to steel causes an increase in the tensile strength, which is due to the formation of the double carbide of manganese and iron. Thus the addition of each 0·1 per cent. of manganese increases the tensile strength of the steel (when heat treated) by 0·6 to 0·9 ton per sq. in.* In this respect manganese exerts a much greater influence than nickel.

The operation of forging these steels requires greater care than the corresponding plain carbon steels, and it is essential that the forgings should be normalised or annealed.

The heat treatment of low manganese steels is very similar to that adopted for nickel or nickel chrome steels. The effect of manganese, however, in lowering the critical range (on heating) is much greater than that of nickel and amounts to about 3° C. for each 0·1 per cent. addition of manganese. Manganese appears to have the effect of increasing the sensitiveness of the steel to abuse of heat-treatment methods. Rolled bars will often crack when quenched in water. This difficulty to some extent is due to imperfect manufacture of the steel, but much depends on the time allowed for soaking when at the correct hardening temperature. It is important that this should be ample in order that diffusion may be complete.

High Manganese Steels.—The predominating quality of high manganese steel is its resistance to wear by abrasion. It is this quality that has brought this steel into such extensive use for railway and tramway trackwork, an application which is now definitely established. Other important applications are colliery tub wheels, crusher jaws, various components for dredgers, excavators and steam shovels, also liners for tube mills, parts for ball mills, and crushing rolls. In regard to railway trackwork it is interesting to record that, at an important junction on one of the London railways, ordinary steel rails having a useful life of seven to nine months were replaced with manganese steel rails,† which at the time of writing (May, 1922) had already lasted nine and a half years and, according to the chief engineer, were likely to last at least four years more.

The amount of manganese found in these steels varies from 10 to 15 per cent., but the usual amount is about 11 to 12 per cent. The carbon content is

---

* Bullens, " Steel and its Heat Treatment."

† Steel supplied by Messrs. Edgar Allen & Co., Ltd., to whom acknowledgment is given for this and other valuable data.

between 1 and 1·5 per cent. Now the retarding influence of manganese on the change from austenite to martensite is so great (see p. 128), that the change does not take place at all in steels containing the amounts referred to above. Thus this steel is permanently hard and cannot be machined, no matter what treatment it is given. This fact, of course, somewhat limits its use, although it is possible in some instances to overcome the drawback, *e.g.* gears, pinions, and other rotating parts can be fitted with a mild steel bush (or hub), which is placed in the mould and cast in position.

If the percentage of manganese is reduced there is a risk of martensite forming, and as this is extremely brittle and weak, steels containing between 2 and 8 per cent. manganese are of no use commercially (even after heat treatment).

The composition of manganese steel rails may be specified as follows :—

Carbon	1·00 to 1·25	per cent.
Manganese	11 „ 12·5	„
Sulphur	under 0·06	„
Phosphorus	„ 0·08	„
Silicon	0·25 to 0·40	„

Sometimes a small proportion of chromium is added to increase the elastic limit, but as this element has a direct effect on the ductility, reducing the elongation figure, it is limited to about 0·5 per cent.

The structure of this steel is capable of profound modification by varying the rate of cooling. The proportions of manganese and carbon, the formation of the double carbide, the extent to which this compound forms and the shape or condition it assumes are all factors which govern the behaviour of the steel in use. Thus the method of casting and the size of the casting directly affect the mechanical properties. Further the forging, rolling, and other mechanical work influences the qualities of the steel, and to obtain the best results it becomes necessary to heat treat the material before use.

In the cast condition the structure is very coarse, the crystal grains being often exceedingly large. This, of course, is very unsatisfactory for most purposes and therefore it is important to adopt some treatment which will reduce the grain size.

An annealing treatment will effect a change in the grain size, but unfortunately it causes the separation of the double carbide (from the austenite) to an extent which is very injurious to the steel. This carbide during the slow cooling is rejected by the austenite grains and forms weak brittle membranes around these grains, together with spines or needles running across the grains.

The heat treatment of these high manganese steels therefore must not only refine the grain structure, but must control the behaviour of the carbide in its relationship to austenite.

Any treatment involving slow cooling is fatal, the effect on the elongation figure being to reduce it to a low percentage. Thus, to prevent the separation of the carbide rapid cooling must be resorted to, preferably by quenching in water. The absorption of the free carbide (by the austenite) that already exists in the casting is a slow process and to accelerate it and also bring about diffusion it is necessary to heat the steel to a high temperature. Usually temperatures between 1,000° C. and 1,100° C. are employed. The mechanical properties of the steel depend mainly on the absorption of the carbide and therefore the temperature is governed by the condition of the structure prior to treatment and the final mechanical requirements.

The tensile strength of the average commercial manganese steel in the treated condition, but not rolled or forged (*i.e.* castings), is about 36 to 38 tons per sq. in., with an elongation of about 30 per cent. The forged or rolled material may have a tensile strength as high as 65 tons per sq. in., but more usually it is about 55 tons per sq. in., with an elongation of not less than 40 per cent. The ductility is of a high order, and is a most valuable property, but, as explained above, this feature depends very much on the rate of cooling after treatment. The ratio of the elastic limit to the ultimate tensile strength is about 5·5 to 10, which means that under heavy shocks the steel has a tendency to flow or spread because of this low elastic ratio. This low elastic limit is valuable in some instances because of the great disparity between the point at which, under load, the steel first takes a permanent set and the point at which it eventually breaks.

The comparatively low tensile strength (55 tons per sq. in.) and, what is more striking, the low Brinell hardness figure (about 200), lead to the belief that this steel will machine, but, as a matter of fact, it appears that any attempt to cut it simply increases its hardness and makes the operation impossible. The cause of this is not fully understood, but whatever it may be, one thing is certain and that is this peculiarity of manganese steels accounts for their extraordinary wear-resisting properties. It seems that as soon as the steel is subjected to any deformation process (while cold), such as crushing or rolling, the skin (or surface) immediately hardens. This is demonstrated by a series of tests * made by means of the Du Nord dynamic hardness testing machine, the results of which are given below :—

DYNAMIC HARDNESS TESTS OF MANGANESE STEEL TRAMWAY CROSSINGS, CARRIED OUT IN POSITION IN THE STREET TO DETERMINE THE SKIN-HARDENING DUE TO WEAR.

Piece tested.	Dynamic hardness.	Per cent. increase of hardness.
Crossing No. 1.		
Unworn surface	32	—
Worn surface	65	103 %
Crossing No. 2.		
Unworn surface	27	—
Worn surface..	57	111 %

DYNAMIC HARDNESS TESTS OF ROLLED "IMPERIAL" MANGANESE STEEL RAILWAY RAILS TO DETERMINE THE PERCENTAGE INCREASE OF HARDNESS DUE TO WEAR.

Condition of rail	Dynamic hardness.	Per cent. increase of hardness.
New	36	—
Worn	70	94·4 %

The rail subjected to traffic was only slightly worn, wheel contact having scarcely covered the width of the tread.

In all cases the increase in hardness is remarkable, amounting to about 107 per cent. in the case of the castings and about 94 per cent. in the case of the rolled material.

---

* By kind permission of Messrs. Edgar Allen & Co., Ltd., Sheffield.

Strength of Alloy Steels at Different Temperatures

The strength of steel at the higher temperatures is sometimes of considerable importance, but the data available is extremely little. A series of tests on alloy steels are described by Dr. L. Aitchison,* and the results of these form the basis of the following notes.

Nickel Steel.—Two samples were tested after a heat treatment consisting of hardening in oil from 830° C. and tempering at 600° C. The results are tabulated below :—

Composition.				Ultimate Tensile, tons per sq. in.	
C.	Ni.	Cr.	Mn.	700° C.	900° C.
0·29	3·22	0·08	0·43	9·4	3·9
0·60	1·99	0·35	0·95	11·5	4·5

Nickel Chrome Steel.—Some results obtained from four steels of different compositions are given herewith :—

Composition.				Ultimate Tensile, tons per sq. in.				
C.	Ni.	Cr.	Mn.	650° C.	750° C.	850° C.	900° C.	950° C.
0·28	2·80	1·34	0·46	15·9	8·5	5·4	4·6	—
0·29	3·90	1·14	0·46	14·4	8·6	5·1	4·2	3·5
0·37	2·76	0·64	0·44	15·0	9·0	5·0	4·5	3·6
0·24	4·47	1·02	0·34	12·8	8·4	5·7	4·4	3·3

The above steels were heat-treated before testing as follows :—The first was hardened in oil from 820° C. and tempered at 630° C., the second hardened in air from 820° C., tempered at 600° C., the third, hardened in oil from 820° C. and tempered at 560° C., and the fourth was tested in the forged state.

Chrome Steel.—The following results were obtained with low chrome steels :—

Composition.				Ultimate Tensile, tons per sq. in.	
C.	Ni.	Cr.	Mn.	700° C.	900° C.
0·35	—	2·75	0·43	8·5	4·2
0·67	—	3·13	0·51	11·7	4·9

The above chrome steels were hardened in oil from 830° C. and tempered at 600° C.

Special Steels.—All the steels referred to above possess approximately the same tensile strength at 900° C. (*i.e.* about 4 to 5 tons per sq. in.), and for

---

* " Valve Failures and Valve Steels in Internal Combustion Engines," by Dr. Leslie Aitchison, D.Met., A.Sc., S.I.C., *The Automobile Engineer*, Nov. 1919.

this and other reasons a number of special alloy steels have been developed. These are tabulated, together with their tensile strengths at high temperatures, below :—

HIGH CHROMIUM SERIES

Composition.				Ultimate Tensile, tons per sq. in.					
C.	Cr.	Ni.	Si.	20° C	650° C.	750° C.	800° C.	900° C.	1000° C.
0·37	12·37	0·15	0·25	43·4	13·6	—	6·5	6·5	—
1·04	10·42	—	0·15	66·5	21·5	—	7·5	7·5	—
0·96	13·1	0·45	0·17	53·8	—	14·0	7·3	7·3	4·1
1·08	13·1	0·50	0·17	56·6	—	15·2	8·5	7·4	4·0
1·18	13·1	0·45	0·10	58·2	—	13·2	7·9	7·5	3·8
1·42	13·1	0·44	0·35	59·7	—	13·3	7·9	7·6	3·9
0·36	11·2	0·23	0·16	43·0	—	12·1	6·6	4·8	4·0

The above steels were heat treated before testing. The first two were hardened in air from 880° C., and tempered at 700° C. The remaining five were hardened in air from 900° C. and tempered at 700° C.

MEDIUM CHROMIUM SERIES

Composition.				Ultimate Tensile, tons per sq. in.		
C.	Cr.	Ni.	Si.	20° C.	750° C.	900° C.
0·54	6·3	0·43	0·14	59·5	17·0	7·0
0·55	7·1	0·50	0·75	57·5	14·9	7·2
0·56	6·6	3·08	0·17	58·1	17·8	7·6
1·09	6·3	0·42	0·19	72·5	18·4	7·5
1·08	6·7	0·51	0·56	69·5	21·0	7·3
1·11	5·8	2·96	0·19	56·6	18·2	6·5

This series of steels were hardened in oil from 820° C., and tempered at 650° C.

TUNGSTEN SERIES

Composition.					Ultimate tensile, tons per sq. in.				
C.	Mn.	W.	Cr.	V.	20° C.	650° C.	700° C.	800° C.	900° C.
0·60	0·08	17·44	3·64	1·00	48·6	—	17·7	—	8·3
0·60	0·09	16·37	3·86	0·06	52·5	—	17·0	—	8·95
0·67	0·09	13·56	3·70	0·10	50·9	—	15·9	—	7·65
0·45	0·07	13·08	3·62	—	47·8	—	14·75	—	7·45
0·45	0·08	15·73	3·75	—	44·6	—	15·5	—	6·3
0·47	0·07	12·68	3·62	0·80	45·5	—	16·85	—	7·25
0·71	0·05	17·30	3·86	0·75	58·4	24·7	—	10·3	8·8
0·43	0·37	12·10	3·19	—	50·0	20·1	—	7·1	8·2

The tungsten steels were tested after refining at 950° C., and tempering at 800° C.

The dynamic strength increases slightly as the temperature is raised to about 600° C. or 700° C., and then more rapidly as the temperature is raised to 900° C. This applies to both the chromium and tungsten steels.

CHAPTER XIII

CASE-HARDENING STEELS

THE process of case-hardening is, speaking broadly, adopted when a hard wearing surface is desired combined with toughness and the ability to withstand shock.

The steel used, therefore, must be capable of absorbing the necessary carbon during the carburising process at an efficient rate and to the depth of penetration required, and also give the desired tensile strength with the highest possible dynamic strength.

The first requirement (*i.e.* a hard surface) can be obtained with almost any steel provided it has been carburised (or cemented) correctly and thus contains the necessary carbon to produce the hardness. Mild steels and medium carbon steels will carburise with equal facility and both produce a good hard " case." So will nickel and nickel chrome alloy steels. The rate and depth of penetration will, however, vary with different classes of steel, and these factors will, in some instances require taking into account. The chief point is that no great difference exists between the different steels so far as actual carburising and producing a hard surface is concerned.

The second requirement, *i.e.* that of obtaining a tough centre or core, depends entirely on the steel used. and it is for this reason that nearly all tests are made on the core of the case-hardened steel, and that specifications issued relate to this portion. The core, in fact, is really the actual part that must be capable of resisting the various stresses that are imposed : the hardened case is there simply to withstand abrasion or wear, and should not be considered as of any assistance in withstanding the stresses referred to. That the case does increase the strength is well known, but as its dynamic strength is almost nil this increase should not be depended upon.

Thus the requirements for the core generally decide what kind of steel shall be chosen, and the case is nearly always a secondary consideration.

At the same time the quality of the case may be of special importance both as to hardness and thickness. Then the requirements of the core may have to take second place, and a steel used which will give the maximum hardness or depth of penetration. For example, a nickel steel retards the carbon penetration, and does not produce so hard a case (with the ordinary methods) as plain carbon steel, hence to obtain a very hard case or one of great thickness a plain carbon steel will give better results. For this reason it may be necessary or desirable that a medium carbon steel should be used.

Selection of Steel.—The core, as explained already, generally governs what kind of steel should be used, but the case may often influence the choice.

A general impression of the qualities of some of the different steels in use can be obtained from the following list :—

SOME CASE-HARDENING STEELS AND THEIR APPROXIMATE PROPERTIES

Kind of Steel.	Core.	Case.
Carbon 0·10 per cent. .. .. 0·08 to 0·14 per cent.	Requires careful heat treatment, close temperature limits. Tensile max. 30 tons per sq. in. Impact (Izod), 50 to 70 ft.-lbs.	Very hard. Scleroscope value, 80 to 90. Cracks easily under heavy load due to soft core.
Carbon 0·15 per cent. .. .. 0·14 to 0·18 per cent.	Requires careful heat treatment, close temperature limits. Tensile max. 38 tons per sq. in. Impact (Izod), 50 to 80 ft.-lbs.	Very hard. Scleroscope value, 80 to 90.
Nickel 2 per cent. .. .. Ni 2 to 2·5 per cent. C 0·10 to 0·15 per cent.	Heat treatment very simple, wide temperature limits, oil quenching. Tensile max. 40 tons per sq. in. Impact (Izod), 70 to 100 ft.-lbs.	Hard. Scleroscope value, 75 to 85. Case does not peel so readily as with carbon steel.
Nickel 2·5 per cent. .. .. Ni 2·5 to 3·0 per cent. C 0·10 to 0·15 per cent.	Heat treatment very simple, wide temperature limits, oil quenching. Tensile max. 45 tons per sq. in. Impact (Izod), 50 to 80 ft.-lbs.	Hard. Scleroscope value, 75 to 85. Case does not peel so readily as with carbon steels.
Nickel 5 to 6 per cent. .. Ni 4·5 to 6·0 per cent. C 0·10 to 0·15 per cent.	Heat treatment not so simple as last but better than carbon steel. Temperature limits still fairly wide. Oil quenching. Tensile max. 55 tons per sq. in. Impact (Izod), 30 to 60 ft.-lbs.	Hard. Scleroscope value, 70 to 80.
Nickel Chrome .. .. Ni 1·8 to 2·5 per cent. Cr 0·6 to 1·0 per cent. C 0·10 to 0·15 per cent.	Heat treatment simple. Temperature limits not so wide as nickel steel but wider than carbon steel. Oil quenching. Tensile max. 60 tons per sq. in. Impact (Izod), 30 to 50 ft.-lbs.	Hard. Sclersocope value, 75 to 85.
Nickel Chrome .. .. .. Ni 3·0 to 3·5 per cent. Cr 1·0 to 1·4 per cent. C 0·10 to 0·15 per cent.	Heat treatment less easy than above. Temperature limits about same as carbon steel. Oil quenching. Tensile max. 70 tons per sq. in. Impact (Izod), 25 to 40 ft.-lbs.	Very hard. Scleroscope value 80 to 90.
Nickel Chrome .. .. Ni 4·0 to 4·5 per cent. Cr 1·2 to 1·6 per cent. C 0·10 to 0·15 per cent.	Heat treatment and temperature limits about same as above. Oil quenching. Tensile max. 80 tons per sq. in. Impact (Izod), 20 to 30 ft.-lbs.	Very hard. Scleroscope value 85 to 95.

This list, which is incomplete, should only be regarded as a rough guide in selecting a steel; there are many other factors which must be considered, and cost is not the least important of these. The more important points are dealt with in the following pages.

Carbon Content.—The carbon content of the steel is of paramount importance since it is this element that is mainly responsible for brittleness. The quenching treatments subsequent to carburising intensify the brittleness, which becomes very serious when the carbon exceeds 0·25 per cent.

Some authorities consider that 0·25 per cent. carbon for a plain carbon steel is satisfactory, and that in the case of alloy steels such as nickel chrome case-hardening steels it is permissible to have a carbon content as high as 0·3 per cent. While there is no doubt that steels containing such a high percentage of carbon are used, and can be heat treated successfully, there is certainly no doubt that their use cannot be considered desirable from a commercial point of view. Certain work may require great strength in the core and high carbon steels may be necessary to meet this requirement, but it is always better to secure this greater strength by the addition of nickel or nickel and chromium instead of carbon. Parts that require straightening after treatment, such as spindles, camshafts, etc., will crack and break quite easily if the core contains carbon to the extent quoted above.

In the other direction low carbon steels mean weak cores and cause difficulty in machining previous to treatment, the material tending to tear badly, thus producing a rough surface conducive to hardening cracks in the case, and also requiring more grinding to obtain a smooth finish on the hardened surface.

As a general rule no case-hardening steel should contain more than 0·2 per cent. carbon, while it is best to keep within the following ranges :—

Plain carbon steel	0·12 to 0·18 per cent. carbon.
Alloy steels	0·08 ,, 0·15 ,, ,,

An exception to the above rule can be made in the case of work which is only subjected to a crushing load, such as ball and roller races, where it is important that the "case" should be supported by a core which is moderately hard.

The carbon content can then be raised to 0·3 per cent., or even to 0·4 per cent. Such "high carbon" steels then require careful heat treatment to reduce the factor of brittleness to the minimum.

Where mass production is under consideration, the carbon content becomes the most important consideration because it is essential to rapid and continuous working that standard fixed temperatures should be adopted for heat treating the parts. With plain carbon steel a change of 0·01 per cent. carbon means a change of 3·5° C. in the upper critical range, and as it is quite usual to find the steel makers supplying steel ranging from 0·14 to 0·24 per cent., it will be necessary to vary the refining temperature (*i.e.* after carburising) by 35° C. at least to obtain a good core. This variation cannot be neglected as the quality of the core is closely dependent on the temperature of refining, and in practice only permits a tolerance of about 10° C. In fact, with the exception of tool steel, the refining and hardening of carburised mild carbon steel demands closer attention than any other heat treatment.

Thus steps should be taken to ensure a supply of steel which always possesses the same carbon content, allowing a tolerance of 0·04 per cent.

The tensile strength of the core of a plain carbon steel when correctly heat treated will be approximately 35 tons per square inch for a steel containing 0·15 per cent. carbon and 0·75 per cent. manganese. A change of 0·01 per cent. in the carbon will account for a change of approximately 1·5 tons per square inch in the tensile strength.

Manganese Content.—This element tends to increase brittleness both in the core and in the case, particularly in the latter, as this becomes a high carbon steel and is much more sensitive to rapid cooling. A high manganese content increases the brittleness produced by the long heating process of carburising and retards the good effects of the subsequent refining treatment.

With plain carbon steels it is the usual British practice to allow about 0·8 per cent. manganese and sometimes 1·0 per cent., while in America the manganese content is kept low, about 0·35 per cent. as a maximum Providing the carbon content is reasonably low the British practice is not dangerous so far as the core is concerned, but it is advisable to keep the manganese down to 0·6 per cent. owing to the case, which is liable to crack during quenching and also during the subsequent grinding operation if the manganese exceeds this amount. Manganese increases the tensile strength of the core.

With alloy steels the manganese must be kept down to about 0·4 per cent. and lower.

Manganese, on the other hand, increases the hardness of the case and to some extent the depth to which the hardening effect of quenching penetrates, hence it is of some service where extreme hardness is vital.

In commercial practice, however, it is usual to employ plain carbon steel containing about 0·75 per cent. manganese, and with ordinary care in quenching and grinding, the risk of developing cracks is not very serious. With alloy steels, however, the manganese should not exceed 0·4 per cent.

Sulphur.—This element if present in large amount will cause trouble during forging and stamping due to the " red shortness " it imparts to the steel. If sufficient manganese is present the effect on cold metal is not great, although it exists as a separate body (manganese sulphide) and therefore breaks the continuity of the structure.

It should not exceed 0·07 per cent. in any steel, and should be as low as 0·05 per cent. in alloy steels.

Sulphur appears to have a softening influence and will tend to prevent the case attaining the hardness desired, but as a rule the steels usually supplied do not contain enough to cause trouble in this manner. Sulphur may, however, enter the steel from the carburising compound and so give trouble, such as soft spots, etc.

Phosphorus.—The tendency of this element is to produce brittleness in both case and core. If present in large amount there is usually associated with it other troubles such as segregation and banded structures, which may cause peeling of the case during quenching and grinding.

It is, however, the practice of some firms to use a high phosphorus steel on account of the improved machining qualities which result from its presence. Thus such steels will contain as much as 0·16 per cent. of phosphorus. This practice is fraught with danger, and can only be adopted for certain unimportant parts where the depth of case is small and no grinding follows the case-hardening operation.

The phosphorus should not exceed 0·06 per cent. for carbon steels, or 0·05 per cent. for alloy steels, although it is common to employ steels containing up to 0·07 per cent.

Silicon.—The amount of silicon found in most steels has little or no influence on its properties, and its presence therefore need not be seriously considered. The usual amounts found are from 0·1 to 0·2 per cent. The maximum limit should be about 0·25 per cent. in either carbon or alloy steels.

Slag.—When present in small amounts, slag has little influence on case-hardening steels, and may in fact impart increased dynamic strength to it. It is actually added or allowed to remain in the steel to meet the demand for a steel which will give a high impact test value. This effect is due to the fact that the slag, which is insoluble in the steel, is rolled out with it and finally takes the form of streaks or layers separating the metal. These streaks, of course, run in the direction of rolling or forging, and tend to prevent a crack (if it should start) proceeding across this direction. Now, as it is usual to machine the impact test piece so that its length is the direction of rolling or drawing, the slag exerts its greatest influence in preventing the rupture or crack taking place. This is shown by Fig. 80, on p. 125, where this effect is fully explained.

Although this is the case so long as the test is carried out in this manner, it is found that the slag confers weakness in the direction of rolling, a crack easily travelling along the slag streak, and a transverse test piece (*i.e.* across the direction of rolling) would give a very low value. A good steel containing a small amount of slag should give an impact value taken across the bar of about twice that taken along the bar, *i.e.* the resistance to shock or rupture across the direction of rolling should be twice that along the direction of rolling.

However, apart from the consideration of the dynamic strength, the presence of slag has an important bearing on the carburised surface. The case of a case-hardened part may be considered as consisting of a number of layers of steel having different carbon contents, and therefore tending to behave differently so far as internal stresses are concerned. Should a layer or streak of slag happen to be separating two layers of the case, the cohesion is lost and the case will peel or flake off. This is a great source of danger, especially when the slag streak runs out to the surface as is often the case in forgings; after machining, the tongue of high carbon steel so produced breaks away at once and peels off.

Raw Material.—The steel is usually supplied in the form of billets, black rolled bars, or drawn bars, all of various sections to suit the requirements of the user. The billet material is required for forgings and stampings, and as a rule the steel makers do not take any special pains over the quality of the structure of the steel, because of the expected forging operation. The black rolled bar is also generally employed for forging and stamping, but may in some cases be machined direct into the parts for which it is intended. Drawn bar is, of course, machined direct.

All three forms of the material are likely to suffer from one or more of the following defects, and it is always advisable to inspect the steel on arrival for these.

Defects Found in Case-hardening Steels

(1) Roaks, laps, and other surface cracks.
(2) Segregation, lamination, and seams.
(3) Slag inclusions—fibrous structure.

The first group are surface defects due to a great extent to the rolling and drawing operations. These are more common in alloy steels than in carbon steels, and are often so serious that billet and black rolled bars are rendered useless for stamping and forging.

The cracks or flaws generally run lengthwise, *i.e.* in the direction of rolling, and although they may not be deep they will open out, during stamping, to an alarming extent, and to such a depth that they still exist in the part after machining. Laps are not common and soon show up. They are caused by one portion of the metal being forced over another portion during rolling, the two portions not welding together because of the scale on their surfaces. They take the form of tongues of metal lying flush with the surface of the billet.

In drawn steel, it is common to find very fine so-called " hair lines " or " hair cracks " running for a considerable distance and penetrating only to a slight depth, although in some instances these cracks may go as deep as 2 mm. The surface may also be pitted with small impressions due to the incomplete removal of the scale before the final drawing operation ; the scale being pressed into the metal.

The above defects can be seen, and bad billets or bars thrown out before any work is done to them, but in the case of the second and third groups of defects discovery is not so easy or certain. Yet they influence the quality of the case-hardened work to a very great extent, more so than if the steel was intended for ordinary heat treatment such as hardening and toughening. The freedom from defects due to segregation and slag inclusions, etc., is more important with case-hardening steels than with any other except tool steels. Thus these steels should be examined for such defects and complaints made to the makers when the steel appears charged with much slag or possesses a strongly marked banded structure. The presence of much slag can be quickly discovered by breaking a piece of the bar and noting the quality of the fracture. A coarse fibrous fracture at once indicates excessive slag inclusion. Seamy steel is also discovered in this manner, the steel appearing to separate into different layers, the inside surface of which may be slightly discoloured. This latter defect is due to gas inclusions, the blowhole in the original ingot having been drawn out during rolling, and the metal not having welded together.

Segregation and the laminated or banded structures that result from it are not easily seen except under the microscope. Some examples of these defects are shown on pp. 159–161, where these and the other defects mentioned above are dealt with in greater detail.

The effect of slag in causing the case to peel off is already referred to in the paragraph on slag. The same trouble is also likely to occur with banded steel Such banded structures are often found in nickel steels and in the other alloy steels, but not so often in carbon steels.

Forging.—The forging and stamping of plain carbon case-hardening steels presents no difficulty, but with nickel and nickel chrome steels this operation requires more care and consideration. In the case of nickel steels containing up to 3·0 per cent. nickel the forging and stamping properties are about the same as with carbon steel. When, however, the nickel content is about 5 or 6 per cent. the steel requires careful heating and stamping. These high nickel steels are often unsound and possess many surface cracks which open out during forging.

Nickel chrome steels are more difficult than nickel steels to forge, the addition of chromium appearing to render the steel less plastic. The preliminary heating requires careful attention and heavier blows are necessary in order to work the steel into its final form. These steels, like nickel steel, often develop fissures due to surface cracks or roaks and must therefore receive careful inspection.

The forging temperatures of both carbon and alloy steels are greatly neglected by the drop stamper, who in his endeavour to shape the pieces with as few blows as possible will heat the billets to very high temperatures. This common mistake is dealt with in Chapter X, but for convenience the following limits for the forging temperatures are given here.

Forging Heats for Case-hardening Steels

	Temperature.
Carbon steel (0·10 to 0·20)	950° to 1,100° C.
Nickel steel (3 per cent. Ni)	900° ,, 1,150° C.
,, ,, (5 to 6 per cent. Ni)	1,000° ,, 1,200° C.
Nickel chrome steel (2 per cent. Ni, 0·8 per cent. Cr)	950° ,, 1,100° C.
,, ,, (2·5 per cent. Ni, 1 per cent. Cr)	950° ,, 1,100° C.
,, ,, (4·5 per cent. Ni, 1·5 per cent. Cr)°	1,000° ,, 1,150° C.

The remarks concerning the heating of alloy steels also apply to the cooling after forging. This, especially with the high nickel chrome steels, should be carried out in a sheltered spot on a bed of ashes.

In general, nickel steel can be finished at a higher forging temperature than carbon steel because the structure does not coarsen to the same extent and the forgings are therefore in a better state. For this reason nickel steel should be favoured since the subsequent heat treatment becomes an easier operation.

Machining Properties.—The machining properties of case-hardened steel should be considered both in the normal or annealed state and in the hardened state. This latter state must be considered because portions of the core may have to be machined after the case-hardening operation is finished.

It is also necessary to consider the machining quality of the steel after undergoing the carburising operation. This is essential as many parts receive further machining between this operation and the final hardening treatment.

Then the machining quality of the carburised surface (*i.e.* containing the high carbon) is also important because in many cases those portions which are to remain soft in the finished part have an excess amount of metal left on, which is then machined off after carburising, leaving a space free of any case. This operation of machining must, of course, involve the removal of the carburised zone.

Throughout all these conditions (excepting the final hardened state) the possibility of annealing the work should be considered because the saving in machining times, and wear and tear of the tools, may more than compensate for the additional expense of the annealing process.

The machining properties of a steel are more or less correlated to the hardness as expressed by the Brinell machine. This quick and easy test forms a valuable guide and should be used more often than at present to settle the very important question of the cutting properties of materials. The following table is given as an approximate guide as to the Brinell hardness of different case-hardening steels at the various stages in its handling and treatment :—

Class of Steel.	Before Carburising.		Core after Carburising.			Case.	
	Normalised.	Normalised and Annealed.	As removed from Box.	Carburised and Annealed.	Refined and Hardened.	As removed from Box.	Annealed.
Carbon 0·10 per cent.	95 6·0 mm.	—	90 6·15 mm.	—	118 5·45 mm.	217 4·1 mm.	—
Carbon 0·18 per cent.	99 5·9 mm.	—	90 6·15 mm.	—	156 4·8 mm.	217 4·1 mm.	—
Nickel Ni 2·5 C 0·15	114 5·55 mm.	105 5·75 mm.	114 5·55 mm.	105 5·75 mm.	166 4·65 mm.	262 3·75 mm.	235 3·95 mm.
Nickel Ni 3·0 C 0·15	131 5·20 mm.	114 5·55 mm.	137 5·10 mm.	114 5·55 mm.	196 4·30 mm.	268 3·60 mm.	235 3·95 mm.
Nickel Ni 5·0 C 0·15	156 4·80 mm.	137 5·10 mm.	166 4·65 mm.	149 4·90 mm.	235 3·95 mm.	311 3·45 mm.	262 3·75 mm.
Nickel Ni 6·0 C 0·15	179 4·50 mm.	156 4·80 mm.	187 4·40 mm.	166 4·65 mm.	262 3·75 mm.	311 3·45 mm.	268 3·60 mm.
Nickel Chrome Ni 2·0 Cr 0·8 C 0·15	149 4·90 mm.	137 5·10 mm.	179 4·50 mm.	149 3·90 mm.	262 3·75 mm.	311 3·45 mm.	262 3·75 mm.
Nickel Chrome Ni 3·0 Cr 0·6 C 0·15	183 4·45 mm.	156 4·80 mm.	196 4·30 mm.	183 4·45 mm.	311 3·45 mm.	314 3·20 mm.	268 3·60 mm.
Nickel Chrome Ni 3·5 Cr 1·0 C 0·15	196 4·30 mm.	183 4·45 mm.	235 3·95 mm.	207 4·20 mm.	332 3·35 mm.	418 3·0 mm.	268 3·60 mm.
Nickel Chrome Ni 4·5 Cr 1·5 C 0·15	228 4·0 mm.	196 4·30 mm.	269 3·70 mm.	235 3·95 mm.	364 3·20 mm.	460 2·85 mm.	311 3·45 mm.

It will be noticed that hardness numbers are given for the alloy steels while in the "normalised and annealed" condition, before carburising. It would appear unnecessary to anneal after normalising, but in practice it will be found that in many cases, especially with the high nickel and the nickel chrome steels, hard spots are found in the steel after normalising, and although these do not alter the average Brinell hardness they have a considerable effect on the tools, particularly during such delicate machining as gear cutting, profiling, or drilling. This annealing process is quite simple (see Chapter X, "Annealing some Alloy Steels"), and consists only of heating the parts up to 650° C., soaking 30 mins., and then cooling in air. It applies equally well to all the steels mentioned.

The nickel chrome steels have a tendency to self-harden which is very pronounced as the percentages increase. This further accounts for the steel being hard when removed from the carburising pots, and is particularly noticeable in the case itself. The annealing treatment just mentioned will tend to correct this, although when the case is super-saturated (*i.e.* contains free cementite) it will fail, and it will become necessary to anneal at a higher temperature above the *Acm* point (about 850° C.), and cool exceedingly slowly in the furnace itself. The free cementite is then diffused and the case will be soft.

The Brinell hardness numbers given for the case in the table are mainly imaginary, since it is not possible to obtain true measurements with this machine unless the case is very deep and the core very strong. Scleroscope readings, however, can be taken and these may be converted into Brinell hardness numbers. The chief point about the table is that it serves as a warning as to the possible hardness of the steel in its different states, and as such should prevent impossible tasks being put on the machine shops. In connection with the table, reference should be made to the table given on p. 206 dealing with the relation of the cutting properties of steel to the Brinell hardness numbers.

The finish of the machined surface is a factor that is often neglected. A rough finish will often lead to the development of cracks in the case, due to the sharpness of the grove or cut at the bottom, and also because of the ragged edges at the top of the grooves. Sharp corners should be avoided, and all shoulders should have a radius so that hardening cracks are not induced so readily.

Heat Treatment.—The carburising and the subsequent operations of refining and hardening are dealt with in Chapter X.

The facility with which a steel can be heat treated and its susceptibility to injurious influences during treatment should always be considered when selecting it for a given purpose. This is specially important with case-hardening steels. For this reason the table given on p. 315 is arranged to give a brief indication of the simplicity or otherwise of the heat treatment required for the particular steel referred to.

Carbon steel, although used so extensively for case-hardened parts, is really not a simple steel to heat treat. It sometimes suffers badly at the hands of the steel stamper or forgeman, who finishes his work at a high temperature and so produces a coarse structure necessitating a careful normalising treatment. The process of carburising itself produces an open coarse structure which is not readily refined in some instances. This refining treatment, too, must be conducted within close temperature limits (10° to 15° C.) to secure good cores with high impact test values. The variation in the carbon content necessitates variations in the refining treatment temperature. In fact, for work requiring the highest standard of " material " efficiency carbon steel is troublesome. On the other hand, its cheapness compels the engineer to employ it wherever possible and for work not requiring the highest efficiency it should certainly be used. Under the conditions of mass production with standard fixed temperatures for carburising and refining, etc., the cores of parts treated successively will be found to vary slightly from a crystalline fracture to one which is silky (velvety) or partly fibrous. The dynamic strength as represented by Izod impact tests will vary from 30 to 90 ft.-lbs.

A low nickel case-hardening steel will be found much easier to handle commercially because of the retarding action of nickel on grain growth. This feature enables better stampings and forgings to be produced, and also prevents the development of a coarse structure during carburising. Thus the amount of refining to be done is very little and, as an operation, can be omitted altogether for many parts. Further the hardening operation (for the case) can be performed by quenching in oil instead of water (which *must* be employed for carbon steel). Hence the distortion is reduced, since oil quenching always produces less distortion than water quenching. Carbon steel does not harden when oil quenched, and therefore must suffer from the distortion due to water quenching.

This important advantage of nickel steel also reduces the danger of hardening or quenching cracks.

Then the temperature limits for carburising, refining (when desired), and hardening need not be so narrow as in the case for carbon steels. This, from the point of view of quantity production is most important, since there is not the need for so close a control of the furnaces, and the work produced is more regular in its quality. This fact is demonstrated by results obtained by quenching a series of test bars in oil from various temperatures over a range from 760° to 900° C. These results are shown graphically by Fig. 175.

From this series of tests it will be seen that over a range of 100° C., from 780° to 880° C., good results are obtained with single quenching only (*i.e.* doing both the refining and hardening at one heating). The best results are obtained in the vicinity of 820° C., when the impact value is highest.

It is often asserted that nickel steel does not carburise so rapidly as carbon steel. Although this is the case with the higher nickel steels (5 to 6 per cent.), it is not so with the low nickel steels (2 to 3 per cent.), which take up the carbon with the same facility and speed as plain carbon steels. Thus so far as speed and depth of penetration are concerned the two steels are equal, but here again nickel steel shows to advantage in that the line of demarcation between the case (carburised area) and core is not so sharp or abrupt : the carbon gradient is less steep with nickel steel than with carbon steel, and in consequence there is not the same risk of peeling or flaking off.

With carbon steel, especially if the carburising is done at a high temperature (950° C. to 1,000° C.), the change from the high carbon zone to the low carbon or original steel is very marked, and the stresses set up in the case (tension stresses) on hardening will often cause the case to leave the softer metal underneath, and cracks are formed which may eventually lead to peeling of the case. This trouble, which is referred to as " exfoliation," is not infrequent, and in many instances does not develop until the grinding stage is reached when, if this is not carefully carried out, the sudden and local heating sets up cracks in the stressed metal and this, once partially released, peels off spontaneously.

With high nickel steels (5 to 6 per cent. nickel) the heat treatment is not so simple as with low nickel steels. The rate of penetration of the carbon during carburising is slower, and to obtain the same depth of case longer periods must be allowed for this operation. The grain growth is slow and therefore the refining operation is not necessary in every case; the single heating and quenching for hardening being sufficient. Oil quenching should be resorted to because water quenching is too drastic, especially if the steel contains about 0·2 per cent. carbon.

Nickel steels sometimes contain small percentages of chromium, which is introduced into the steel from the scrap alloy steels used in making. These small amounts up to 0·25 per cent. do not influence the behaviour of the steel appreciably, and can be neglected. They probably improve the steel to a slight extent.

Nickel chrome steels require more care than nickel steels in heat treatment especially if the carbon content exceeds 0·2 per cent. These steels possess the advantages that nickel steels have over carbon steels in regard to grain growth and the gradual change from the high carbon zone to the low carbon core. They carburise more rapidly as a rule than carbon or nickel steels, and generally give a harder case due to the influence of the chromium.

The temperature limits for the refining and hardening treatments, however, cannot be made so great as with nickel steels, but as a rule are wider than those required for carbon steel. The necessity for refining after carburisation is not so great and, as in the case of nickel steel, can be omitted for many parts. It is, however, advisable to give all important parts this treatment because the improvement obtained is fairly considerable, more so than in the case of nickel steels, and as nickel chrome steel is usually only employed for highly stressed parts, the fullest advantages of the steel should be obtained.

The great hardness imparted by chromium to the case makes these steels invaluable for heavy wear, and as this hardness is easily obtained by oil quenching the minimum distortion is secured with the maximum of hardness. Nickel steel does not produce so hard a case as either carbon steel or nickel chrome steel, and for very hard wear is inferior.

The low nickel chrome steel (2·0 per cent. Ni, 0·8 per cent. Cr) can be treated like low nickel steel except that it is advisable to refine after carburisation. The temperature of carburisation should be kept low, and not exceed 920° C. on account of the tendency for free cementite to form in the case, with the consequent danger of cracking.

The higher nickel chrome steels (4·5 per cent. Ni, 1·5 per cent. Cr) are more sensitive to bad treatment, and should not be carburised at higher temperatures than 920° C. Generally, splendid results are obtained with a single refining and hardening heat combined, and as a rule the best temperature for this is quite low (about 800° C.), the quenching medium being oil.

The nature of the quenching medium is of the greatest importance and influences the strength of the core and hardness of the case to a surprising extent. This is particularly pronounced with alloy steels, where water quenching will give tensile results often 50 per cent. higher than those obtained with oil.

This is shown clearly by Figs. 174 and 175, which are graphs of the results obtained by quenching in water and in oil a nickel case-hardening steel (containing 2·83 per cent. nickel and 0·16 per cent. carbon). A series of test bars $1\frac{1}{8}$ in. diameter were carburised, machined down to $\frac{7}{8}$ in. diameter, and then heated to various temperatures, some being quenched in water (Fig. 174), and the others quenched in oil (Fig. 175). Such results, however, are obtained at the expense of the dynamic strength, and are often accompanied by serious distortion. Quenching in boiling water will give results more comparable with oil quenching, and this is sometimes recommended. But if an alloy steel is decided upon for a particular part then it is advisable to select one which will give the desired strength with oil quenching, for not only is the risk of

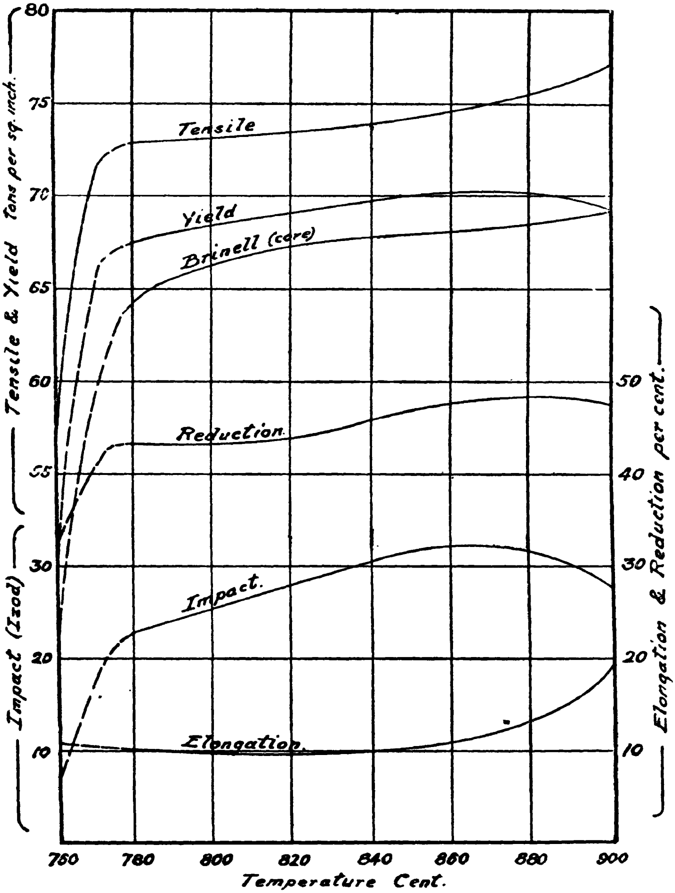


FIG. 174.—Nickel Case-hardening Steel. Effect of water quenching, one heat only, at different temperatures as shown. All test bars were carburised and turned to $\frac{7}{8}$ inch diameter. Analysis: C 0·16, Mn 0·58, Ni 2·83, Cr 0·20.

distortion minimised, but the results will be more uniform since oil quenches just as well when moderately hot as when cold.

With the low nickel steels the greatest hardness of the case is only obtained by water quenching, but with the higher nickel and nickel chrome steels no advantage is obtained by water quenching, and with high nickel chrome steels a harder case is obtained by oil quenching than with water quenching, while such steels will harden appreciably in air alone.

All case-hardened parts should be tempered at a temperature of 150° to 180° C. to reduce the tendency to "chip" at sharp projecting corners such as the teeth of gears, keyways and splines, etc. This simple operation will add considerably to the life of the parts, and prevent much annoyance without in any way reducing the hardness of the case.

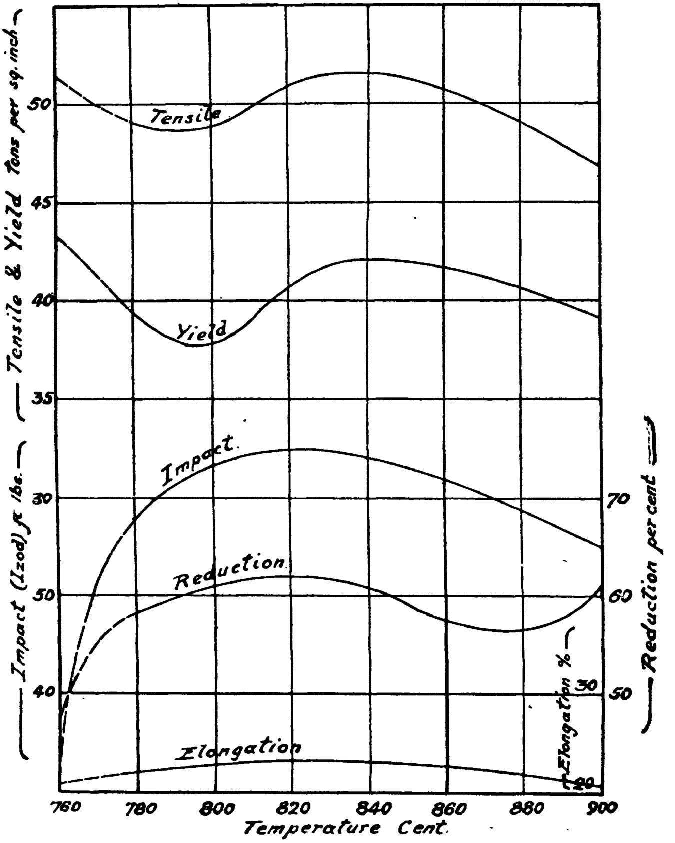


FIG. 175.—Same Steel as Fig. 174. Effect of oil quenching instead of water.

Distortion.—In the foregoing paragraphs reference is made to the influence of oil quenching in reducing distortion. Since carbon case-hardening steels can only be hardened by water quenching, it is evident that when distortion is an important factor, an alloy steel which will harden in oil must be used.

Further, every time a steel is heated and quenched the distortion, whether it be expansion or contraction or both, is increased, hence an alloy steel like nickel steel which only requires one heating and quenching must be better than one that requires two heatings and quenchings after carburisation.

For this reason the alloy steels are preferable to carbon steels, and if used for case-hardened gears will be found to give little difficulty through change in size. This is important because the necessity for gear grinding is eliminated, and with it the disturbing feature of cracks in the case.

Further the straightening of shafts, spindles and other parts is a safer operation with the nickel and low nickel chrome steels than with carbon steels, particularly after the carburising operation. This is mainly due to oil quenching in the case of hardened parts.

Strength of the Core.—With carbon steels the strength of the core is dependent not only on the carbon content but on the completeness of the refining operation. The dynamic strength is particularly susceptible to the latter factor, more so than to the carbon content, while the tensile strength is less affected. Therefore the temperature of carburisation should be kept low (900° C.) to prevent the development of a coarse-grained structure and thus make the refining operation an easier and less uncertain one.

Apart from the increased strength due to their composition, the strength of the alloy steels is not so susceptible to the temperature at which the refining operation is carried out, but it is influenced very greatly by the medium used for quenching in the hardening operation.

TESTS ON 6-PER-CENT. NICKEL STEEL.

Quenching Medium.	Yield. Tons per sq. in.	Ultimate. Tons per sq. in.	Elongation per cent.	Reduction of Area per cent.	Impact, ft.-lbs.
Cold water, 20° C. ..	79·9	83·0	14·5	48·4	39
Boiling water, 100° C. ..	30·9	43·0	25·0	56·8	45
Oil, about 30° C. ..	49·3	62·7	19·0	54·5	33

The hardening temperature can be raised considerably without causing much change in the tensile strength, but the dynamic strength is more dependent on this and a "best" temperature can be found for each steel, which gives a maximum impact figure, and any variation from this will cause a falling off, the rate of which depends on the steel, and on the quenching medium: oil giving the lesser rate of falling off.

The effect of varying the treatment after carburising is shown by Figs. 176, 177, and 178. These three graphs represent the results obtained with a series of test bars all of the same composition (C 0·18, Mn 0·56, Ni 2·57, Cr 0·06). These bars ($1\frac{1}{8}$ ins. diameter) were carburised at the same temperature (900° C.) for 8 hours, cooled in the box, and then machined to $\frac{7}{8}$ in. diameter. They were then divided into three sets; the first set being heated to various temperatures and then quenched in oil (Fig. 176). The second set were all quenched in oil from 850° C. and then reheated to various temperatures and quenched in oil again (Fig. 177). The third set were heated to various temperatures and quenched in oil, and all were then reheated to 780° C. and quenched in water (Fig. 178).

Comparing the results of the first and second sets it will be noticed that the single quenching in oil produces a higher average tensile strength than the double quenching in oil. On the other hand, the double quenching gives a higher impact value. The average tensile strength of the third set is higher than that of the other sets, this being due to the final water quenching. The impact values are higher than those obtained with a single oil quench but lower than those obtained with double oil quenching.

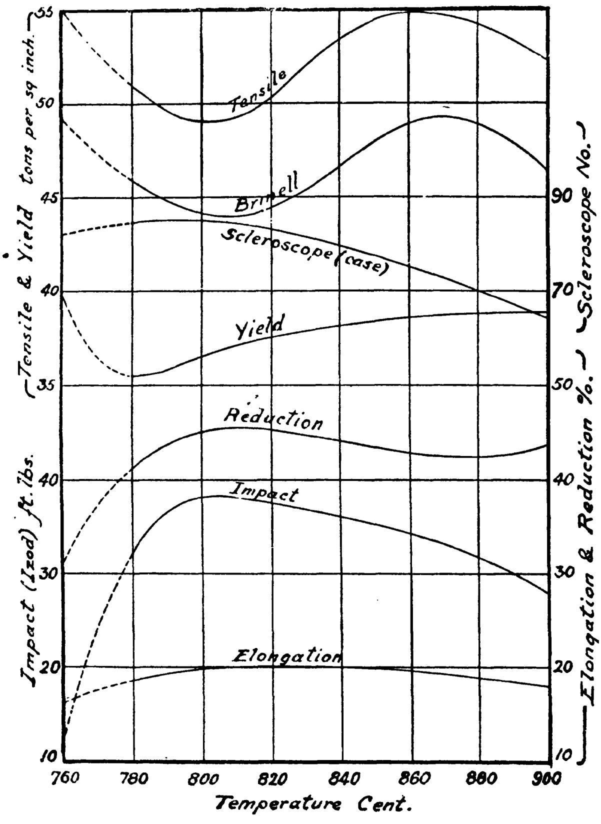


FIG. 176.—Nickel Case-hardening Steel. Effect of oil quenching, one heat only, at different temperatures as shown. All test bars were carburised and then turned to ⅞ in. diameter. Analysis: C 0·18, Mn 0·56, Ni 2·57, Cr 0·06.

Grinding.—The greatest difficulty in producing a finished ground case-hardened surface is the prevention both of cracks and the development of peeling. This serious trouble generally shows up during the process of grinding and is usually attributed to defective carburising and heat treatment. A close investigation, however, soon reveals the fact that it is the grinder who is more often at fault.

This troublesome feature opens up so much controversy, and often appears so difficult to solve that it is advisable to consider here all the possible causes of cracking, chipping, and peeling of the case. Reference has already been made to this in previous paragraphs, but, for convenience, the subject is dealt with completely in the following lines. The possible causes of cracks are tabulated below.

(1) Faults in the original material: high manganese content, slag inclusions, high phosphorus content, segregation troubles such as banded structures, surface defects due to rolling and drawing.

(2) Faults due to stamping and forging: laps, seams, overheating.

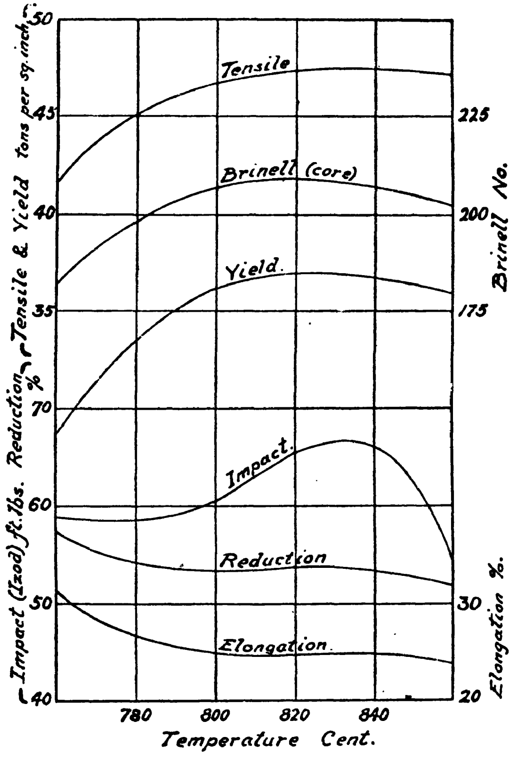


FIG. 177.—Nickel Case-hardening Steel (same as Fig. 176). Effect of double quenching, *i.e.* two successive heatings and quenchings. All test bars were carburised and then turned to $\frac{7}{8}$ inch diameter, then quenched in oil from 850° C. and reheated as shown and then quenched in oil. Analysis: C 0·18, Mn 0·56, Ni 2·57, Cr 0·06.

(3) Rough machining: coarse feeds producing ragged surfaces, sharp corners and edges, ragged edges.

(4) Design of parts: keyways, grooves and slots, holes situated close to the edge leaving only thin sections of metal, hollow parts of thin section and deep case, thin fins, shoulders or spigots, screw threads.

(5) High temperature carburisation producing free cementite or network form (or as needles), high phosphorus content in case due to use of poor carburising compound containing large amounts of phosphorus, exfoliation or sharp demarcation of case due to rapid carburising or high temperature.

(6) Refining temperature not high enough to reduce coarse crystalline structure of core, thus making the steel difficult to straighten or "true up," also not high enough to dissolve free cementite caused by high-temperature carburising.

(7) Hardening temperature not low enough to refine the case (*i.e.* to reduce the coarse crystalline structure to a fine-grained one), sudden heating by placing cold parts into heated furnace so that projecting parts come into contact with hot floor.

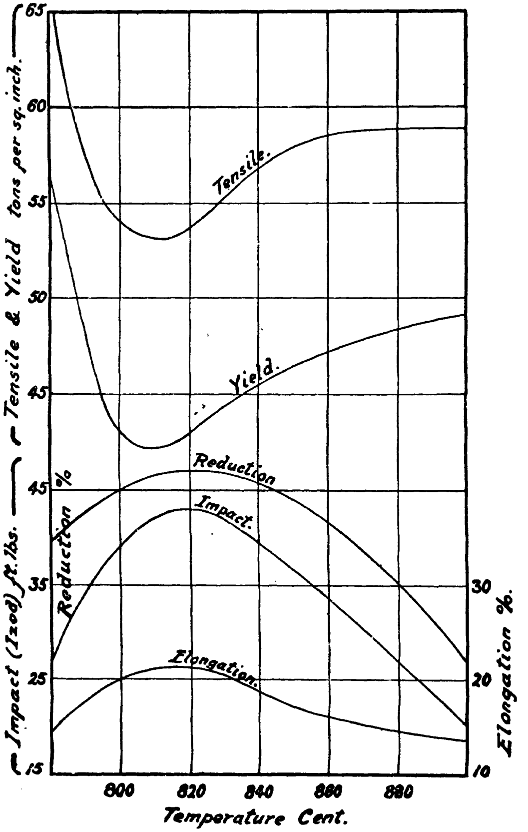


FIG. 178.—Same Steel as Figs. 176 and 177. Effect of double heating, quenching first in oil and then in water. All test bars were carburised, turned to $\frac{7}{8}$ inch diameter, heated to various temperatures as shown, and quenched in oil, then reheated to 780° C. and quenched in water.

(8) Quenching troubles—water too cold, heated metal splashed before actual quenching.

(9) Straightening or trueing up after carburisation, and after hardening.

(10) Grinding: lack of cooling lubricant, use of close hard wheels, lack of clearance, coarse feed and traverse, high speeds.

To these may be added other causes due to local conditions and careless handling in transport.

Dealing with the above causes or faults in turn: reference has already been made to the ill effects of slag, segregation, and banded structure (see pp. 318–9), also the effects of surface faults such as seams, roaks, due to rolling and drawing. The effect of manganese in increasing brittleness is mentioned on p. 317. Chromium also tends to induce cracks during grinding, but its influence is not so serious as manganese.

The faults due to stamping and forging are obvious. Overheating is mentioned because this, in the case of alloy steels, is not usually rectified by the ordinary heat treatment, and its ill effects (brittleness) still persist in the finished part.

Rough machining produces sharp grooves and ragged edges which easily start cracks during quenching, especially if water is employed. The machining previous to carburising should be moderately good as regards finish, or, better still, the carburised parts should be rough ground (while soft) before refining and hardening.

Much can be written about defects in design, but the examples quoted will serve as a guide as to the nature of the faults that should be avoided. Keyways with sharp bottoms or edges tend to start cracks, and these should not be cut out before carburising unless it is intended to have them hard as in the case of splines on shafts and in wheels, then the bottoms should have a radius, and the edges should have their extreme sharpness removed. When a hole exists near the edge of a part so that the section of metal is very thin, and the case itself forms the greater part of it, a crack is almost certain to start. This is due to the rapidity of quenching at this point, and the extreme tension set up in it when the rest of the part cools down. Hollow shafts of thin section and with a thick case often give trouble due to distortion in quenching, and the subsequent straightening operation strains the metal so much that cracks are started up in the case, which itself is already in serious tension. Such shafts should be hardened before boring. Thin fins, shoulders, spigots, and other projections of small section will often be carburised right through, and will therefore behave like tool steel. These quench more rapidly than the body of the part, and are therefore subjected to severe internal stresses, with the result that they split off and crack. When carburised right through they lack the support of a tough core and consequently easily snap off.

Screw threads should not, of course, be machined until after the carburising operation. If already present and if carburised they will easily cause cracks and must be softened after hardening by local heating with a blowpipe, etc. Or they should be protected with some kind of anti-carburising compound or paint.

The effects of high temperature carburising have been dealt with elsewhere (see p. 219). The presence of the fine network and needles of free cementite is serious because of the extreme weakness of this constituent, and the paths of weakness it sets up. The use of high phosphoric carburising compounds is dealt with on p. 215. This element always induces brittleness, but, fortunately, the compounds supplied by reliable firms are usually fairly low in phosphorus (in its unstable form).

The refining temperature only influences the cracking trouble in so far that it affects the core, and if not high enough will make straightening of shafts, etc., a more difficult operation. Also the reduction of free cementite from its network or needle form to a less dangerous form can only be accomplished by high refining temperatures.

The hardening temperature for the case is important, since the coarseness of the grain structure depends very much on this, particularly with carbon steels. With nickel or nickel chrome steels it is not so important since the grain size is generally not large. A coarse-grained structure in the case is fatal since it will cause chipping, cracking and flaking, and is in fact the most common source of these troubles. This temperature therefore should be watched very closely with carbon steels. With nickel steels the trouble does not occur much, but with nickel chrome steels it is a little more common, although to nothing like the same extent as with carbon steels. The sudden heating, especially if local, will readily cause cracks in parts which have only been refined. These are already hard, but because the refining temperature is high the grain size of the case is large and therefore weak and brittle. Being under tension already the sudden application of heat easily causes a crack to start. The hot air of the furnace will do little harm, but by placing the part in contact with the furnace floor those parts which rest on it heat up at once and the damage is done. With camshafts and other parts with projections this is a common source of trouble—such parts should be preheated or suspended in the furnace in jigs or fixtures.

Quenching is not often the cause of much trouble, although it is at this stage that most hardening cracks appear. The cause of the cracks as a rule is some defect such as those referred to above. With carbon steel requiring water quenching the water can be too cold, and any tendency to crack is then emphasised by the more rapid cooling. Thus, water taken from a running stream in winter may cause more cracking than in summer because of its lower temperature. A source of trouble is splashing, which produces local hardening and sets up conditions similar to those mentioned under defects in design.

Straightening and trueing up after carburisation and after hardening is always a drastic operation in so far that the material must be stressed beyond the yield point or elastic limit to take up a permanent strain. Thus the stress approaches the maximum required to break the steel, and, therefore, with the rather crude methods in vogue for carrying out this operation it is not surprising to find cracks developing after the parts have been straightened. With carbon steels the elastic limit is usually about 50 to 60 per cent. of the maximum breaking load, while with alloy steels it is more nearly 80 per cent., which thus accounts for the greater difficulty in straightening alloy steel parts and their tendency to crack or break more often than carbon steel parts. The margin between the yield of the metal and the actual breaking stress is narrower than with carbon steel. While many of the cracks produced during straightening can be detected immediately, there are many very minute ones which are not visible until after hardening or until after grinding. For this reason the straightening operation should be provided for in the design of the spindle or shaft by arranging for portions to be left soft in the finished part. Spaces between journals and other parts which must be hard should have an excess of metal left on them and this should be removed after carburising so that no case is left. Thus in the hardened shaft these portions are free from the delicate, brittle high carbon skin and will give readily under the force of the press used for straightening. By this means lower initial stresses are set up in the shaft, since it takes less force to deform these soft portions, and also the case-hardened portions are practically free from bending stresses.

The grinding operation is without doubt one of the most difficult. The very nature of case-hardened steel will at once explain this: a thin skin of hard, brittle, and comparatively non-elastic steel (the case) enveloping under great tension a large mass of softer and totally different material (the core) represents the piece that is to be ground. The procedure of grinding is itself of a drastic nature, and the combination is not a happy one. Yet the average grinder will proceed as though the article was made of solid tool steel, and it is not uncommon to find that dry grinding is being employed instead of wet grinding, with resulting disaster. The essentials to successful grinding may be summed up as follows: selection of soft, bonded coarse wheels, plenty of cooling lubricant (soda solution) well directed on to the surface being ground, a big clearance angle between the wheel and the work thus causing only a narrow portion of the wheel to do the grinding and allowing free access of the cooling medium, slow feed and traverse, and slower speeds for the wheel. Grinders used to tool work will inevitably meet with trouble as soon as they start on case-hardened work, and for this reason careful supervision is required with such men. The effect of grinding is to cause local heating, as is demonstrated by the sparks which fly off during dry grinding. The action of the abrasive wheel is to tear out with great suddenness (and shock) minute pieces of the metal, a process which develops a considerable amount of heat locally. This sudden heating of a small area of the hardened case reduces its strength at this point, and as the metal is under considerable tension in a plane parallel to its surface the result is rupture, the metal giving way under this stress.

The surface after grinding is often soft and a file will bite into it. This softness, however, only penetrates to about 0·0005 inch, and it will be found that below this the metal is quite hard. This soft film of metal is probably the result of the heating during grinding, and is difficult to prevent: only the greatest care and slowness during the operation will prevent its occurrence, and as a rule commercial considerations will not allow such a procedure. This peculiarity must not be confounded with the trouble known as soft spots, which is quite a different matter and is dealt with under "Hardness of case." Careless grinding, however, will produce soft spots owing to excessive feeds and traverse, and lack of cooling lubricant.

Hardness of Case.—The hardness of the case should always be tested before, as well as after, grinding, in order that the cause of any softness can be correctly assigned.

Unfortunately, there is no really satisfactory method for determining the hardness of the case. The Brinell hardness machine is useless on account of the soft core and the consequent crushing in of the case (by the ball) especially with thin cases. The scleroscope is too dependent on the smoothness of the surface, which must be carefully prepared—an expensive proceeding. In spite of the claims made for these two instruments the only practical method of testing the hardness is with a file. This rather crude method is surprisingly reliable in the hands of a man who has had a little experience; the presence of scale does not influence the test nor does the quality of the surface, which may have machine marks or may have been sand-blasted. Of course, when the work has been carefully ground the surface is good enough for the scleroscope and for large quantities of the same piece this instrument can be employed, but even then semi-skilled hands cannot be relied upon because of the sensitiveness of the instrument to slight variations in the conditions (see "Scleroscope Test," Chapter VI). The presence of a soft film due to grinding may influence the readings of the instrument, and it is always advisable to watch out for this defect, and not reject any work giving a low reading until the surface has been carefully cleaned with a piece of emery cloth and rechecked.

A generally accepted term for hardness is "glass hardness," but if this be taken as a standard it should be understood as the resistance to abrasion of a good-quality flint-glass bottle. A medium-cut file of about 6 to 8 inches length should make no impression on such a bottle, whereas it will on some qualities of glass. Thus a well case-hardened piece of steel should not receive any scratches from a new file of this size and cut. Perhaps the best guide as to the hardness of the surface is the manner in which the file itself is destroyed. A really hard surface will instantly round off the cutting edges of the file, producing what appears as a white streak along the file.

When such a surface is being tested it will be noticed that the test is so definite, the file glides so easily over it, that no doubt exists about its quality.

The real difficulty in testing is with those surfaces that are soft enough for the file to "bite," and it is then that experience is required to judge as to the amount of "bite," *i.e.* the degree of hardness. Clearly there is not always the necessity for a glass-hard surface, nor in commercial work is such a surface produced with regularity. It then remains to decide what *degree of softness* may be permitted rather than what degree of hardness is desired.

The hardness test, then, may be described as a limit test for softness since no maximum for hardness is fixed. Unfortunately the file test is one requiring experience, and its results are only expressed by the "feel," results which cannot be expressed to any scale. Thus, although the test is a fairly reliable one commercially, it is necessary, for the sake of comparisons and for future records, to adopt an instrument like the scleroscope. The hardness figures, therefore, in this chapter will be expressed in scleroscope units.

Now as to the factors that govern the hardness of the case. These are set out as follows:

(1) Richness of carbon content in case.
(2) Nature of quenching medium and cleanliness of same.
(3) Class of steel used.
(4) Temperature at quenching for hardness.
(5) Previous heat treatment.
(6) Cleanliness of parts both before carburising and hardening.
(7) Decarburisation during the refining and hardening heats.
(8) Machining errors.

The percentage of carbon in the case influences the hardness. With plain carbon steel, amounts less than 0·8 to 0·9 per cent. will not give the quality known as glass-hardness, hence it is necessary to use a carburising compound which is rich enough to produce a case containing 0·9 per cent. carbon. The temperature of carburising influences the carbon richness as also does the time. Another factor which is controlled by the above is the carbon gradient or rate at which the richness of the carbon falls off at different depths from the surface. For convenience typical instances of this are shown by the diagrams, Fig. 179.

The first graph shows the result of carburising at an ordinary rate and at a temperature of about 900—920° C. The dotted line represents the richness of the carbon at different depths in millimetres just after carburising, and the full line the final result of refining and hardening. According to this diagram the surface of the steel can be ground to a depth of 0·3 mm. before the carbon content falls to 0·85 per cent. Such a case will prove to be hard and satisfactory The second graph shows a very different state of affairs, for although the surface after quenching appears hard, it will be seen that as soon as 0·2 mm. (0·008 inch) is ground off the carbon content has fallen to 0·75 per cent., and in consequence the final surface is not so hard. Such a case is produced by rapid carburising (short time), at a higher temperature. The carbon content on the outer surface is rapidly raised to above 1 per cent., but the time has not been sufficient for the carbon to diffuse to a satisfactory depth. The carbon gradient is therefore steeper.

The rate of cooling affects the degree of hardness, and consequently water quenching gives a harder case and hardens to a greater depth than oil quenching, but although this is true for carbon steel and the low nickel and low nickel chrome steels, it is not true for the high nickel and ordinary nickel chrome steels. For the latter oil quenching is preferable since it gives the same degree of hardness or, in some instances, a harder case than water quenching. With the high nickel chrome steels, water quenching retains the case in an austenitic condition, and this is appreciably softer than the martensitic state which is produced by oil quenching. Of course other considerations such as the mass effect come in and may alter this relationship ; for example, very thin sections may give better results by cooling in air instead of oil, which may cool the piece too rapidly to permit the change from the austenitic state to the martensitic condition.

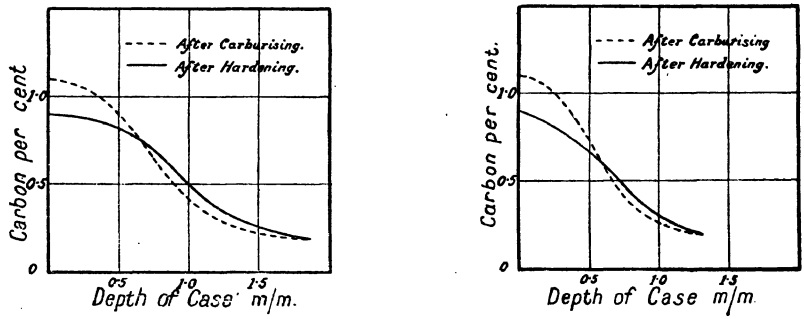


FIG. 179—Importance of Carbon Gradient in Case-hardened Parts. The first graph shows the result of carburising at the correct temperature with a good compound. The second graph shows the effect of carburising at a high temperature for a shorter time.

When water is employed care should be taken to see that it is free from oil or grease, otherwise soft spots may be found.

The class of steel used is also important since one steel may not harden to the same extent that another does. For example, nickel steel will not give so hard a case as plain carbon steel, while nickel chrome will give a harder case than either. The following table gives the approximate hardness of the different steels used :—

HARDNESS OF CASE

Class of Steel.	Quenching Medium.	Scleroscope Hardness Number.
Carbon	Water, normal temperature	80 to 90
Nickel 2 to 3 per cent. ..	Oil ,, ,,	75 ,, 80
	Water ,, ,,	80 ,, 85
Nickel 5 to 6 per cent. ..	Oil ,, ,,	70 ,, 80
	Water ,, ,,	65 ,, 75
Nickel Chrome	Oil ,, ,,	75 ,, 85
Ni 2·0, Cr 0·8 per cent.	Water ,, ,,	75 ,, 85
Nickel Chrome	Oil ,, ,,	80 ,, 90
Ni 3·0, Cr 0·6 per cent.	Water ,, ,,	80 ,, 90
Nickel Chrome	Oil ,, ,,	80 ,, 90
Ni 3·5, Cr 1·0 per cent.	Water ,, ,,	75 ,, 85
	Air ,, ,,	70 ,, 80
Nickel Chrome	Oil ,, ,,	80 ,, 90
Ni 4·5, Cr 1·5 per cent.	Water ,, ,,	70 ,, 80
	Air ,, ,,	75 ,, 85

The hardness of the case also depends on the hardening temperature. This is shown by the curve Fig. 176, which represents the effect of hardening and quenching in oil, at different temperatures, of a low nickel steel. The scleroscope hardness reaches a maximum at the hardening temperature of 800° C.

The treatment previous to hardening has an important influence on the case, in so far that it affects the diffusion of the carbon, tending to equalise it and thus reduce the carbon richness of the case. Thus a carburised piece of steel, if hardened straight away after carburisation, will give a harder surface than if it had been heated two or three times previous to hardening. The refining heat required for the core always tends to reduce the richness of the case by diffusion (apart from decarburisation by oxidation), and therefore for this reason should not be prolonged more than is absolutely necessary to attain the desired object. Nickel steel and low nickel chrome steel, which give a good core and a hard case with a single heating and quenching, have this advantage over carbon steel, which must be refined before hardening, *i.e.* must be heated and quenched twice. Further with the alloy steels diffusion takes place more slowly than with carbon steel, and even when refining is necessary the loss in richness of carbon through diffusion is only slight.

On the other hand, the refining heat tends to improve the case, in that it breaks down the very coarse structure resulting from carburisation and thus renders the hardening operation more effective. With good carburisation, producing a case of about 1 per cent. carbon, the refining heat is usually a safe operation, the diffusion not being serious enough to lower the richness to below 0·85 per cent.

A common source of soft spots and softness generally is dirt or scale on the steel. In carburising the presence of dirt or scale will tend to prevent the steel taking up sufficient carbon, whilst other portions that are clean will absorb the desired amount. The result of this is a soft place whereever the carbon has penetrated only slightly. The use of clay or anti-carbon cement which is applied to those portions that are to remain soft may cause trouble through careless application and the partial covering of other portions which are to be carburised. When copper plating is resorted to, to prevent carburisation of the soft places, it is highly important to see that it is completely ground off those portions which are to be hardened. The mere removal of the copper film is not sufficient, because the copper appears to penetrate a slight distance into the steel, and this must be removed entirely. The steel after grinding may appear quite free from copper, but on heating and cooling there will still be evidence of the copper and while this remains the carburisation will not be efficient. The use of clay or anti-carbon cement is liable to bring about another trouble, which is the partial carburisation of those portions of the steel it is intended to protect. This is brought about by the cracking of the clay or cement during heating thus allowing the carbon-rich gases to penetrate the steel at these points. Copper plating, to be effective, must be continuous and dense (not spongy). The thickness may be about 0·0004 provided the coating is dense, continuous, and adherent to the steel. Unless this condition is obtained a certain amount of carbon will penetrate into the steel.

Sulphur introduced from the carburising compound will produce soft spots, but as a rule it penetrates only to a slight depth and the usual grinding allowance generally removes any soft portions which result.

In the refining treatment, subsequent to carburisation, it is not so essential that the work should be clean—in fact, where it is highly important to prevent decarburisation (by oxidation) asbestos paint can be used to protect the surface. But for the final hardening operation cleanliness is most essential and the work should be well sand-blasted to remove scale, grease, and other dirt which, if left on, would prevent the quenching medium coming into contact with the steel, thus losing the full effect of quenching and producing soft spots.

Too much stress cannot be laid upon the subject of cleanliness before carburising and before the final hardening. It is exceedingly annoying to finish a cam shaft and then to find one soft spot (only) situated right on a vital part of one of the cams. The use of soda solution for dissolving grease, and the sand blast for taking away scale and other hard matter, should never be omitted.

Another frequent source of trouble is decarburisation by oxidation during the refining and hardening operations.

This is caused mainly by the bad adjustment of the air and gas supplies to the furnace, and is due to the excess of air, which at once oxidises and scales the surface of the steel, and in so doing oxidises a portion of the carbon away from the outer layers. Such parts will be quite soft, while at some depth below the surface a hard layer will be found, proving at once that the carbon from the outer layer has been removed by oxidation. Good adjustment of the air supply is the preventative, while as an additional precaution * the presence

---

* This precaution is really unnecessary now that efficient heat-treatment furnaces can be obtained. Such furnaces are provided with controls that make it possible to maintain a neutral or reducing atmosphere and thus eliminate oxidation troubles.

of a few lumps of coke will tend to prevent the gases from becoming too oxidising.

A last, but by no means uncommon, trouble is due to incorrect machining before carburisation. Parts are often left with an excessive allowance for grinding either by design or through carelessness, and when carburised and hardened are finally ground to the correct size only to find that the bulk of the case has been ground off. The importance of machining to limits which are carefully fixed with regard to the depth of case will be clearly seen by referring to the diagrams, Fig. 179. For a depth of case of 1 mm. the allowance should not exceed 0·02 mm. (0·008 inch) on the diameter or 0·01 mm. (0·004 inch) on the surface, while for $\frac{1}{16}$ inch an allowance of 0·010 inch on the diameter or 0·005 inch on the surface can be allowed for final machining and grinding.

Sometimes it is desired to obtain two depths of case on the same part. This can be done by leaving an excess of metal on those portions which are to have the shallower case and then to carburise the whole part to the full depth, after which the excess of metal is machined off before refining and hardening.

Wearing Properties.—The wearing properties of the case are naturally dependent on its hardness, and this has been considered already in the preceding paragraphs. The hardness, however, is not always a measure of the wearing quality, the structure of the case has an important influence on the wear, and it will be seen on referring to Chap. X., that by suitable carburising and heat treatment, a case which is chiefly austenitic in character can be obtained, and which therefore is comparatively soft.

Also the presence of chromium adds to the wearing qualities of the case-hardened surfaces, and where very heavy duty is required a high chrome nickel steel should be employed.

Specifications of Typical Steels.—Some of the principal case-hardening steels at present in use are mentioned in the table given on p. 321. These and one or two more are dealt with in greater detail in the following pages. The figures given represent the average range of results obtained in practice. The variation in carbon content, especially of the alloy steels, has a great influence on the results, and it will be found that in many cases actual tests on steels containing more than 0·15 per cent. will give results very different from those tabulated. The size of the piece and the nature of the quenching medium also influence the figures considerably. In the following specifications the size of the test bar has been taken at $1\frac{1}{8}$ inches round, and this after carburising has been turned down to $\frac{7}{8}$ inch diameter, refined and hardened while at this size. The hardness of the case is not included in these specifications, but a table is given on p. 336 showing what degree of hardness can be obtained with the principal steels using different quenching media.

Low Carbon

CHEMICAL COMPOSITION

Carbon	0·08 to 0·14 per cent.
Manganese	0·40 „ 0·60 „
Sulphur	Not more than 0·05 „
Phosphorus	„ „ 0·05 „
Silicon	„ „ 0·20 „

Mechanical Tests (Core)

	Hardened.
Yield, tons per square inch	16 to 25
Ultimate, „ „ „	27 „ 33
Elongation per cent.	30 „ 25
Reduction of area per cent.	60 „ 50
Impact (Izod), ft.-lbs.	70 „ 50

Heat Treatments

Carburise at 900° to 925° C., cool in box.

Refine core at 920° to 930° C., quench in water.

Harden at 760° to 770° C., quench in water.

Temper at 100° to 150° C. (in oil bath), soak 30 minutes, cool in air. This is necessary only for parts subject to shock.

Applications

Camshatts, small spindles for oil and water pumps, and all parts of light section not requiring much strength.

Ordinary Carbon—Grade I

Chemical Composition

Carbon	0·14 to 0·18	per cent.
Manganese	0·40 „ 0·70	„
Sulphur	Not more than 0·05	„
Phosphorus	„ „ 0·05	„
Silicon	„ „ 0·20	„

Mechanical Tests (Core)

	Hardened.
Yield, tons per square inch	21 to 28
Ultimate, „ „ „	35 „ 40
Elongation per cent.	33 „ 27
Reduction of area per cent.	65 „ 55
Impact (Izod), ft.-lbs.	100 „ 60

Heat Treatments

Carburise at 900° to 925° C., cool in box.

Refine core at 890° to 900° C., quench in water.

Harden at 760° to 770° C., quench in water.

Temper at 100° to 150° C. (in oil bath), soak 30 minutes, cool in air. This is necessary only for parts subject to shock.

Applications

This grade of steel may be regarded as the best quality. It will give the most consistent results but will, of course, be more expensive than Grade II., which is next described, and which is suitable for very many parts in automobile construction. When the maximum results are required, such as in aero-engine work, then Grade I. should be employed.

Ordinary Carbon—Grade II

Chemical Composition

Carbon	0·14 to 0·18	per cent.
Manganese	0·60 „ 1·0	„
Sulphur	Not more than 0·07	„
Phosphorus	„ „ 0·07	„
Silicon	„ „ 0·25	„

MECHANICAL TESTS (CORE)

	Hardened.
Yield, tons per square inch	23 to 32
Ultimate, ,, ,, ,,	38 ,, 44
Elongation per cent.	32 ,, 26
Reduction of area per cent.	65 ,, 55
Impact (Izod), ft.-lbs.	70 ,, 40

HEAT TREATMENTS

Carburise at 900° to 925° C., cool in box.
Refine core at 890° to 900° C., quench in water.
Harden at 760° to 770° C., quench in water.
Temper at 100° to 150° C. (in oil bath), soak 30 minutes, cool in air. This is necessary only for parts subject to shock.

APPLICATIONS

Gears, spindles, camshafts, and other shafts.

High Carbon

CHEMICAL COMPOSITION

Carbon	0·26 to 0·32 per cent.
Manganese	0·40 ,, 0·60 ,,
Sulphur	Not more than 0·04 ,,
Phosphorus	,, ,, 0·04 ,,
Silicon	,, ,, 0·15 ,,

MECHANICAL TESTS (CORE)

	Hardened.
Yield, tons per square inch	28 to 38
Ultimate, ,, ,, ,,	42 ,, 50
Elongation per cent.	26 ,, 20
Reduction of area per cent.	55 ,, 45
Impact (Izod), ft.-lbs.	30 ,, 20

HEAT TREATMENTS

Carburise at 880° to 900° C., cool in box.
Refine core at 840° to 860° C., quench in water.
Harden at 750° to 760° C., quench in water.
Temper at 100° to 150° C. (in oil bath), soak 30 minutes, cool in air. This is necessary only for parts subject to shock.

APPLICATIONS

Ball and roller races, and other parts subjected to high local pressure. Also for shafts where the torsion stresses are high.

2 per cent. Nickel

CHEMICAL COMPOSITION

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 ,, 0·50 ,,
Nickel	2·0 ,, 2·50 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·20 ,,

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.	Treatment II.	Treatment III.
Yield, tons per square inch ..	20 to 25	32 to 40	34 to 40	27 to 32
Ultimate, ,, ,, ,, ..	28 ,, 32	40 ,, 45	42 ,, 48	36 ,, 42
Elongation per cent.	38 ,, 30	25 ,, 20	33 ,, 28	30 ,, 25
Reduction of area per cent. ..	65 ,, 55	65 ,, 55	70 ,, 60	70 ,, 60
Impact (Izod), ft.-lbs.	90 ,, 60	70 ,, 50	90 ,, 70	100 ,, 80

HEAT TREATMENTS

Normalising.—Heat to 850° to 870° C., soak 30 minutes, cool in air.
Carburising.—At 900° to 925° C., cool in box.
Treatment I.—Heat to 820° C., soak 10 minutes, quench in water.
Treatment II.—Heat to 820° C., soak 10 minutes, quench in water. Reheat to 780° C. and quench immediately in water.
Treatment III.—Heat to 840° C., soak 15 minutes, quench in oil.
Tempering.—Heat to 150° to 180° C. in oil bath, soak 30 minutes, cool in air.

APPLICATIONS

This steel can take the place of plain carbon steel in very many cases with advantage because of the more consistent results obtained. If oil quenching is adopted, distortion difficulties are reduced very considerably, but the case will not be so hard as with water quenching.

2 per cent. Nickel (High Carbon)

CHEMICAL COMPOSITION

Carbon	0·27 to 0·32	per cent.
Manganese	0·40 ,, 0·60	,,
Nickel	1·80 ,, 2·20	,,
Sulphur	Not more than 0·03	,,
Phosphorus	,, ,, 0·03	,,
Silicon	,, ,, 0·20	,,

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.
Yield, tons per square inch	20 to 30	40 to 50
Ultimate, ,, ,, ,, ...	32 ,, 44	48 ,, 55
Elongation per cent.	35 ,, 25	17 ,, 13
Reduction of area per cent.	60 ,, 45	55 ,, 45
Impact (Izod), ft.-lbs.	50 ,, 30	60 ,, 40

HEAT TREATMENTS

Normalising.—Heat to 840° to 860° C., soak 30 minutes, cool in air.
Carburising.—At 900° to 925° C., cool in box. This operation should be carefully timed in order that too rich a case is not obtained.
Treatment I.—Heat to 800° C., soak 10 minutes, quench in water. Reheat to 720° C. and quench immediately in water.

APPLICATIONS

Ball and roller races, transmission shafts, and all parts subjected to either high local pressure or high tensile and torsional stresses. The case will be exceptionally hard. This is a better steel than the plain high carbon one intended for the same class of work.

In the uncarburised state the surface can be hardened appreciably by simply quenching the steel in water from a temperature of 750° C. The centre of the steel will stiffen and give results very similar to those specified.

2·5 per cent. Nickel

CHEMICAL COMPOSITION

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 ,, 0·50 ,,
Nickel	2·50 ,, 3·0 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·20 ,,

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch	22 to 27	30 to 36	32 to 40
Ultimate, ,, ,, ,,	30 ,, 34	40 ,, 46	42 ,, 50
Elongation per cent.	38 ,, 30	30 ,, 22	28 ,, 20
Reduction of area per cent.	65 ,, 60	55 ,, 45	55 ,, 45
Impact (Izod), ft.-lbs.	90 ,, 60	80 ,, 50	70 ,, 40

HEAT TREATMENTS

Normalising.—Heat to 850° to 870° C., soak 30 minutes, cool in air.

Carburising.—At 900° to 925° C., cool in box.

Treatment I.—Heat to 820° C., soak 10 minutes, quench in oil.

Treatment II.—Heat to 820° C., soak 10 minutes, quench in oil. Reheat to 780° C. and quench immediately in water.

Tempering.—Heat to 150° to 180° C. in oil bath, soak 30 minutes, cool in air.

APPLICATIONS

The effect of varying the heat treatment on this steel is shown by Figs. 174–5–6–7–8.

The slight increase in nickel from 2 to 2·5 per cent. raises the strength of the steel into a very useful range between the plain carbon and the higher and more expensive alloy steels.

5 per cent. Nickel

CHEMICAL COMPOSITION

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 ,, 0·50 ,,
Nickel	4·50 ,, 5·50 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·20 ,,

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch ..	26 to 34	45 to 55	40 to 50
Ultimate, ,, ,, ,, ..	35 ,, 44	50 ,, 60	45 ,, 55
Elongation per cent.	30 ,, 20	25 ,, 18	28 ,, 20
Reduction of area per cent. ..	60 ,, 50	60 ,, 50	65 ,, 55
Impact (Izod), ft.-lbs.	70 ,, 50	50 ,, 30	60 ,, 40

HEAT TREATMENTS

Normalising.—Heat to 830° to 850° C., cool in air.

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, cool in air.

Carburising.—At 900° to 925° C., cool in box.

Treatment I.—Heat to 840° C., soak 10 minutes, quench in oil. Reheat to 770° C., quench immediately in oil.

Treatment II.—Heat to 830° C., soak 10 minutes, quench in oil.

Tempering.—Heat to 150° to 180° C. in oil bath, soak 30 minutes, cool in air.

APPLICATIONS

Transmission shafts, spindles and other parts subjected to high tensile stresses.

6 per cent. Nickel

CHEMICAL COMPOSITION

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 ,, 0·50 ,,
Nickel	5·50 ,, 6·10 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·20 ,,

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch ..	28 to 38	48 to 60	45 to 55
Ultimate, ,, ,, ,, ..	38 ,, 48	55 ,, 65	50 ,, 60
Elongation per cent.	28 ,, 20	22 ,, 15	25 ,, 18
Reduction of area per cent. ..	55 ,, 45	55 ,, 45	60 ,, 50
Impact (Izod), ft.-lbs.	70 ,, 50	45 ,, 25	50 ,, 30

HEAT TREATMENTS

Normalising.—Heat to 830° to 850° C., cool in air.

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, cool in air.

Carburising.—At 900° to 925° C., cool in box.

Treatment I.—Heat to 840° C., soak 10 minutes, quench in oil. Reheat to 760° C. quench immediately in oil.

Treatment II.—Heat to 820° C., soak 10 minutes, quench in oil.

Tempering.—Heat to 150° to 180° C. in oil bath, soak 30 minutes.

APPLICATIONS

Same as 5 per cent. nickel steel.

2·0/0·8 per cent. Nickel Chrome

Chemical Composition

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 ,, 0·50 ,,
Nickel	1·80 ,, 2·30 ,,
Chromium	0·60 ,, 1·0 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·20 ,,

Mechanical Tests (Core)

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch	20 to 28	45 to 55	40 to 50
Ultimate, ,, ,, ,,	30 ,, 38	55 ,, 65	50 ,, 60
Elongation per cent.	30 ,, 25	18 ,, 14	20 ,, 16
Reduction of area per cent.	50 ,, 40	55 ,, 40	55 ,, 40
Impact (Izod), ft.-lbs.	—	45 ,, 30	60 ,, 40

Heat Treatments

Normalising.—Heat to 850° to 870° C., soak 30 minutes, cool in air.

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, cool in air.

Carburising.—At 890° to 910° C., cool in box.

Treatment I.—Heat to 850° C., soak 10 minutes, quench in water. Reheat to 760° C. and quench immediately in water.

Treatment II.—As above, but quench in oil instead of water.

Tempering.—Heat to 150° to 180° C., in oil bath, soak 30 minutes, cool in air.

Applications

Gears, worms, camshafts, and all parts where good wearing qualities are required.

3·0/0·6 per cent. Nickel Chrome

Chemical Composition

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 ,, 0·50 ,,
Nickel	2·90 ,, 3·50 ,,
Chromium	0·50 ,, 0·80 ,,
Sulphur	Not more than 0·05 ,,
Phosphorus	,, ,, 0·05 ,,
Silicon	,, ,, 0·20 ,,

Mechanical Tests (Core)

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch	25 to 35	50 to 60	45 to 55
Ultimate, ,, ,, ,,	35 ,, 45	60 ,, 70	55 ,, 65
Elongation per cent.	30 ,, 25	18 ,, 13	18 ,, 14
Reduction of area per cent.	50 ,, 35	50 ,, 35	50 ,, 35
Impact (Izod), ft.-lbs.	—	40 ,, 30	50 ,, 35

HEAT TREATMENTS

Normalising.—Heat to 840° to 860° C., soak 30 minutes, cool in air.

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, cool in air.

Carburising.—At 890° to 910° C., cool in box.

Treatment I.—Heat to 840° C., soak 10 minutes, quench in water. Reheat to 760° C. and quench immediately in water.

Treatment II.—Heat to 840° C., soak 10 minutes, quench in oil. Reheat to 770° C., and quench immediately in oil.

APPLICATIONS

Gears, camshafts, etc.

3·0/1·0 per cent. Nickel Chrome

CHEMICAL COMPOSITION

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 „ 0·50 „
Nickel	3·0 „ 3·50 „
Chromium	0·90 „ 1·20 „
Sulphur	Not more than 0·04 „
Phosphorus	„ „ 0·04 „
Silicon	„ „ 0·15 „

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch ..	30 to 40	60 to 70	50 to 60
Ultimate, „ „ „ ..	40 „ 50	70 „ 85	60 „ 70
Elongation per cent.	25 „ 20	16 „ 12	18 „ 14
Reduction of area per cent. ..	50 „ 30	50 „ 35	50 „ 35
Impact (Izod), ft.-lbs.	—	35 „ 20	45 „ 25

HEAT TREATMENTS

Normalising.—Heat to 840° to 860° C., soak 30 minutes, cool in air.

Annealing.—After normalising as above, reheat to 650° C., soak 30 minutes, cool in air.

Carburising.—At 890° to 910° C., cool in box.

Treatment I.—Heat to 840° C., soak 10 minutes, quench in water. Reheat to 760° C. and quench immediately in water.

Treatment II.—Same as above, but quench in oil instead of water.

APPLICATIONS

This steel will give a harder core than the last because of the higher percentage of chromium. The oil quenching treatment is the better one, the case being just as hard and the distortion being lessened.

3·5/1·5 per cent. Nickel Chrome

CHEMICAL COMPOSITION

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 „ 0·50 „
Nickel	3·30 „ 3·80 „
Chromium	1·30 „ 1·60 „
Sulphur	Not more than 0·04 „
Phosphorus	„ „ 0·04 „
Silicon	„ „ 0·15 „

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.	Treatment II.
Yield, per tons square inch ..	35 to 45	60 to 75	55 to 70
Ultimate, ,, ,, ,, ..	45 ,, 55	75 ,, 90	65 ,, 80
Elongation per cent.	25 ,, 20	16 ,, 11	18 ,, 12
Reduction of area per cent. ..	50 ,, 30	50 ,, 35	50 ,, 35
Impact (Izod), ft.-lbs	—	30 ,, 20	40 ,, 25

HEAT TREATMENTS

Normalising.—Heat to 840° to 860° C., soak 45 minutes, cool in air.

Annealing.—After normalising as above, reheat to 650° C., soak 45 minutes, cool in air.

Carburising.—At 880° to 900° C., cool in box.

Treatment I.—Heat to 840° C., soak 10 minutes, quench in water. Reheat to 760° C. and quench immediately in water.

Treatment II.—Same as above, but quench in oil instead of water.

Tempering.—Heat to 150° C. to 180° C., in oil bath, soak 30 minutes, cool in air.

APPLICATIONS

The oil-quenching treatment should be adopted in preference to the water-quenching on account of the tendency to crack.

4·0/1·5 per cent. Nickel Chrome

CHEMICAL COMPOSITION

Carbon	0·10 to 0·15 per cent.
Manganese	0·30 ,, 0·50 ,,
Nickel	3·90 ,, 4·50 ,,
Chromium	1·20 ,, 1·60 ,,
Sulphur	not more than 0·40 ,,
Phosphorus	,, ,, 0·40 ,,
Silicon	,, ,, 0·15 ,,

MECHANICAL TESTS (CORE)

	Normalised.	Treatment I.	Treatment II.
Yield, tons per square inch ..	35 to 45	60 to 75	55 to 65
Ultimate, ,, ,, ,, ..	45 ,, 55	75 ,, 95	70 ,, 90
Elongation per cent.	25 ,, 20	16 ,, 10	18 ,, 12
Reduction of area per cent. ..	50 ,, 30	50 ,, 35	55 ,, 40
Impact (Izod), ft.-lbs.	—	35 ,, 25	40 ,, 25

HEAT TREATMENTS

Normalising.—Heat to 840° to 860° C., soak 45 minutes, cool in air.

Annealing.—After normalising as above, reheat to 650° C., soak 45 minutes, cool in air.

Carburising.—At 880° to 900° C., cool in box.

Treatment I.—Heat to 840° C., soak 10 minutes, quench in oil. Reheat to 760° C., and quench immediately in oil.

Treatment II.—Heat to 800° C., soak 10 minutes, quench in oil.

Tempering.—Heat to 150° C. to 180° C. in oil bath, soak 30 minutes, cool in air.

Applications

The effect of varying the quenching temperature of this class of steel is seen in Fig. 180. The test bars ($1\frac{1}{8}$ ins. diam.), after carburising at 900° C., were machined to $\frac{7}{8}$ in. diam. and then heated to the temperatures specified and quenched in oil. The effect on the hardness of the case as shown by the scleroscope readings * is most pronounced.

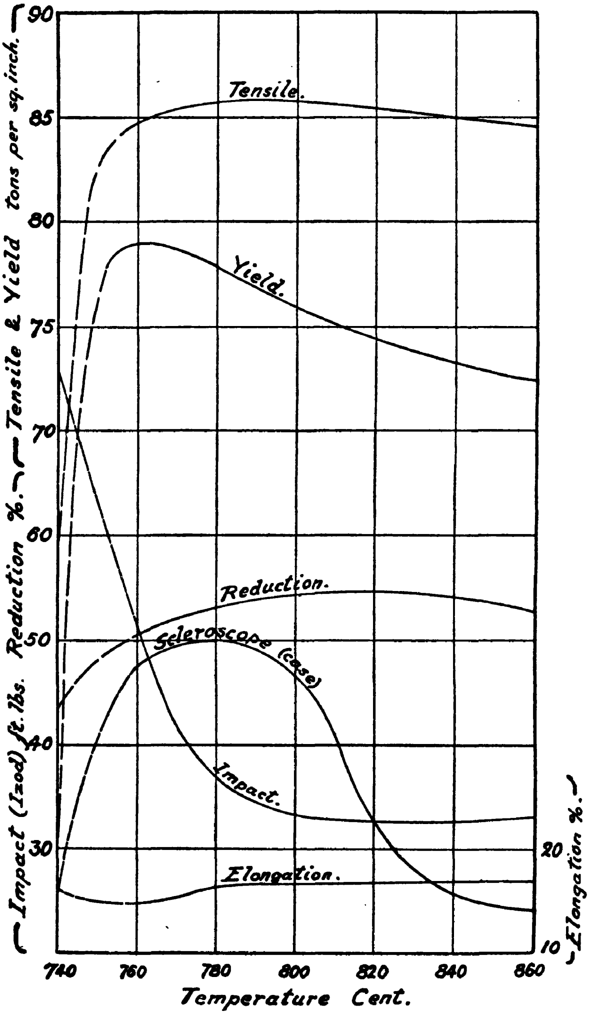


FIG. 180.—Nickel Chrome Case-hardening Steel. Effect of quenching in oil from different temperatures. All test bars were carburised and turned to $\frac{7}{8}$ inch diameter. Analysis, C 0·15, Mn 0·41, Ni 4·22, Cr 1·46.

---

* Unfortunately the scale for this curve has been omitted from the graph, but if the impact figures are increased by 40 units this scale will give the scleroscope values for the case.

CHAPTER XIV

IRON AND STEEL CASTINGS, INCLUDING MALLEABLE IRON AND SEMI-STEEL CASTINGS

CAST-IRON is perhaps the commonest of all engineering materials, owing no doubt to the ease with which it can be cast into almost any shape. A good foundry will produce castings free from blowholes and having a good surface which, except for those portions that carry other parts, will not require machining.

Malleable iron castings are made from a special grade of iron and are then "annealed" for a prolonged period, which process renders them ductile or malleable. The fact that complicated parts can be cast and then made tough and malleable is one of some importance to engineers.

Steel castings are not used so extensively as iron castings: their production is not so simple, and has only been developed during recent years. The higher melting point of the metal gives rise to many difficulties, and as a rule the surface of the castings is not so clean and sharp as in the case of iron. Their higher tensile and dynamic strength, however, renders the material valuable for many parts, and there is an increasing demand for such castings.

Cast-iron

Composition.—For the general run of castings the iron used is that known as foundry pig, but for many purposes other irons, mainly grey irons, are melted down, and a large amount of scrap iron is used up. Hence the composition of the metal will be found to vary considerably unless the requirements are specified particularly. Of course, for many parts the only quality required is good machinability and clean, sharp castings, in which case the composition is of little importance except that the amount of combined carbon must be low (about 0·5 per cent.) to reduce the hardness. In such cases, particularly for intricate parts of thin section, the foundryman will use an iron containing a high percentage of phosphorus (over 1·0 per cent.), since this element helps the metal to flow readily, and thus gives a sharp, clear casting. The silicon content may also be high, but this will depend very much on the size and section of the parts, and is adjusted by the foundryman to suit the parts, a high percentage being used for small thin sections and a lower percentage for large bulky parts.

Thus for the general run of small castings the following composition is found to be satisfactory :—

Carbon (total)	3·0 to 3·9	per cent.
Carbon (combined)	0·4 „ 0·7	„
Carbon (graphite)	difference	
Manganese	0·5 to 1·0	„
Sulphur	Not more than 0·15	„
Phosphorus	„ „ 1·3	„
Silicon	1·2 to 2·4	„

A test bar $\frac{7}{8}$ inch diameter cast in a sand mould and then turned down to 0·564 inch diameter should give an ultimate tensile strength of 8 to 10 tons per sq. inch.

The above iron is suitable for general purposes such as foundation plates, standards, brackets, etc. When, however, important parts such as cylinders, pistons, piston rings, and others subjected to considerable and varying stresses or conditions such as varying temperatures are to be made, the composition of the material has to be limited in respect to certain constituents. In many cases it is difficult to decide what the composition should be, and opinions of different foundry authorities will be found to vary a good deal. However, a few general, if somewhat broad, statements will be helpful in judging the quality of a given iron.

The hardness, tensile, and crushing strengths are controlled to a great extent by the combined carbon, and increase as this increases. Incidentally machining becomes more difficult with increasing carbon in the combined form. The rate of cooling and the amount of silicon present control the percentage of combined carbon, this being higher with more rapid cooling, and lower with increasing amounts of silicon. Thus the outer surface of a casting is generally harder owing to the chilling action of the mould. For this reason more silicon is added to the iron when thin-section pieces are to be cast, as this tends to counteract the effects of rapid cooling.

Thus three important factors must be considered :—(1) The combined carbon, which is controlled by (2) the rate of cooling, *i.e.* the section of the casting, and (3) the silicon content.

For the first a good value is 0·5 to 0·7 per cent. combined carbon, above this the iron becomes difficult to machine. With thin sections, say, $\frac{1}{4}$ to $\frac{1}{2}$ inch, cast in sand the silicon content may be as high as 1·8 to 2·0 per cent., while with large sections the silicon should be low, in some cases only about 1·1 per cent.

The brittleness or dynamic strength is also dependent on the combined carbon, and becomes seriously low when this exceeds 0·8 to 0·9 per cent. It is, however, more dependent on the size of the graphite flakes, and if these are large the iron will be very poor. The rate of cooling and the pouring temperature affects the size of the graphite; slow cooling from a high temperature producing a large coarse flake. In large castings this is a common source of trouble. This is distinctly seen in the micrograph, Fig. 81.

Phosphorus in amounts exceeding 1·0 per cent. increases the brittleness, although it facilitates the machining. In good work the amount of this element should not exceed 1·2 per cent. and if possible should be kept as low as 1·0 per cent.

The other constituents in cast-iron—sulphur and manganese—are generally in such proportions and in such a condition as to cause no harm. It is, however, advisable to limit the sulphur content to 0·12 per cent., and the manganese to 1·0 per cent.

The following analysis of some good quality iron castings are of interest :—

	Iron for Automobile Engine Cylinders (water cooled).	Piston Ring from Automobile Engine.	Good quality Normal Foundry Iron.	Specially Soft Iron.
Total Carbon	3·48	3·36	3·56	3·08
Combined Carbon ..	0·52	0·56	0·56	0·08
Graphitic Carbon ..	2·96	2·80	3·0	3·0
Manganese	0·84	0·48	0·87	0·34
Sulphur	0·074	0·08	0·075	0·10
Phosphorus	0·59	0·75	1·20	1·28
Silicon	1·52	2·25	1·65	2·89

Thus for the special class of work such as pistons, cylinders for automobile engines, and other parts of fairly thin section subjected to varying and high temperatures, the following composition will prove useful :—

Carbon (total)	2·60 to 3·40	per cent.
Carbon (combined)	0·50 ,, 0·85	„
Carbon (graphite)	difference	
Manganese	0·40 to 0·80	„
Sulphur	Not more than 0·12	„
Phosphorus	„ „ 0·90	„
Silicon	1·20 to 1·90	„

The tensile strength of this material, cast in sand as a bar $\frac{7}{8}$ inch diameter and turned into the standard form of test piece, should be between 11 and 14 tons per sq. in.

Casting Temperature.—The extremely variable results found in cast-iron of a particular composition are usually assumed to be due to varying pouring temperatures, but while this is probably the case it would appear that no really definite rule can be laid down as to what should be the pouring temperature.

Clearly with thin sections the pouring temperature should be high in order to fill the mould completely, while in the case of heavy sections and solid masses, it only need be high enough to enable the iron to run. Too high a temperature will cause portions of the mould (and also the cores) to be washed away and this, besides giving the casting an untrue shape, means that the sand is carried elsewhere, and is probably trapped in the metal, thus eventually leading to machining and leakage troubles. On the other hand, low temperatures cause the metal to be sluggish or more viscous, and very often it will not allow the free escape of gases, which are then trapped and thus account for blow holes. From the above, therefore, it will be seen that the pouring temperature must be adjusted to suit different castings, and that the foundryman is more or less bound to certain limits in order to produce sound castings. It is evident, however, that the practice adopted in the iron foundry of pouring a number of castings from the same ladle will often lead to varying results, on account of the fact that the iron at the commencement of pouring the first casting is much hotter than when pouring the last one. Should the castings all be of one type, as is often the case, the question of section is not present and, therefore, the only changing factor is that of the pouring temperature.

The melting point of ordinary grey iron is between 1,100° C. and 1,200° C., and according to Longmuir, who has investigated the question, the strongest iron is obtained when the pouring temperature is neither high nor low. Dr. Hatfield,* however, is not able to confirm this, and the figures in the following table show results that appear to have no connection with the pouring temperature :—

EFFECT OF CASTING TEMPERATURE ON GREY IRON

Combined Carbon.	Graphite Carbon.	Casting Temperature. Degs. C.	Maximum stress. Tons per sq. in.
0·70	2·60	1,300, hot	9·85
0·74	2·55	1,215, fair	10·32
0·73	2·57	1,135, cold	7·56
0·80	2·40	1,290, hot	9·37
0·82	2·45	1,243, fair	7·53
0·80	2·40	1,210, fairly cold	8·50
0·52	2·93	— hot	7·01
0·54	2·94	— fair	8·40
0·54	2·96	— cold	12·98

It is quite definite, however, that for thin, light castings the iron should be as hot as possible. This is particularly true with green-sand castings.

Centrifugal Castings.—Extremely good results are obtained by pouring the molten iron into rotating moulds. This method of casting is applied to the manufacture of piston rings for locomotive cylinders, internal combustion engines, and other engines. It is applied also to piston valve liners, cylinder liners, and wheel blanks, etc. Cast-iron wheels with a chilled tread are now being made in rotating moulds.

Metal moulds are employed generally for such parts and these in themselves produce castings having a fine grain, due to the greater cooling action of the metal mould as compared with a sand mould. The principal advantages of the centrifugal method, however, may be summarised as follows :—

1. Absence of blowholes.
2. Elimination of porosity.
3. Absence of large slag and dirt inclusions.
4. Surfaces free from sand.
5. Dimensions more accurate.
6. Exact concentricity of outer and inner diameters.
7. Fine-grained structure throughout the complete section.

The rapid rotating of the mould while the metal is being poured sets up a centrifugal force that is sufficient to cause the metal to displace any gases that would otherwise produce blowholes or porosity, and at the same time slag and

---

* "Cast-Iron in the Light of Recent Research," by Hatfield, p. 110.

dirt (except for minute particles) are forced into the last portion of the casting to cool, and this usually is cut off. The centrifugal action is responsible also for the concentricity of the casting.

The metal mould eliminates the sand difficulty and accounts for the greater accuracy of the castings as compared with those produced in sand moulds.

The agitation of the metal during solidification due to rotation of the mould appears to have the effect of producing a very fine, and at the same time regular, grained structure throughout the entire section.

In the manufacture of piston rings a cylindrical-shaped casting is made, one end of which is of a heavy section in order to collect the slag, dirt, and other troublesome elements. This heavy-section end is cut off and the remainder of the cylinder is machined inside and outside to the correct diameters, after which operation it is cut into slices each of which forms a piston ring.

Chill Castings.—The use of metal moulds makes it possible to produce castings having a hard surface and a comparatively soft core. The action of the metal mould is to increase the rate of cooling (chilling) and thus prevent, to a great extent, the separation of graphite. The iron in immediate contact with the metal mould cools so rapidly that the carbon is retained in the combined state and in consequence the surface is extremely hard. The interior of the casting, of course, cools more slowly and there is sufficient time for the graphite to separate out. Castings made in this manner will show, when broken, a grey centre and a hard white outer layer, the thickness of which depends (apart from composition) on the rapidity of the cooling.

In the majority of cases the mould is partly sand and partly metal. The metal portions, or chills as they are called, are placed wherever it is desired to obtain the chilling effect on the casting. Thus car wheels are cast in moulds consisting of a sand centre and an outer metal ring which acts as a chill on the tread of the wheel and causes it to be very hard.

This process is adopted for such parts as rolling mill rolls, grinding mills, rock crushers, etc. The depth of the chilling action can be varied from say ½ inch up to 3 inches to suit the size of the part and the duty it has to perform. Reducing the silicon content and increasing the thickness of the chill (metal portion of mould) increases the depth of the chilling action. Thus the amount of silicon in the iron is an important factor.

The chilled layer of castings made in this manner consists of white iron which, owing to the high percentage of combined carbon present, is too hard for machining and can only be fashioned by grinding. Chilled rolls and similar parts are generally ground to size.

To reduce brittleness in the chilled portions it is essential that the phosphorous content should be low (0·20 to 0·40 per cent.). The composition of the chilled layers of an ordinary roll employed for rolling thin steel sheets is approximately :—

Carbon, total	3·10 per cent.
Carbon, combined	1·80 ,,
Silicon	0·70 ,,
Sulphur	0·10 ,,
Phosphorus	0·50 ,,

In a well-made casting the change from the white iron (forming the outer layers) to the grey iron (forming the centre) should be gradual, otherwise there is a risk of portions of hard outer layer breaking away.

Shrinkage and Contraction.—The shrinkage effect in cast-iron must not be confused with contraction. When iron is poured into a mould the portions that solidify first are those in contact with the mould, and a shell is formed having the shape and practically the same size as the mould. The inner portions of the iron solidify next, the freezing taking place inward, proceeding from the walls and, because the freezing is accompanied by shrinkage, the last portions to solidify will be spongy or a cavity may even be formed. If a feeder is provided the extra molten metal necessary to make up the shrinkage can be added before the casting is completely solid. This, of course, is done in most cases, especially with large and heavy sections. The casting temperature influences the shrinkage, which is greater the hotter the metal.

The solid metal during cooling *contracts* in the natural manner common to most heated metals but, over and above this change, there are other changes due to internal chemical and physical changes. These secondary changes are expansion effects, and are greater in grey irons than in white irons.

For practical purposes, however, it is the complete or net change that is important, and must be allowed for.

This is least in grey irons and depends to a great extent on the silicon content. The most useful work in this direction is that of Keep, and his table is given here.

"NET CONTRACTIONS" OF CAST-IRON

Average Silicon per cent.	Size of Test Bars (all 12 inches long).						Kind of Iron.
	½ in. square	1 in. square	2in. × 1in.	2 in. square	3 in. square	4 in. square	
0·80	0·183	0·160	0·148	0·131	0·116	0·102	"Iroquois," with silicon added by Pencost, ferro-silicon.
1·21	0·172	0·150	0·138	0·125	0·110	0·106	
1·88	0·166	0·145	0·130	0·109	0·069	0·039	
2·01	0·162	0·143	0·123	0·099	0·066	0·128	
3·19	0·157	0·105	0·094	0·075	0·067	0·057	
3·04	0·169	0·130	0·086	0·077	0·085	0·033	
0·93	0·176	0·149	0·144	0·139	0·115	0·072	"Hinkle" and Pencost.
1·17	0·160	0·145	0·126	0·122	0·093	0·092	
1·67	0·156	0·141	0·134	0·128	0·083	0·036	
2·23	0·154	0·124	0·092	0·094	0·075	0·067	
2·71	0·157	0·102	0·090	0·062	0·053	0·023	
3·50	0·144	0·098	0·092	0·068	0·043	0·023	
2·82	0·148	0·098	0·083	0·072	0·063	0·035	Ulich Stove Co.
3·18	0·130	0·095	0·091	0·079	0·072	0·052	,, ,,
3·50	0·123	0·094	0·096	0·091	0·078	0·032	,, ,,
0·77	0·238	0·153	0·142	0·144	0·126	0·115	Car-wheel Iron.
1·76	0·171	0·151	0·143	0·129	0·100	0·069	Light machinery.
2·06	0·161	0·139	0·120	0·091	0·067	0·042	Heavy machinery.
0·89	0·248	0·247	0·221	0·201	0·157	0·144	Air furnace for malleable.

It will be seen that the contraction is less in the case of the large sections, a factor of considerable importance in large castings. Generally, the allowance made in practice is ⅛ inch to the foot for ordinary foundry iron. With white irons the allowance should be $\frac{3}{16}$ to $\frac{1}{4}$ inch, but if "black-heart" malleable castings are required this allowance is too much since the annealing process tends to expand the metal (due to the precipitation of fine carbon), and the net allowance need only be about $\frac{1}{8}$ inch to the foot. With English "white-heart" castings an allowance of $\frac{3}{16}$ inch should be made.

Strength of Cast-iron.—The strength of cast-iron is greatest under a crushing load, and for this reason is most suitable for supporting machinery in the form of base or foundation plates, columns for supporting floors or roofs in buildings, etc.

The crushing strength of cast-iron may be assumed as 40 tons per square inch, but results as high as 60 tons and as low as 30 tons per square inch are obtained. Such results are, however, influenced by the proportions of the test piece, as is shown by the following experiments carried out by Hodgkinson on cylinders $\frac{1}{2}$ inch in diameter.

Height of cylinder, inches	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{3}{4}$	$1\frac{1}{2}$	2	$3\frac{3}{4}$
Crushing strength, tons per square inch ..	*69·3*	*63·5*	*60·0*	*55·0*	*53·3*	*53·3*	49·6	34·4

Professor Unwin considers "That if the height does not exceed three diameters the strength is fairly uniform." He also points out that the usual form of fracture under test "is shearing at an oblique plane making an angle of about 56° with the axis."

The tensile strength varies from 5 to 18 tons per square inch, the usual value for the commoner grades being about 9 tons per square inch, while with the better grades it varies from 11 to 15 tons per square inch. The higher values are, however, obtained only with high percentages of combined carbon, and the machining properties of the metal in consequence are not so good.

The yield point or elastic limit is practically the same as the breaking load, and there is little or no elongation or reduction in area.

The dynamic strength of cast-iron is very poor, and impact tests on the Izod machine are generally not higher than 2 ft.-lbs., compared with steels that give values from 20 to 100 ft.-lbs.

The most common test for cast-iron is the transverse test, which consists of applying a load to the centre of a bar supported at its ends. The standard test bar is 40 inches long, and 2 inches deep by 1 inch wide. This is supported on knife-edges placed 36 inches apart, and the load is applied at the centre, where a third knife-edge is placed. The load is increased gradually, and the deflection of the bar is noted. The breaking load for good average quality iron is 26 to 30 cwt., but higher values are often obtained. Adamson[*] quotes typical results obtained in practice, and these are reproduced on next page.

According to some experiments made by Hailstone[†] it would appear that the best bar is one cast 42 inches long, and $2\frac{1}{8}$ inches by $1\frac{1}{8}$ inches section, and then machined down to 2 inches by 1 inch section, and tested on 36-inch centres. This size of bar gives the most consistent and comparable results, both as regards breaking load and deflection. The load should be applied at a rate not exceeding 1 cwt. every 15 seconds.

The test bar adopted by the American Society for Testing Materials and known as the Arbitration test bar, is 15 inches long by $1\frac{1}{4}$ inches diameter (at top). This bar is cast vertically, and the bottom is $\frac{1}{16}$ inch less in diameter than the top, to allow for draft. The bar is tested on supports 12 inches

[*] Adamson, *Iron and Steel Institute*, 1909, vol. iii.

[†] George Hailstone, *Iron and Steel Institute*, 1914.

TRANSVERSE TESTS

Analysis.							Transverse 3 ft. centres.	Deflection.
Total carbon.	Graphite carbon.	Combined carbon.	Silicon.	Sulphur.	Phosphorus.	Manganese.		
Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Cwt.	Inches
3·56	2·98	0·58	1·53	0·110	1·19	0·90	34·75	0·336
3·56	3·03	0·53	1·65	0·089	1·19	0·85	38·5	0·386
3·57	3·04	0·53	1·67	0·106	1·20	0·85	36·5	0·329
3·56	3·00	0·56	1·65	0·075	1·20	0·87	35·0	0·329
3·58	2·99	0·59	1·88	0·10	1·17	0·80	36·5	0·359
3·57	2·98	0·57	2·0	0·09	1·17	0·81	30·0	0·314
3·56	2·98	0·58	1·30	0·077	0·59	0·68	31·5	0·329
3·59	3·05	0·54	1·46	0·073	0·84	0·65	28·5	0·347
3·56	3·02	0·54	1·72	0·072	0·78	0·66	29·5	0·350
3·56	3·00	0·58	1·86	0·072	0·70	0·65	27·5	0·321

apart, the load being applied at the centre. The load to produce a deflection of 0·10 inch should not be less than 2,500 lbs. for light castings, 2,900 lbs. for medium, and 3,300 lbs. for heavy castings.

A testing machine intended for this form of test is shown in Fig. 181.

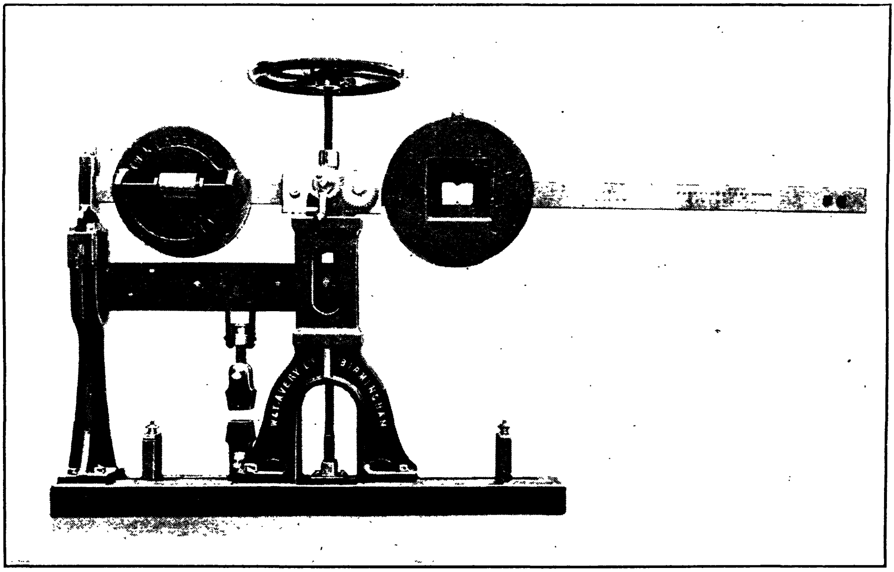


FIG. 181.—Transverse and Tensile Testing Machine for Cast-iron.

The specimen is supported by two adjustable dogs mounted on the frame of the machine, and is pulled upwards at the centre by a swinging stirrup. The latter is operated by the handwheel at the top of the machine, which carries a scale and vernier, for indicating the deflection of the specimen before breakage. The machine has knife-edges for two standard centre distances—36 inches and 12 inches, and a capacity for bending of 50 cwt. It is also conveniently arranged to test standard tensile pieces, and has a range in tension up to 4 tons total load.

Hardness tests for cast-iron are mainly of service for determining the machining properties of the metal, but are also helpful in selecting metal for bearings and slides, etc., where the wearing quality is highly important. Such tests, however, require careful judgment because of the difference that exists between the outer surface of the casting and its interior, due to the chilling effect of the mould. The Brinell testing machine gives fairly satisfactory results and, according to Stead and Jones,* the following figures are typical ones for the irons mentioned :—

BRINELL TESTS. BALL 10 MM. DIAMETER. PRESS. 3,000 KILOS.

	Average Hardness No.
Glazed iron	143
No. 1 ,,	104
No. 3 ,,	112
No. 4, foundry	156
No. 4, forge	160
Hard forge	197
White iron	418
Pure Swedish wrought iron	87
Hard face of chilled casting	445
Middle of chilled casting (mottled)	350
Grey back of chilled casting	207

The Shore scleroscope may be used, and with ordinary grey irons readings from 29 to 38 will be obtained. This instrument, however, is not recommended owing to the difficulty in obtaining a satisfactory surface and uniform figures.

Effect of Temperature on Strength.—The strength of cast-iron falls off as the temperature is increased. This is shown by the experiments carried out by H. Meyer, who tested bars 19·7 inches long, and 1·18 inches diameter on a Krupp bending machine while they were heated in baths of oil, tin, lead, and aluminium. The following curve, Fig. 182, shows how serious this change in strength is.

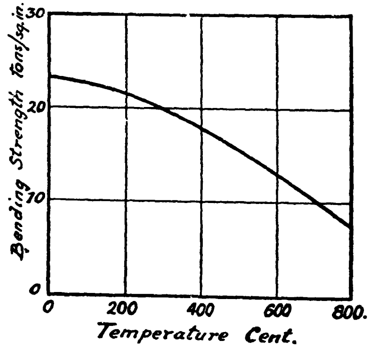


FIG. 182.—H. Meyer's Tests showing how the Strength of Cast-iron falls off at Higher Temperatures.

---

* *Proc. Cleveland Inst. of Engineers,* 1906–07.

Hatfield states that Cary's results support the above characteristic of cast-iron, and quotes the following figures :—

Temperatures.	Strength.
900° F.	30,000 lbs.
1100° F.	20,000 lbs.
1500° F.	10,000 lbs.

It is important, therefore, when fittings or other parts which are intended for use at high temperatures, such as superheated steam or internal combustion engine cylinders, are being designed that due allowance should be made for this loss of strength at the working temperatures.

At still higher temperatures the growth effect commences, but this is a distinctly different effect to that now explained, and is dealt with in the next few paragraphs.

Heat Treatment.—The normal form of treatment for grey cast-iron is annealing, and this is carried out with the object of relieving the internal stresses set up during the casting operation, and also in many cases to improve the machining qualities.

Ordinary annealing of grey iron may be done at a temperature of 750° to 800° C., when the combined carbon is converted into free graphite. Thus the hardness of the metal is materially reduced and it becomes quite easy to machine. This treatment is described in Chapter X.

The strength of the iron, however, is also lowered to a very great extent, and because of this the process of annealing should not be undertaken without realising what the diminution of strength will be in the treated parts.

Hatfield * gives the results of some tests made to determine the effect of annealing grey cast-iron, and shows that irons having a tensile strength of 8 to 12 tons per square inch give only about 3 tons per square inch after annealing at 900° C. for several hours and slow cooling over 48 hours. The combined carbon, which was about 0·5 per cent as cast, was reduced to about 0·2 per cent. by the annealing.

More recently Jean Durand † has undertaken a series of tests on the heat treatment of grey cast-iron which confirm Hatfield's results with annealing at 900° C. and show that 45 minutes' heating at this temperature reduces the tensile strength of 13 to 15 tons per square inch to about 10 tons per square inch. The most important phase of Durand's investigation, however, is the quenching and reheating treatment. Thus the quenching in oil at 900° C. and the reheating to 650° C. gave the following results :—

Sample No.	Ultimate Tensile Strength, tons per sq. inch.		Mean Breaking Height in inches.	
	Before.	After treatment.	Before.	After treatment.
A ..	14·6	19·4	25·3	43
B ..	16·1	19·2	21·4	31·2
C ..	13·0	16·8	21·4	37·0
D ..	14·6	17·3	25·3	31·2

---

* *Journ. Iron and Steel Inst.*, 1907

† *French Académie des Sciences*, 1922.

These results are of considerable importance because they show the possibility of improving many castings required for special service. The dynamic strength of the material must be improved by this treatment; in fact, this is shown by the drop test figures.

Low temperature annealing, however, may be applied to overcome stresses set up in rough machining, and to partly relieve the casting stresses. Heating up to temperatures of about 350° to 400° C. (which turns the machined surface to a blue-grey colour) will be found beneficial, and will not reduce the strength of the metal considerably.

Hard metal can be heated to about 600° C. for a short time to improve its machinability, but this will affect its strength appreciably.

The heat treatment of cast-iron is confined more to the white varieties, and is dealt with further under the heading of Malleable Iron.

Growth of Cast-iron.—The effect of repeated heating and cooling on cast-iron is a permanent increase in volume. This change is much greater with grey irons than with white irons, and may be very serious in its results because of its enormous extent.

According to Rugan and Carpenter,* who carried out a most exhaustive research on this subject, it appears that with a grey iron, beyond a permanent change that takes place at the temperatures of superheated steam and which is of a different character, no growth takes place until the metal is heated to about 650° C., while at 730° C. it appears to reach a maximum, although at higher temperatures up to 900° C. a very slight increase is just perceptible. Further, the maximum increase was obtained by three hours' heating at the given temperatures, and any further increase in the heating time made no difference.

Some test bars were cut from a new annealing oven casting made from ordinary commercial iron containing 3·14 per cent. carbon and 0·96 per cent. silicon, and were repeatedly heated to temperatures varying from 850° to 950° C. and kept at these temperatures for four hours. One of these bars to commence with was 5·9968 inches long, and 0·750 inch diameter, having a volume of 2·648 cubic inches. The change in size after a given number of heatings is shown by the following figures—

Heat No.	Increase in Length.	Increase in Diameter.	Per cent. Increase in Volume.	Per cent. Increase in Weight.
1	0·0572	0·007	2·91	—
7	0·2817	0·0362	14·80	1·91
21	0·4602	0·0539	23·15	2·52
32	0·4804	0·0564	24·65	2·66
42	0·5162	0·0597	26·50	3·68
52	0·5342	0·0625	27·70	3·70
61	0·5703	0·0673	29·70	4·42
71	0·6008	0·0730	32·25	5·16
81	0·6282	0·0775	35·40	6·29
99	0·6572	0·0840	36·80	7·90

From these results it will be seen that the length of the bar increased by 0·6572 inch, or nearly 11 per cent., while the diameter increased by over

---

* Paper, *Iron and Steel Inst.*, May, 1909

11 per cent., the total volumetric increase being 36·8 per cent. The other bars behaved in much the same way. The increase in weight is due probably to oxidation of the iron and the silicon contained in it. This more than counterbalances the loss due to oxidation of the carbon.

A series of bars of white iron, free from graphite but of varying carbon content, were tested in a similar manner, but instead of an increase in the volume being found, an actual decrease took place, varying in extent from about ½ to 1½ per cent.

As a result of these and other experiments, Rugan and Carpenter suggest that a good iron for resisting the effects of repeated heating is one containing about 3 per cent. of carbon with only very small percentages of other elements present. This deduction is considered by Hatfield * to be correct. This should be amplified by adding the statement that the carbon must not be in the graphitic condition.

Silicon appears to influence the growth, and the same authors show that the growth is proportional to the amount of silicon present (up to 6 per cent.).

Carpenter,† who has carried out further investigations, showed how little the following irons grew with repeated heating at high temperatures.

	No. 1.	No. 2.	No. 3.
Carbon	2·40	2·40	2·25
Silicon	0·485	0·471	0·406
Sulphur	0·01	0·01	0·01
Phosphorus	0·01	0·01	0·01
Manganese	0·51	0·735	0·935
Change in volume per cent.			
After heat 11	−0·08	−0·09	−0·22
,, ,, 27	+1·66	+1·05	−0·09
,, ,, 100	+4·92	+4·15	+1·61
,, ,, 151	+7·49	+6·06	+3·09

From the above it will be seen that the growth becomes less as the manganese content is increased, and it was shown that an iron containing 1·60 per cent. manganese, but otherwise similar to the above, had practically no tendency to grow.

Further, it was found that these irons retained their strength while the grey irons became very weak.

Arnold takes exception to the low carbon content, while Hatfield considers that this could be raised to 3 per cent. without materially decreasing the good results obtained above, but with some improvement in the flowing properties of the metal which would otherwise run rather sluggishly. It would be necessary to keep the sulphur and phosphorus low in order that this increase in the carbon should not render the material more brittle.

The causes of this growth are discussed at some length, and the reader is

---

* "Cast-Iron in the Light of Recent Research," 1918, p. 132.

† *Iron and Steel Inst.*, May, 1911.

referred to the actual papers or to the very excellent presentation of the whole subject given in Hatfield's book, "Cast-Iron in the Light of Recent Research."

Advantage has been taken in America of this growth to reclaim castings that were too small, but this method is questionable owing to the tendency to weaken the castings, and it is now clear that with castings that are too small the only thing to do is to break them up and remelt.

Internal Combustion Engines.—It is common practice to make the cylinders and pistons of internal combustion engines of cast-iron, and as these are subjected to rapidly changing stresses and variations in temperature, it is important that the metal used should be carefully chosen. Experience with gas, petrol, and other internal combustion engines shows that the iron used for such parts as the piston, cylinder (or cylinder liner), and cylinder head tends to expand permanently, and that the piston will sometimes seize after running a little time. The trouble also extends to the cracking of the piston top and of the cylinder (usually close to the valve openings). This troublesome feature is referred to as growth of the iron, and it would at first appear that this growth is of the same character as that described under the heading, "Growth of Cast-Iron," but there is some uncertainty about this, as is shown by J. E. Hurst.*

Hurst considers that the change in volume is due to an expansion among the grains composing the liner and piston surfaces, caused by the rapid succession of changes of pressure within the cylinder. As a result of this, gas and lubricant penetrate between the grains by way of the graphite plates. This action is confined to the surface layer only, and causes a loosening of the outer grains which becomes the principal factor in the wear of the liners and pistons.

The cracking trouble, which is most pronounced in the tops of pistons, is explained by Hurst as due to the changing state of the carbon constituent brought about by the changing temperatures, which effect is greater with increasing percentages of phosphorus. Also the behaviour of the phosphorus constituent is no doubt partly responsible, and so also the internal gas pressure.

Hurst's experiments tend to show that at the high temperatures existing in a Diesel engine cylinder the combined carbon is first of all dissociated at temperatures between 750° to 900° C., and is then reabsorbed at the higher temperature of about 950° C. The free carbon resulting from the dissociation causes an internal stress due to its lower density, while the reabsorption produces gaps or cavities in the metal which at once weaken it. This trouble is aggravated by the presence of phosphorus which assists the reabsorption considerably. The repeated changing of the carbon from the combined state to the free state and back again, is sufficient itself to cause repeated expansions and contractions in the metal, and to lead eventually to cracking. In all probability the phosphorus constituent (phosphide of iron eutectic), which melts at 953° C. is partially liquated and thus contributes to the breaking apart of the grains. Further, the high and rapidly fluctuating pressures in the cylinder forces the gas into the cavities and cracks produced by the absorption of the carbon (graphite) and the liquefaction of the phosphide eutectic, and also tends to bring about rupture.

The chief statement made by Hurst is that "it has been found, as a result of long experience, that the ultimate cracking of Diesel engine piston tops

---

* *Engineering,* August 4, 1916; *Iron and Steel Inst.*, September 20, 1917.

(apart from those cases of mechanically defective pistons), can as a general rule be traced to the phosphorus content of the cast-iron."

" A typical analysis of an actual cast-iron piston is given below :—

Combined carbon	0·73	per cent.
Graphite	2·80	,,
Total carbon	3·53	,,
Silicon	1·92	,,
Sulphur	0·144	,,
Phosphorus	1·08	,,

" Cast-iron pistons of this type almost invariably crack after actual use in the Diesel engine. By the reduction of the phosphorus content of the cast-iron to the lowest possible limits, the life of the piston was considerably prolonged and the troublesome cracking practically eliminated."

The German chemical authorities, as reported in the proceedings of the Chemical Society, state that where iron has to be used in work at which the temperature widely varies the phosphorus content should not exceed 0·66 per cent. The reason for this is that the phosphide eutectic takes up varying forms with each change from high to low temperatures, and the iron crystals (grains) regroup themselves round the new form, thus causing a change in shape.

It is difficult to secure a regular supply of castings containing 0·5 to 0·6 per cent. phosphorus, although many foundries will undertake to do it. Usually the metal contains about 0·8 per cent., and this appears to be a practical limit (maximum).

Semi-Steel Castings

This material is regarded by many engineers with suspicion, and not without cause, because many foundries do not understand the method for its production.

Briefly semi-steel is simply a high grade cast-iron possessing fewer impurities and a better physical structure than the ordinary grades of cast-iron. In practice it is produced by adding from 10 to 40 per cent. of steel scrap to the grey iron ; melting the mixture in the cupola. Some foundries add the steel to the molten iron when in the ladle, but the proportion that actually melts can only be small (seldom more than 5 per cent.), and the mixing is very imperfect, the resulting metal being patchy and of uneven grain and hardness. Obviously, the melting together of the two main ingredients, scrap steel and grey iron, must tend to produce a metal of a more uniform and consistent quality than that obtained by the ladle method. Moreover, a greater proportion of steel can be added to the metal.

Semi-steel is superior to ordinary grey iron in regard to tensile, compression, transverse, and impact tests. It resists shocks and wears better than cast-iron and it also possesses a higher degree of elasticity and toughness. The structure is close-grained, uniform, and generally the castings are free from blowholes and hard spots. The steel appears to prevent the formation of large graphite flakes and these are finely broken up and well distributed. The phosphide areas also are small and well distributed. Although the composition of the metal is important the qualities of semi-steel are mainly dependent on its physical structure. Thus the close fine-grained structure, the formation of the graphite, and the uniform distribution of the phosphide areas account for its high physical strength. The machining quality of semi-steel is superior to that of grey iron and high speeds can be adopted, while the metal also takes a better polish.

The composition of semi-steel depends on the class of iron used, and on the proportion of steel scrap added. One of the claims of the semi-steel enthusiasts is that the ordinary common grades of iron can be used and that good results are obtained. Although this is correct to a certain extent, there is no doubt but that the use of better irons such as hematite will produce still better results.

For light castings of thin sections a small proportion only of steel is added (10 to 20 per cent.), but for the heavier castings the percentage of steel may reach 40 or even 50 per cent.

The following results quoted by Cameron * are interesting because they represent regular everyday practice. Three transverse test bars, 15 inches long by 1 inch square, were cast and on test were found to have an average tensile strength of 15 tons per square inch and an average transverse strength of 26½ cwt. with a deflection of 0·12 inch under 2,500 lbs. (on 1 inch by 1 inch bar at 12-inch centres).

The compositions of these bars are given below :—

	No 354.	No. 355.	No. 356.
	Per cent.	Per cent.	Per cent.
Carbon (total)	3·409	3·426	3·279
Carbon (combined) .	0·510	0·578	0·589
Carbon (graphite)	2·899	2·848	2·690
Manganese	0·810	0·520	0·680
Sulphur	0·052	0·038	0·058
Phosphorus	0·600	0·550	0·570
Silicon	2·450	2·120	2·380

Other bars gave higher tensile figures, and with some bars of smaller section (5 inches long by ⅝ inch diameter) an average of 18 tons per square inch was obtained.

The specification adopted by the American Society for Testing Materials in 1922 is summarised as follows :—

The transverse test specimen is 15 inches long by 1¼ inches diameter and is cast vertically, a taper of 1/16 inch being allowed for drawing and for the strain of pouring. This specimen when placed horizontally upon supports 12 inches apart must withstand a load (centrally applied) of 3,800 lbs., and deflect under this load at least 0·12 inch at the centre.

The tensile test piece is machined from one of the broken pieces of the transverse test specimen and must show a minimum tensile strength of 12·5 tons per square inch.

Semi-steel is employed successfully for cylinders, pistons, gear wheels, hydraulic valves and cylinders, and also for many other castings that are required to resist wear and friction. Owing to its close-grained structure this material will withstand high water pressures without signs of leakage.

---

* "Semi-Steel," J. Cameron, *Inst. British Foundrymen*, 1922.

Mr. Fletcher suggests the following composition for semi-steel for use in cylinder, hydraulic valves, and fairly heavy munition castings :—

Carbon, total	2·8 to 3·2 per cent.
Carbon, graphitic Carbon, combined } ratio	3·0 „ 3·2 „
Manganese	0·6 „ 0·9 „
Phosphorus	under 0·30 „
Silicon	1·0 to 1·5 „

The relationship of the total carbon to silicon should be :—

Castings 2 inches thick and above ..	C+Si=4·2 per cent.
„ 1 inch to 1¾ inches thick ..	C+Si=4·3 „
„ ½ „ ¾ inch thick ..	C+Si=4·5 „
„ ¼ „ ½ „ ..	C+Si=5·0 „

David McLain is probably the biggest exponent of semi-steel castings and many foundries have adopted his system for producing this material. The procedure in melting and casting is very different to that for producing ordinary grey iron, and, in consequence, some foundries are failing to obtain satisfactory results although they offer to supply semi-steel castings.

Malleable Castings

Malleable castings are made from a special quality of white pig-iron, and, in order to reduce the brittleness associated with cast-iron, they are subjected to what is commonly referred to as an " annealing process."

This process of annealing or malleablising, which is a lengthy one, gives to the castings the property of resisting shock to a remarkable degree. This likeness to ordinary malleable iron (wrought-iron), and the fact that the parts can be produced and machined with such ease, compared with forgings, makes the process a valuable one.

Two distinct variations of the process are in use :—

(1) the original or Reaumur, generally referred to as the " European " or " White-heart " method ; and

(2) the " American " or " Black-heart " method, used extensively in America.

The difference between the results obtained by these methods is seen at once by examining the fractures : the Reaumur castings having a white glistening uniform structure which gives them the name of white-heart in contradistinction to the latter or black-heart castings, which exhibit a dark or black structure often surrounded with an outer layer of white iron * following the contour of the casting and situated at its surface.

The object of both processes is to reduce the carbon from the combined form (iron carbide) to a state in which it exerts little or no influence on the mechanical properties of the metal, which then behaves in a manner similar to wrought-iron.

" White-heart " Method.—In the Reaumur process the carbon (during the annealing operation) is not only reduced from the combined form, but is removed to a great extent by oxidation, thus leaving the metal nearly free of carbon, which accounts for the white structure referred to above.

---

* In America this type of fracture is considered poor and the material is known as " picture frame stuff," because of the white layer of iron that surrounds the black centre.

The castings are made in the ordinary way and then subjected to the annealing process, which oxidises and removes the carbon. The process, however, is not adaptable to any class of iron; grey iron cannot be used because the large graphite flakes when oxidised away leave spaces, and the metal becomes useless. White iron must be employed, and must be carefully selected with regard to its impurities. The castings when taken from the mould should be hard, brittle, and free from graphite.

The castings are "packed" in iron oxide (usually red hematite ore) and heated to 900° to 950° C. for a considerable period, often running into several days, when the carbon is almost completely oxidised away.

Although the malleable casting industry is a very old one the average engineer has not had sufficient faith in the past in malleable castings to employ them for important and reliable mechanical structures. This is due to the variable and uncertain qualities of the castings produced by many foundries, a condition of affairs that was undoubtedly the result of a policy of secrecy and trade jealousy, and to the fact that the main underlying principles were not known or understood by more than a few of the trade. Fortunately these conditions have given way to a more enlightened policy, and malleable iron castings of a consistent and high standard of quality are now produced quite regularly. Apart from their application to railway purposes, white-heart castings are used in large quantities for many important parts in automobile construction.

Since the majority of malleable castings produced in England are of the white-heart type, it is necessary to consider the characteristics of this type and to appreciate some of the factors that govern the success of such castings in their applications to general engineering. In the first place sulphur is the dominating factor. It is the high percentage of sulphur in the British irons that prevents the general adoption of the black-heart method in this country. In America low sulphur irons are readily obtainable and this, combined with the fact that production is on a large scale, makes it possible to produce the black-heart type of casting. Sulphur retards the dissociation of the combined carbon and in consequence it is necessary to anneal the castings at high temperatures to break down the combination and to effect oxidation of the carbon with sufficient rapidity. Some of the English foundries are producing castings of the black-heart type, using a proportion of iron that is obtained either from America or Sweden, but, judging by published figures, this material is not equal to that produced in the U.S.A.

Most of the metal for white-heart castings is melted in the cupola, as this is the cheapest method of melting. Crucible melting is also adopted, but owing to the higher cost of this method it is confined to work in which quality is the main consideration. The chief advantage of crucible melting is the absolute control of the composition, whereas with cupola melting the iron absorbs sulphur from the coke and loses silicon and manganese by oxidation. The cupola can be controlled so as to produce cast after cast each having the same composition (within fairly narrow limits), but the main defects of this method of melting still remain and these are the absorption of sulphur and the loss or variation of the other constituents silicon and manganese. Although fairly low sulphur pig-iron can be obtained and is generally used, it is not uncommon to find the castings containing up to 0·4 per cent. sulphur and even more. With care in the selection of the iron and in the melting it is possible to prevent the sulphur exceeding 0·2 per cent.

During solidification in the moulds the metal shrinks more than ordinary grey cast-iron and for this reason the feeders are usually made larger to prevent "drawing" or sponginess. Thus it is important to avoid abrupt changes in section unless it is possible to provide a feeder to the heavy section. The castings when taken from the mould are extremely hard and brittle and if the part is a complicated one of varying section the casting may crack quite easily because of the internal stresses set up during cooling. This difficulty is overcome to some extent by removing the castings from the moulds (while hot) to a furnace in which they are allowed to cool slowly. The design of the part, however, should be considered from the foundryman's point of view, when no doubt it will be found that increasing the thickness of certain portions of a pattern will reduce the manufacturing risks and thus reduce the cost of production.

The packing of the hard castings in the annealing cans for the annealing operation is an important phase of the process. Hematite ore (iron oxide) is used, and is kept up to strength by adding a proportion of new ore. The ore serves two purposes: firstly to oxidise the carbon in the castings and, secondly to support the castings during the prolonged heating which the process of annealing requires. Unless the packing is efficient a proportion of the castings will sag or become distorted to an extent which will render them useless for service. Most foundries employ a "straightener," whose work is to correct the castings that have distorted during the annealing operation.

Very few foundries produce true white-heart castings (*i.e.* metal almost free from carbon); in fact, the only castings that come up to this standard are those of thin section, varying from the thinnest up to ¼ inch thickness. The reason for this lies in the difficulty of removing the carbon from the inner portions of the castings. The annealing process depends on the action of gases which enter the casting and oxidise the carbon. This action naturally commences at the outer layer of the casting and then gradually penetrates into the metal, the centre portions being the last to be affected. Thus a casting when broken will be found to have more carbon in the centre of the section than in the outer layers. When the section is a large one the time required to effect removal of the carbon (even to within a reasonable amount) is very considerable and might be 15 to 20 days. Further, it is evident that the thinner sections of a casting will lose their carbon more completely than the thicker sections, and therefore will be softer and more ductile.

In the black-heart method the object of annealing is not to remove the carbon (although a small amount is oxidised), but simply to precipitate it from the combined into the free state (as nodules of graphite). This precipitation of carbon proceeds uniformly over the entire section of the casting and, because of this, thick sections possess almost the same qualities as thin ones. No carbon is left in the combined state and the annealing does not depend on the action of gases for the removal of carbon. Thus black-heart castings possess a structure which is uniform over the complete section, whereas white-heart castings have a structure which varies from the outside surface to the centre of the section, there being more carbon (in the combined state) in the centre portions than at the surface layers.

This variation in white-heart castings sometimes accounts for the fact that such castings can be machined on the surface (perhaps to a considerable depth), but owing to the hard core in the centre it is difficult, if not impossible, to drill a hole through them. This condition is an extreme one, and such castings may be said to have been annealed insufficiently. Even when large castings have been annealed well, there is a considerable difference in the machining qualities of the metal at the centre of the section as compared with the outer portions.

To overcome this difficulty many foundries modify the composition of the iron in such a manner as to bring about the precipitation of a proportion of the combined carbon (in the same manner as with black-heart metal), and by this means reduce the percentage of combined carbon in the centre portions of the casting. The greatest care is taken to prevent the percentage of sulphur from increasing, and the silicon content is adjusted to ensure the rapid precipitation of carbon (when annealing). Such metal is not true white-heart nor is it black-heart, but it gives very satisfactory results and in practice it is found that castings of thick section are fairly uniform in structure from outside to centre and machine with equal facility almost at any portion. Thus castings produced in this manner contain a certain proportion of carbon in the form of graphite nodules, which are distributed over the main portion of the metal. A small amount of carbon remains in the combined state and takes up the form of pearlite. This pearlite will be more in evidence at the centre of the section than at points nearer the surface of the casting.

The principal defects in malleable iron castings are as follows :—

(1) Hard metal, due to insufficient annealing which in turn may be the result of an unsuitable composition.

(2) Peeling of the metal, generally due to over-annealing or over-heating during annealing.

(3) Distortion, caused during the annealing operation through inefficient packing. Such castings may often be reclaimed by hammering or pressing back to shape (thick sections should be heated to a dull red, about 650° C.).

" Black-heart " Process.—This differs from the white-heart process in that only a little of the carbon is oxidised away, and this only at the outer surface of the castings. The carbon is reduced from the combined form and remains distributed throughout the mass in a fine granular state giving the characteristic black appearance to the fracture.

This process is the one adopted generally in America, where malleable iron castings are produced on a large scale and are employed more widely than in England. As stated already the success of this method depends on using irons of very low sulphur content and, as such material is readily obtainable in America, the process is almost universal there, whereas in England such iron is difficult to obtain and, for most purposes, is too expensive. Moreover, owing to the fact that the iron must be melted in the open-hearth, or air type of furnace, it is necessary to produce a large tonnage in castings in order to make the process a commercially economic one. With a few notable exceptions the malleable iron foundries in England are too small to adopt this process on a competitive basis. There are a few, however, who manufacture black-heart castings, but it is doubtful whether these compare favourably with the American-made material.

The iron is melted in open-hearth furnaces or more generally in air furnaces in order to prevent it absorbing sulphur from the fuel and in order to regulate its composition more closely. The castings when taken from the moulds are hard and brittle and exhibit a fracture somewhat similar to those obtained with the cupola metal. They contain much less sulphur, however, and because of this the annealing operation is simpler and can be carried out at a lower temperature than that required for the white-heart material.

The annealing operation is conducted at a temperature of about 750° C. to 850° C., and no attempt is made to oxidise the carbon, the castings being packed in sand, slag or scale, simply with the object of supporting them during annealing. The combined carbon dissociates completely (or nearly so), and takes up the form of nodules or rosettes, which are distributed uniformly over the entire section of the casting. A small amount of oxidation may take place at the surface, in which case a thin white skin of iron is formed but in good material this is not pronounced. This dissociation of the combined carbon proceeds more or less uniformly throughout the mass of the casting and for this reason the annealing of thick sections is almost as rapid as with thin ones, a condition which is very different to that experienced in the annealing of white-heart castings. Thus black-heart castings machine with equal facility at any portion of their section.

Since the process is one of dissociation and precipitation only, and does not depend on the slow action of an oxidising gas (as with white-heart annealing), the time required for annealing is much less than that required with the white-heart method. This combined with the fact that a lower temperature is employed, results in less distortion of the castings and thus eliminates one of the most serious troubles of the white-heart process.

Comparison of the two Types of Castings.—The average compositions and physical properties of the two materials are given in the table below. In practice it will be found that both materials often depart very considerably from the figures quoted. This is the case particularly with white-heart castings, the mechanical properties of which depend very much on their thickness. The figures given in the table are based on the results of tests made on the standard test bar (section 1 inch wide by $\frac{3}{8}$ inch thickness with elongation centres 3 inches apart).

Usually true white-heart castings do not exceed $\frac{1}{4}$ inch in thickness and then the total carbon may be as low as 0·2 per cent. (no free carbon). The tensile strength will be about 22 tons per square inch and the elongation about 5 to 7 per cent. The more common material contains a greater amount of carbon, and as a rule the percentage increases as the thickness of the casting increases. This reduces the elongation to about 2 to 3 per cent., but the tensile strength may be anything between 17 and 30 tons per square inch.

Black-heart castings made in England do not give test results equal to those claimed for the American-made material. Usually the elongation is under 10 per cent. with a tensile strength of about 20 tons per square inch, but with the American material elongation figures of 12 to 15 per cent. are common and the tensile strength is about 25 tons per square inch.

	" White-heart."	" Black-heart."
Carbon, combined . .	Less than 0·4 per cent.	Nil or trace
Carbon total	,, ,, 0·8 ,,	1·5 to 2·5 per cent.
Manganese	0·10 to 0·40 per cent.	0·10 ,, 0·35 ,,
Sulphur	0·25 per cent.	0·10 per cent.
Phosphorus	0·10 ,,	0·20 ,,
Silicon	0·50 to 1·10 per cent.	0·50 to 1·20 per cent.
Tensile strength (ultimate)	18 to 25 tons	16 to 22 tons per square inch
Elongation per cent. . .	3 to 5 per cent.	5 to 10 per cent.
Bending test	45° to 90°	90° to 180°
Surface of casting . .	Rough, often with scabs	Clean and regular

It will be noticed that with the white-heart method a high sulphur content is permissible, but that the phosphorus should be low. On the other hand, the black-heart method demands a low sulphur content, but is workable with a high phosphorus value.

Reference is made to the surface of the castings because it is generally desirable to leave these in their natural state if possible, and thus reduce machine work and corrosion. Thus the white-heart method, on account of the higher annealing temperature, produces a rougher surface, often with scabs, and is not so good in this respect as the black-heart method.

The principal tests on malleable iron are the tensile and bending tests. These are usually made on test bars $1 \times \frac{3}{8}$ inch section as cast, and the elongation measurement is made over a distance of 3 inches. For the bend test the bar is bent over a bar of 1 inch radius.

The impact test is also applied in some cases, but the values obtained are very low, varying from 3 to 10 ft.-lbs. on the Izod machine for black-heart castings and much less for white-heart castings.

Steel Castings

Steel castings are being used more and more for portions of rolling stock, automobile and other vehicles, thus showing that the qualities of soundness and dynamic strength have reached a level which enables designers to place confidence in the material.

Some of the more up-to-date foundries have installed electric furnaces for melting the steel, and apparently the purity of the resulting steel is well under control, and sound castings are more easily obtained. The difficulty, however, of producing castings of varying cross section, especially if the change in section is abrupt, still remains, and it is necessary, therefore, to design parts intended as steel castings so that such changes in section are eliminated as much as possible. The contraction of the castings is considerable, and this is responsible for many of the difficulties in casting, such as cracks and flaws. For this reason the castings should be removed from the mould as early as possible after solidification.

The pouring temperature is about 1500° to 1550° C., and the metal during cooling contracts about $\frac{1}{4}$ inch per foot. Below the temperature of 1500° C. the metal runs thick while only a few degrees lower it is quite pasty. Thus it will be understood how difficult these castings are to produce, and how easily the metal is likely to be contaminated with gases obtained not only in the furnace by occlusion, but also from the mould itself which of course consists of silica sand and other heat-resisting materials. The use of silicon in removing these occluded gases is important, and its presence in such amounts as 0·3 to 0·4 per cent. is explained.

It is common to employ chills, and to apply these to the thicker sections to expedite the cooling and thus prevent rupture. These chills, of course, are placed in the mould or form part of it. Iron nails are frequently employed for the purpose, and examination of some steel castings will reveal such nails embedded in them. This practice, however, cannot be considered good owing to the fact that the nails do not unite with the molten steel and consequently cannot add to the strength of the casting apart from their action in chilling. Also they are liable to produce leaky castings.

Composition.—The compositions of several castings are given in the following table :—

SOME ANALYSES OF STEEL CASTINGS

	Automobile Frame Brackets.	Automobile Castings.	Automobile Castings.	Common Steel Castings.	Heavy Section Castings.
Carbon	0·19	0·26	0·16	0·42	0·25
Manganese	0·39	0·56	0·27	0·88	0·60
Sulphur	0·023	0·012	0·065	0·023	0·054
Phosphorus	0·025	0·028	0·038	0·024	0·048
Silicon	0·29	0·29	0·14	0·32	0·35

The composition of good steel castings should comply with the following specifications :—

Carbon	0·16 to 0·21	per cent.
Manganese	0·4 „ 0·5	„
Sulphur	Not more than 0·03	„
Phosphorus	„ „ 0·03	„
Silicon	0·20 to 0·35	„

For less important work, where a lower dynamic strength is permissible, the composition may comply with the following specification :—

Carbon	0·2 to 0·4	per cent.
Manganese	0·5 „ 0·7	„
Sulphur	Not more than 0·04	„
Phosphorus	„ „ 0·04	„
Silicon	0·25 to 0·35	„

Mechanical Strength.—The average test figures obtained with steels of the above compositions are as follows :—

Spec.	Yield, tons per sq. in.	Ultimate, tons per sq. in.	Elongation on 2 ins., per cent.	Reduction Area, per cent.	Impact (Izod) ft.-lbs.
No. 1	20	30	28	40	25
No. 2	18	28	22	30	10

These tests are on heat-treated castings as supplied by the foundry people.

The most usual test applied is the bending test, the size of the test piece being 1 inch × ¾ inch section and 7 inches long. Such a test piece should bend round a radius of ¾ inch through an angle of 180° for the best composition, and about 90° to 120° for the second composition.

Heat Treatment.—All castings should be supplied in the heat-treated condition. A coarse crystalline fracture indicating a low impact figure at once shows that the material is unsuitable, and that the heat treatment has not been carried out, or at least has not been sufficient to refine the structure.

The importance of heat treatment on the dynamic strength is shown by the following test. A casting of about 0·16 per cent. carbon content gave an impact value of 3 ft.-lbs. when received, but on normalising it at 870° C. (soaking time 15 minutes) the impact value rose to 36 ft.-lbs, thus showing that the heat treatment had been omitted. Two pieces cut from another casting adjacent to each other were tested, one in the received state and the other after annealing at 850° C., and slowly cooling in the furnace for 15 hours. The results were as follows :—

State.	Yield, tons per sq. in.	Ultimate, tons per sq. in.	Elongation, per cent.	Reduction Area, per cent.	Impact (Izod), ft.-lbs.
As received ..	17·8	28·4	27·0	33·6	11, 13, 15
Annealed ..	18·1	30·3	36·0	58·5	27, 35, 27

From the above results it is evident that the heat treatment of steel castings should be watched. The temperatures and mode of treatment are the same as for ordinary mild steel, but naturally the breaking down of coarse crystalline structures will require more time or higher temperatures, or perhaps more heats, than are usually necessary for steel forgings. This matter is dealt with more fully in Chapter X.

Applications of Ferrous Castings

The selection of one or other of the four classes of ferrous castings for a particular component is usually a simple matter. Each class has a fairly definite range of applications and, generally, the size of the component and the duty it is called upon to perform place it into one or other of these ranges. There are, however, many instances in which one class of casting may be more suitable than another for a particular part although it may have been customary to employ the latter. In some cases the selection of the material may be the result of a very fine balance between the qualities or virtues of two classes (say, malleable cast-iron and steel castings), the points in favour of one only just outweighing those of the other. Thus it is necessary at times to compare one type of casting with another, bearing in mind the various factors that enter into the construction of the part and the work it has to do when in use.

The engineer and designer have to consider a number of points when deciding which of the ferrous castings is the more suitable for a certain component, and these points may be classified roughly as follows :—

(1) Stresses when in use.
(2) Durability and reliability.
(3) Machining qualities.
(4) Total cost.
(5) Appearance and finish.

The above points and the extent to which each type of casting fulfils the requirements are dealt with briefly below.

Stresses.—Castings that weigh more than, say, 5 cwt. are either ordinary grey iron or steel. Very few malleable iron castings are made that exceed 2 cwt. in weight, while semi-steel is mainly confined to parts under this weight. Thus the choice of materials for all large and heavy castings lies between iron and steel. Now grey cast-iron (owing to its high compressive strength) is particularly suitable for bed plates and other parts that are required to resist heavy loads under compression. It is, however, inferior to cast steel in regard to tensile strength and resistance to shock, and because of this it is customary to employ steel castings for all parts subjected to severe tension loads as in the case of rolling mill housings. Cast-iron is of little use for parts required to withstand sudden or repeated shocks, thus many of the castings used in ship construction, such as stern posts and rudder frames, are made of steel. Large gear wheels are now made in cast-steel in preference to cast-iron because of the greater strength of steel and the high resistance which the teeth of the gear offer to the suddenly applied load. In the case of flywheels weight is the principal factor, and as this means a large cross-section the bursting stress is usually low enough to enable cast-iron to be used with safety.

Castings of medium and lighter weights may be made of malleable iron or semi-steel as alternatives to grey iron or steel, and the choice of material, therefore, is greater than with the very heavy castings.

Malleable cast-iron is much stronger and much more ductile than cast-iron, and there are many instances where it could be used with advantage in place of cast-iron. The weight of the part could be reduced considerably, and because of the greater ductility of malleable iron the factor of safety could be lowered. This applies particularly to thin sections, in which, with grey iron, there is always a tendency to produce a hard, brittle material.

Steel castings are even better than malleable iron castings for the heavier and thicker-section parts, but when the section is less than half-inch thick then malleable iron is probably the better of the two. Malleable iron melts at a lower temperature than steel and is more fluid, a condition which makes it possible to obtain castings as thin as one-sixteenth of an inch. With steel, the main difficulties are due to the rapidity with which it freezes (owing to the high freezing point). This fact and the rather serious contraction that takes place accounts also for the difficulty in obtaining sound castings, especially when the section changes abruptly from a thin one to a thick one. As a rule, malleable castings are freer from blowholes than steel castings, so that, taking all the factors into account, steel, in spite of its higher tensile strength and greater ductility, is not always a better material than malleable iron for the smaller castings.

Distortion is an important factor with both malleable and steel castings. Usually it can be corrected, but with very large castings it may be impossible to force the casting back to its correct shape, and in consequence it may not be possible to machine certain faces to the correct dimensions.

Semi-steel castings will replace cast-iron in the near future for many of the smaller parts in machinery because of its greater strength and increased toughness. It is, however, a material that is more nearly like cast-iron than either malleable iron or steel. It cannot be regarded as a substitute for either of these two latter materials.

Durability and Reliability.—The useful life of a material depends on its degree of resistance to wear and corrosion. Unusual or unexpectedly high stresses may be set up and may cause a more or less rapid rupture of the part, but ruling out such infrequent occurrences, and also the slow internal changes that take place in most materials, wear and corrosion may be regarded as the principal factors that limit the period of usefulness.

Reliability is to some extent, interconnected with durability, but in the early stages of the useful life of the material it represents the degree with which the actual performance approaches the expected or calculated performance. Thus small steel castings of thin section are not so reliable as malleable iron castings, chiefly because of their unsoundness. Castings as a class are not so reliable as forgings because a bigger percentage fail in use.

The wearing properties of a material must not be confused with the qualities that go to make up an efficient bearing material. In the one case the material must resist rubbing or abrasive action, and in the other it must be capable of wearing away in preference to the part that runs in it.

Steel castings are more suitable that grey iron castings for parts subjected to constant friction. Malleable iron castings of the white-heart type also are superior to grey iron. On the other hand, steel and malleable iron castings do not possess the qualities of a bearing material which are associated with cast-iron, and which are dependent on the presence of graphitic carbon in the metal. Semi-steel resists wear to a greater extent than grey iron, but not to the same degree as steel or malleable iron castings.

The whole range of ferrous castings resists corrosion to a much greater extent than do parts made of iron or steel which has been rolled, drawn or forged. Malleable cast-iron, and steel castings in a lesser degree, are remarkable for their great resistance to corrosion. The wide use of these two materials for railway rolling stock, mining equipment, and agricultural machinery is mainly due to this special quality, which makes it possible to leave such machinery exposed to the full action of the elements without serious risk of a breakdown. With such castings a coating of rust very soon forms on the surface, but this appears to prevent any further attack, and in consequence the part can be left exposed for years without any real weakening of the section taking place.

Grey iron and semi steel possess this valuable characteristic also to a very great extent, as is shown by the use of cast-iron columns for supporting piers and jetties in the sea. For the smaller and the more general run of castings for mechanical work, however, the better materials are steel and malleable iron castings.

Machining Qualities.—The machining properties of the four classes of ferrous castings are influenced often by certain faults in their manufacture. Generally, it may be said that semi-steel can be machined at higher speeds than ordinary cast-iron. Malleable iron and steel castings machine with equal facility and, as a rule, at higher speeds than cast-iron. On the other hand, cast-iron when annealed to improve its machining qualities will cut almost like brass and at about the same speeds. Occasionally, white-heart malleable castings will prove to be exceptionally hard and will behave like tool steel. Such castings, of course, have not been annealed sufficiently and for most purposes should be rejected. Steel castings sometimes prove patchy, and will machine readily in some parts and yet be exceptionally hard in others. In all probability the annealing is at fault or has been omitted altogether. Grey iron is often troublesome in thin sections, due to the chilling action of the mould, which action retains a large proportion of the carbon in the combined form. In most cases annealing for one hour at 700° C. will overcome the difficulty and the metal will machine with ease. Semi-steel is subject to the same trouble.

Total Cost.—The size of the part or the duty it is designed for often limits the choice to one kind of casting only, and therefore cost does not influence the selection. Thus cast-iron may be ruled out because the part must be capable of resisting shocks, and then steel castings may prove unsuitable on account of shape of the part (owing to extreme variations in thickness) or because the section is too thin for this material. Malleable cast-iron then becomes the only material available, since semi-steel is only one degree better than cast-iron. Resistance to wear may limit the choice to steel castings and alternatively the necessity for a material having a low coefficient of friction will compel the engineer to use grey iron for cylinder castings, piston rings, and other sliding parts.

On a weight basis grey iron is the cheapest material, the others following in the order given: semi-steel, steel, and malleable iron. Thus for all heavy parts it is desirable to employ grey iron, but with medium and light parts advantage may be taken of the greater strength and ductility of malleable iron and steel castings to reduce the section of the part, and thus to reduce its weight to an extent which will result in lowering the cost or, at any rate, in providing a superior article at a cost no greater than that obtained with grey-iron. A desire to secure such a result must not, however, lead the designer into reducing the section of the part to such limits as to sacrifice strength for economy in cost.

Appearance.—As a rule steel castings have a very rough and unfinished appearance due to the high casting temperature and the class of sand employed for the moulds. Grey iron castings, on the other hand, can be made so that their surface is quite smooth and regular. This is very pronounced with the high silicon and high phosphorus irons such as are used for very small castings.

Malleable iron castings of the black-heart type are almost as clean and smooth as grey iron castings of the same size. The white-heart type of castings, however, are not always so clean and regular as the black-heart, owing to the higher annealing temperature and the action of the ore on the surface, resulting in pitting, and sometimes forming scabs.

CHAPTER XV

NON-FERROUS METALS AND ALLOYS

In general engineering practice very few of the non-ferrous metals are used alone. As a rule they are alloyed to other metals, in which state they then become of immense service to the engineer, and his interest, therefore, centres more on these alloys than on the actual metals themselves. There are, however, two metals which in their unalloyed state are used very extensively, and these are Aluminium and Copper. Also there are others which are used to a much less extent, and among these may be included Lead, Tin, and Zinc. These metals, however, cannot be regarded as constructional materials owing to their extreme softness and low mechanical strength. They form what may be regarded as "accessory materials": Lead being used mainly for piping or as sheet for covering; Tin for linings, pipe work, and sometimes sheet; while Zinc is mainly useful in its sheet form for such purposes as ventilators and other weather-exposed parts. It was at one time used for roofing, but has been almost superseded by galvanised iron.

The two principal metals, aluminium and copper, will first be considered in this chapter, and then the various alloys which are of most use commercially.

Aluminium

The extreme lightness of this metal, combined with malleability and moderate resistance to corrosion, accounts for its ever-increasing use. Also, its high electrical conductivity has given it a prominent place in electrical work.

Owing to the method of manufacture, the commercial metal contains copper, iron, and silicon as impurities. In good material, however, the total impurities should not exceed 1 per cent. In second-grade material the aluminium may be only 98 per cent. but should not be less.

The metal is readily rolled or drawn, and can be obtained in almost any form such as sheet of all thicknesses down to foil, rod and wire, tubes and bars of various sections. It is also used for castings, but as the practice now is to add copper, zinc, or other metals to form a definite alloy, this particular application is dealt with under the heading of alloys (page 384).

Although the cost of aluminium by weight is higher than for such metals as copper, zinc, lead, it should be borne in mind that its low density (2·70) places it in a very favourable position when considered on the volume-for-volume basis. Thus bars, sheets, tubes, etc. have approximately the following weights when compared with other materials such as those listed below :—

Material.	Specific Gravity.	Relative weight of Aluminium.	Relative weight of material, taking Aluminium as 1.
Aluminium	2·70	1	1
Copper (rolled)	9·00	0·300	3·33
Brass (rolled)	8·40	0·321	3·11
Steel (or Iron)	7·80	0·346	2·88
Tin	7·40	0·365	2·74
Zinc	7·20	0·375	2·66

Mechanical Strength.—The rolled, drawn, or forged material gives the highest tensile figures, but annealing at, say, 400° C. lowers the strength considerably. Taking the annealed condition as the normal state of the metal, good quality commercial aluminium should comply with the following test figures :—

Yield (Elastic Limit)	3·5 to 4·0 tons per square inch
Maximum Tensile	5·5 „ 6·8 „ „ „
Elongation on 2 inches ..	10 „ 35 per cent.
Reduction of area	20 „ 30 „

Rolling and drawing increase the tensile strength, the effect being greater as the section becomes smaller. The following figures are those given by the Aluminium Company of America :—

	Tons per sq. in.		Per cent.	
	Tensile Strength.	Yield Point.	Elongation in 2 ins.	Reduction Area.
Sheet (half hard) ..	8 to 10	4 to 5·4	5 to 12	20 to 30
„ (hard) ..	10 „ 15·5	5·5 „ 11·0	1 „ 7	20 „ 30
„ No. 12 Gauge	11·3	—	—	—
„ No. 16 „	12·6	—	—	—
„ No. 20 „	13·5	—	—	—
Wire (hard)	11·3 to 25·0	7·2 to 15	—	40 to 60
„ 40 mil. ..	14·0	—	—	—
„ 80 „ ..	12·6	—	—	—
„ 120 „ ..	11·3	—	—	—
„ 200 „ ..	10·0	—	—	—

The crushing strength is also given as :—

Yield point	2·7 to 11·3 tons per square inch.
Ultimate strength	7·2 „ 45·0 „ „ „

Cast aluminium has an average value of 30 tons per square inch for the ultimate crushing strength.

The strength of aluminium is considerably affected by temperature as is shown by Bengough, who obtained the following results :—

Temperature of Test. °Cent.	Tensile Strength, tons per sq. in.	Elongation in 2 ins.	Reduction of Area, per cent.
20	8·57	12	75
200	6·29	15	78
275	4·96	17·2	79
330	3·39	20·3	88
375	1·70	25·0	88
396	0·96	56·0	90
520	0·40	88·5	to finest possible point.
565	0·24	70·3	
610	0·29	75·0	
525	0·18	39·0	92

Heat Treatment.—The only heat treatment of aluminium is that of annealing the worked metal. The process of working (rolling, drawing or forging) deforms the grain structure and hardens the metal, and then annealing is the best method of obtaining a good uniform structure. The best temperatures for annealing are between 400° and 500° C., but both this and the duration of heating (soaking) depend on the degree of cold work put into the metal. The greater the work the more difficult it is to restore the metal to the normal crystalline condition. This is dealt with more fully in Chapter X.

Copper

This metal is used mainly in the form of sheet, tubing, and wire. It is sometimes cast, but such castings are often unsound and weak. The addition of phosphorus, however, appears to remove the difficulty, and good castings can then be obtained.

Copper is one of the purest of the commercial metals. Usually samples of tubing and sheet contain 99·90 per cent. of copper, and wire intended for electrical conductors may contain only 0·05 per cent. of impurities. The following analyses are typical of such materials :—

Element.	Electrolytic, re-melted.	Wire.	Tubing.
Copper	99·92	99·976	99·890
Arsenic	0·008	nil	0·021
Bismuth	nil	nil	0·008
Lead	nil	0·0056	0·004
Antimony	trace	0·0008	0·053
Iron	0·001	0·0044	0·004
Nickel	nil	0·0018	0·011
Sulphur	nil	0·0016	0·002
Oxygen	0·07	0·0070	0·006

It will be seen from the above table that the amount of each impurity is very small, but as the effect is often very considerable, it is necessary to keep each below a certain limit. The effects of these impurities are described in Chapter IX.

Many tests have been devised to check the quality of copper. Most of these are of a mechanical character, but a test which has been adopted by many authorities (particularly certain Government departments) is the Muntz metal test, which is as follows :—

> 3 lbs. of copper are placed in a melting pot, covered with pieces of hard wood or charcoal to prevent the loss of zinc when added. When the metal has melted, 2 lbs. of zinc are added, and the mixture is then stirred and run into a cake about 4 inches by 4 inches in an open iron mould. When the cake has set, it is allowed to cool gradually in the air ; when cold, the cake is nicked with a cold chisel and broken carefully to show the fracture. If the cake is tough and breaks with a fine silky fracture, the quality is considered good, but if it breaks short with a coarse, stringy fracture, and with a yellow colour, the metal is considered bad.

This test, although an important one, is not an easy one for the engineer to carry out, hence the usual common standard tests adopted by the principal authorities are mostly favoured. These may be summarised as follows :—

(1) **Copper Sheets** (annealed) Gauge, S.W.G. 6 down to 24 or thinner.

Tensile strength : 14 tons per square inch (minimum).

Elongation (on 4 inches) : 20 per cent. Test piece 1¼ inches wide × 4 inches between gauge points.

Bending test : strips, to be cut lengthways and crossways from the sheet, to be bent cold through 180°, closed down tight, and then hammered to a fine edge. No cracking should occur.

(2) **Copper Plates,** as used for fireboxes.

Tensile strength : 14 tons per square inch (minimum).

Elongation (on 8 inches) : 35 per cent.

Bending test : strips to be tested both cold and at a red heat by being doubled over on themselves, *i.e.* bent through 180°, and should not show any cracks or flaws.

(3) **Copper Rods** (annealed).

Tensile strength : 14 tons per square inch (minimum).

Elongation : 40 per cent.

Gauge-length : to be 8 times diameter of test piece.

Crushing test : a piece of rod 1 inch long is placed on end and hammered or crushed down to ⅜ inch long, when no crack or flaw should show up on the circumference.

(4) **Copper Tubes** (seamless) (annealed).

Tensile strength : 14 tons per square inch (minimum).

Elongation (on 2 inches) : 35 per cent.

Crushing test : a piece 1½ times the diameter is placed on end and crushed endways to half its original length. No splitting or cracking should occur.

Drift test : a drift should be driven down the tube so that its diameter is increased by 25 per cent. No cracks or flaws should show up.

Flanging test : a flange should be formed at the end of the tube, having a diameter 40 per cent. greater than the tube. No crack or flaw should appear.

Flattening and bending : an annealed tube should stand flattening and then bending, doubled over on itself, namely, through 180°, without cracking or showing flaws.

Bursting tests: these are usually hydraulic and are arranged to suit the requirements of the actual task.

Other tests are in use, such as the twisting test for copper conductors, and, of course, conductivity tests for electrical purposes; particulars of these are found in most pocket books or standard specifications.

Hard-drawn Copper.—The cold working of copper induces greater hardness and strength, but reduces its ductility. The degree of hardness depends on the amount of work put into the metal, and also on the size of the final product. The tensile strength of hard-drawn copper varies from 22 to 32 tons per square inch, with an elongation of less than 4 per cent. down to 0·5 per cent.

Effect of Temperature on Strength.—The effect of temperature on the strength of copper is considerable, as the following table shows:—

Temperature °C.	50	100	150	200	250	300	350	400	450	500	550
Tons per square inch ..	14·8	14·4	13·8	12·9	12·0	10·4	9·7	8·8	7·7	6·3	4·8

Hard copper changes more than annealed copper, but does not fall below the figures given above, although it may be very nearly as low. The importance of this change in strength is obvious in view of the temperature at which copper tubes and plates are used in such plant as boilers and other steam apparatus.

Non-Ferrous Alloys

The number and variety of these alloys are apt to confuse the average engineer, particularly as many are sold under special trade names by makers who claim nearly all the virtues for their alloys. However, the tendency with most engineers is towards obtaining alloys of certain defined compositions, and in time such alloys will be sold and bought under some clear and distinguishing numerical system which will indicate the approximate composition of the material. Such a system is really a necessity, because the present one enables unscrupulous firms to foist all sorts of unsuitable alloys on to the engineer, who is not always able to check his supplies and often does not discover how poor the material is until it has been in service for some time.

It might be said that for certain definite purposes, there are certain definite alloys that will give the best results; all other alloys are unsuitable, or at the best are only poor substitutes. This rather simple method of discriminating is unfortunately not easily carried out in practice.

Deoxidisers.—Most alloys will be found on analysis to contain traces or even fairly high percentages of what might be considered impurities. These additional elements are often purposely put into the alloy with the object of improving its soundness when cast, and thus increasing its strength.

During the melting or preparation of an alloy, there is usually a certain amount of oxidation taking place, and as some metals are capable of dissolving or absorbing these oxides, the result is that the alloy is made weaker, and often exceedingly brittle—due in most cases to the fact that oxide does not remain in solution in the solid alloy, but is thrown out to the crystal grain boundaries, thus forming a weak path through the metal.

The manufacturers of alloys of course take precautions to prevent this oxidation occurring by covering the metal in the crucible with such substances as charcoal, resin, borax, etc., but at the same time, in order to clear the molten alloy of any oxides which are unavoidably formed, they add certain deoxidising agents. Thus, with copper alloys phosphorus in the form of phosphor copper (or phosphor tin) is added, and this having a very strong affinity for oxygen, reduces the dissolved oxides and floats to the surface as phosphate of copper. Aluminium is also used, and also many other elements, the choice depending on the alloy being made. Although such deoxidising agents are added to eliminate the injurious oxides it often happens, owing to the comparative absence of these, or to the precautions taken in adding a slight excess, that a small proportion of the agent is left in the metal. Thus, many bronzes will be found to contain traces of phosphorus or of aluminium.

The addition of these deoxidisers generally increases the fluidity of the alloy, thus facilitating casting and eliminating gases which would produce blowholes.

As a guide in this matter, the following list of the usual deoxidising agents is given :—

Alloy.	Deoxidiser.
Bronzes and brasses and other copper alloys	Phosphorus Aluminium Silicon Zinc Manganese Boron compounds Magnesium
Aluminium Alloys	Manganese Phosphorus Magnesium

Pouring Temperature.—The strength of many alloys depends on the temperature at which they were cast or poured into the mould. Unfortunately, there is little published information, but in any case this is a matter which must be settled by the foundry people, since it is more or less controlled by the size and character of the casting. Thin sections naturally solidify much more quickly than thick sections, and it is usual to pour these at high temperatures, whereas the thicker sections are cast at lower temperatures in order to reduce the time of cooling, and consequent grain growth.

If the metal is poured at too low a temperature there is a risk of the mould being incompletely filled, or because the alloy is thick and sluggish there is a tendency for slag, scum, or other foreign matter to be carried into the mould simply because it cannot float to the top. Again, even when the metal is free from such defects it probably solidifies as soon as it enters the mould, and succeeding additions do not completely adhere to each other. The result of this is lack of cohesion and the formation of unsound castings.

Rate of Cooling.—The cooling of cast metal can be divided into two stages : (1) liquid into solid, and (2) hot solid to cold solid. During the first stage the shrinkage effects take place, and the size of the grain or the coarseness of the structure is determined in many alloys. Dealing with the shrinkage first, it is clear that when the molten metal has been run into the mould the cooling will proceed from the walls of the mould and from the cores (if there are any). Thus, those portions of the metal in contact will solidify first and will take up the size and shape of the mould, while the remainder will solidify later. During solidification, however, a change in volume takes place and the metal shrinks and, unless there is more to run in and make up for the shrinkage, the interior of the casting will not be completely solid, but will be spongy or even contain cavities. This sponginess and any cavities will, of course, be formed in the portions of the metal that are the last to cool. To overcome this defect the foundryman generally arranges for a good head of metal to remain in the gates or feeders, and this runs into the body of the casting as the shrinkage takes place.

In the second stage of the cooling the alloy may only contract in the manner normal to most heated bodies, but in very many cases various internal changes, both chemical and physical, take place, and these are often accompanied by a change in volume. Apart from such volume change (which is simply one that affects the ultimate contraction and can be allowed for) there is the question as to whether the rate of cooling hinders these internal changes in any way. As a matter of fact, in those alloys which undergo chemical or physical changes at certain temperatures during cooling, the structure existing at a higher temperature can often be fixed by rapid cooling from above this temperature; such a structure is sometimes more desirable than that found in the alloy when cooled slowly. On the other hand, rapid cooling, by retaining the structure normal to the higher temperature, is not always advisable, because such structure may not be so useful as that obtained with slow cooling. Generally speaking, the more rapid the cooling the denser is the hardness being increased, but usually its brittleness is also increased.

Rapid cooling is secured by the use of metal chills placed so as to form part of the mould, or the mould itself may be of metal. Die castings are produced in metal moulds and are usually very dense.

Form.—Some alloys are only suitable for use as castings and cannot be rolled into sheet, or drawn into bar or wire. Others are more useful after rolling or drawing, the castings being weaker and less reliable. Thus, it does not follow, because a certain alloy gives good results when cast, that it will be as good if rolled or drawn; or *vice versâ*, if it is good in the form of sheet or rod, that it will be good as a casting. As a matter of fact, very few alloys are serviceable in both the cast and the worked states, and it is therefore essential when designing parts to bear in mind what form the raw material will take. Parts intended for repetition work on automatics using bar material must necessarily be made from a different alloy to that employed when they are to be produced from castings.

Again, alloys used for castings made in sand moulds are often unsuitable for die castings, and it is necessary to discriminate between these two methods of producing castings when considering the choice of alloys.

Sand Castings.—These are so described in order to distinguish them from those produced in chill moulds or in dies. They form the bulk of the castings produced at the present time, and because the mould is made of sand they are the most slowly cooled. The rate of cooling is an important factor so far as the quality and strength of the casting is concerned, and contributes in no small measure to the success or otherwise of the work.

It is evident from the general law of crystallisation, that when the alloy cools slowly the grain growth is greater, and that castings of a heavy or thick section will have a coarse structure, and will in all probability be weaker. This is one of the difficulties in producing strong castings of thick section, and should not be confused with the altogether different troubles caused by shrinkage, which generally take the form of sponginess, and which depend on the size and position of the gate, and the maintenance of a sufficient head of metal to supply the deficiency caused by shrinkage.

Die Casting.—This method of producing castings has been developed considerably in recent years, and it must eventually become one of very great commercial importance. The facts that castings can be made within an accuracy of 0·005 inch per inch and that their surfaces are clean and smooth render the method of very great value. The necessity for machining is often completely eliminated since holes, even threaded holes, can be accurately cast in the part, and parts intended to fit together are very easily obtained, no machining or other work being required.

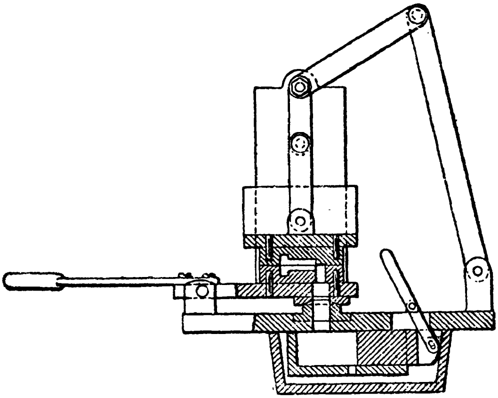


FIG. 183.—Underwood Die-casting Machine.

The process consists of forcing molten metal, under pressure, into a metallic mould or die. Many different machines have been made for this purpose, all with the object of overcoming various practical difficulties, but it is not possible to enter into a description of these here. The simplest system, to give an impression of method of working, consists of immersing a cylinder and piston in the molten metal, and thus forcing some of it into the die situated above. This is clearly shown in Fig. 183, which represents the Underwood Machine, patented in 1902.

Some of the difficulties encountered are as follows :—

Sponginess.—This is common in die castings, especially in those of heavy section. This is mainly due to the fact that the metal on entering the die chills around the inner walls and takes up the form of the die, while the remaining metal which fills this shell may not solidify until after the metal at the entrance (or " gate ") to the die is solid, in which case the shrinkage that takes place causes the last portions which cool to be porous or spongy, and cavities are thus formed.

Dies or Moulds.—These are usually made of carbon steel, and for the low melting point alloys such as zinc, tin, and lead, and white anti-friction alloys, offer no trouble and last almost indefinitely. But with the higher melting point alloys it is found necessary to employ various alloy steels, and even then their life is often short on account of the action of the alloy. Close-grained chilled cast-iron * is also used, and is found to be very satisfactory for these high temperature alloys.

The principal consideration from the commercial point of view is the cost of the die or mould, which will range from a few pounds for a very simple and small part, to perhaps £250 for a very complicated and perhaps fairly large part. Thus their deterioration is one of considerable importance, and may actually defeat the object of adopting the process, *i.e.* the saving in cost of machining.

When designing parts that are intended to be made by the die-casting method it is advisable to have in mind the construction of the die and to avoid complication, especially if such necessitates the employment of loose parts in the die.

Die-casting Alloys.—The alloys used generally have one of the following metals as a base: zinc, tin, lead, aluminium, or copper, and, as would be expected, the first three, having the lowest melting points, are the simplest to cast. The aluminium and copper base alloys, having high melting points, present considerable difficulty, and the production of castings is not always a commercial success.

One of the difficulties with aluminium alloys is their solvent action on iron, and it is possible that the castings may contain as much as 3 per cent. Iron, however, has a very small influence on the alloy when cast, but it tends to raise the melting point and makes the metal unsuitable for casting.

Another difficulty with die-casting alloys lies in the poor elongation of the metal at high temperatures. This point is probably the most important of all to the die caster. The reason for this can be explained by taking the example quoted by Charles Pack.† Assume that a ring 12 inches diameter is to be cast, using a metal core. When the molten metal strikes the mould it solidifies, and here a change of state occurs that is accompanied by a reduction in volume, commonly called shrinkage. Unlike a sand core, the metallic core is not compressible, and retains its original size and form so that the shrinkage of the metal is converted into a stretching action in the solidified casting. If the elongation of the alloy at that temperature is not high enough to withstand this stress the casting will crack.

It is not practicable to remove the casting from the die at its solidification temperature, and as it has not been found satisfactory to run the casting dies above a temperature of 260° C., it follows that this figure is about the temperature at which the castings are withdrawn. Thus the casting is subjected to further stretching action on account of the contraction in volume that must occur when the casting cools from its solidification temperature to that at which it is withdrawn.

---

* "Die-casting of Aluminium Bronze," H. Rix and H. Whitaker, *Inst. Metals*, March 13, 1918.

† "Die Castings and their Application to the War Programme," *Amer. Inst. Mining Engineers*, Feb. 1919.

That the elongation value of the alloy at normal temperature is no guide to its probable value at the higher temperatures has been abundantly proved. For instance, the addition of copper to aluminium reduces its elongation at normal temperature, yet the 12-per-cent. copper alloy is a better die-casting alloy than the 6-per-cent., simply because its elongation is better at higher temperatures.

In addition to the importance of the elongation value at higher temperatures, there is the fact that most alloys are very weak at these temperatures, *e.g.* the 12 per cent. copper-aluminium alloy, which has a tensile strength of about 10 tons per square inch, falls off to about 4 tons per square inch at 350° C.

Design of Die Casting.—The design of the casting and the choice of the alloy should only be settled after due consultation with the die caster. The die is the most important factor, and much experience is required in designing this, hence the shape of the actual casting must conform to the requirements of the die-casting process. This is particularly necessary with castings of intricate shape or of large dimensions when the number and shapes of the different parts of the die and cores, the method and order of withdrawal of the cores, venting, situation, shape and size of the gate, must all be considered.

Rolling and Drawing.—The effect of working an alloy generally entails increased hardness and brittleness: the tensile strength being increased and the ductility reduced. This, however, is not always the case, as some alloys are not improved by rolling or drawing, while many cannot be worked at all, even at higher temperatures. In those cases where cold rolling or drawing produces a large increase in the tensile strength it often happens that the strength falls off in time, the metal tending to become softer. This "return" effect has very serious consequences sometimes, especially in the harder alloys, because these deform very much and even break. This phenomenon is usually referred to as "season cracking." *

Heat Treatment.—Owing to the hardness, and distortion of the grain structure, caused by rolling and drawing, it is often necessary to anneal or soften alloys. Although it is possible to anneal such alloys at very low temperatures, the process may be unduly long, and therefore, from the commercial standpoint, it is necessary to anneal at those temperatures which will give the required result in the least time. This is dealt with more fully in Chapter X, and is also referred to under the various alloys described in this chapter.

Heat treatment is also resorted to, to produce or to eliminate a certain constituent in the alloy, one which could not be obtained in the normal cooling during casting. Gunmetal is an example of this: it is considerably improved for certain purposes by heating to 700° C. and slow cooling.

Extrusion Process.—Certain metals and alloys when heated to a suitable temperature become sufficiently plastic to permit of their being forced through a die. The flow of the metal (or alloy) through this die is referred to as "extruding," and the finished product is known as "extruded" metal. The size and shape of the cross-section of the extruded material is almost exactly the same as the die used for extruding. Thus various sections can be extruded, many of which could not possibly be rolled or drawn.

The process is carried out in a form of press consisting of a cylinder in which the metal is placed, and a hydraulic ram or plunger which enters the

---

* For illustrations of this see "Season Cracking of Brass during the Great War," by O. W. Ellis, *Faraday Society*, April 6, 1921.

cylinder at one end and forces the metal through a hardened die situated at the other end. These extrusion presses are made in various sizes and usually are very powerful. The cylinder or pressure chamber is made generally of tungsten steel to withstand high pressures at high working temperatures when extruding brass or bronze alloys.

The high pressure exerted on the metal appears to improve its mechanical properties, increasing the tensile strength and rendering it more homogeneous. Compared with rolling or drawing the compressive action on the metal is not so confined to the outer portions of the finished bar, and in consequence extruded metal is more uniform throughout its cross-section than is rolled or drawn bar.

The most important feature of the extrusion process, however, is the immense range or variety of sections that can be manufactured. Apart from the ordinary and quite normal sections such as rounds, ovals, squares, and hexagons, it is easy to obtain sections from which small pinions or gears can be made, the teeth being already formed on the bar. Ribbed strip, flat or curved, ornamental sections, special angle and tee sections are all made with equal facility.

The metals and alloys that are commonly used for extruding are as follows :—

- Copper.
- Aluminium.
- Zinc.
- Brass.
- Delta metal.
- Aluminium brass and bronze.
- Manganese bronze.
- Naval brass.

The special properties of these extruded materials are described later in this chapter under the heading of "Extruded Metals and Alloys."

Forging and Hot Stamping.—Some alloys can be forged or stamped in the hot state, and because of the regularity and comparative sharpness of the stampings produced, this process is becoming one of importance. At present it is confined to certain bronzes and brasses and also duralumin.

Ageing Effect.—With certain of the zinc alloys there is a serious drawback in practice, the nature of which is their tendency to disintegrate. Parts made from such material will gradually change shape and may actually fall to pieces.

Effect of Temperature on Strength.—The change in strength of alloys with temperature is a very important matter to the engineer. It is customary to test materials at normal temperatures and to judge by the results obtained, yet in many cases the actual parts are required to work at temperatures which may be much higher or perhaps considerably lower.

Much work could be done on this subject, our knowledge being very limited, but what has been done shows that most metals and alloys undergo very serious changes in strength with rise in temperature. It is most essential in designing parts for use at higher temperatures that reliable data should be obtained as to the falling off in strength of the materials under consideration.

Aluminium Alloys

Aluminium is seldom used for castings, owing to its high shrinkage, softness, and poor machining properties. Certain alloys, however, have proved to be excellent and to give good sound castings, both in sand moulds and in chilled moulds. Very fine die castings are also obtained, and the use of aluminium alloys in this direction has grown at a tremendous rate during the last few years. Certain very important points must be observed during the casting, otherwise very poor and weak material is produced. The foremost of these is the precaution of not allowing the alloy to reach a temperature much higher than the melting point, and not to pour at a high temperature. The actual pouring should be done at the lowest temperature possible consistent with filling the mould completely. Such a temperature will be in the vicinity of 700° C. or lower. This is necessary because of the high specific heat of the metal and the consequent serious heating of the mould resulting in slow cooling, and the development of a coarse grain structure which is essentially weak.

The importance of the pouring temperature and the rate of cooling is shown by Figs. 184 and 185.

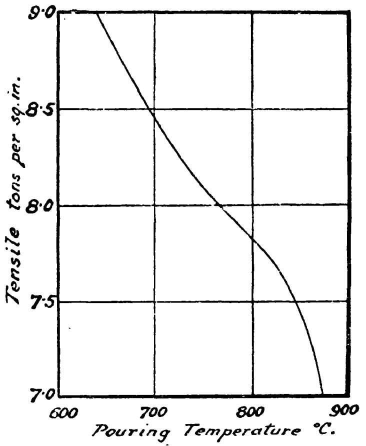


Fig. 184.—Effect of pouring temperature on strength of aluminium alloy casting (Gillett).

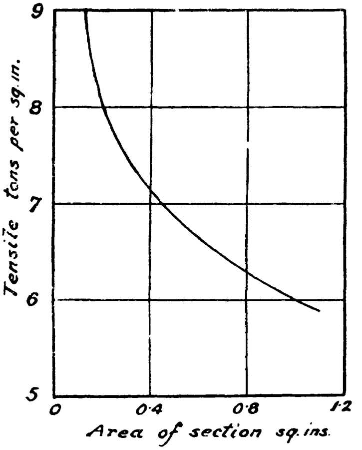


Fig. 185.—Effect of section on strength of aluminium alloy casting (Gillett). This demonstrates the influence of the cooling rate.

These graphs represent approximately the results of a series of tests carried out by Gillett. The falling off in the strength of the aluminium alloy as the pouring temperature is raised is quite pronounced, and shows how important this factor is. Fig. 185 shows the effect of varying the section of the casting, or, in other words, the rate of cooling.

With regard to the testing of aluminium alloys, the Air Ministry, in connection with the testing of crankcases, pistons, etc., have come to the conclusion that the best test is to take the metal from the pot and cast a test piece in a chill mould. Prior to this decision large numbers of these particular parts were rejected because the tests had been made on sand-cast test pieces which did not fairly represent the actual casting.

Aluminium-Copper Alloys

The most common alloys used at present are those containing copper. They are suitable for both sand and die castings.

This series of alloys has been investigated by Carpenter and Edwards, and the following curves form part of their results :—

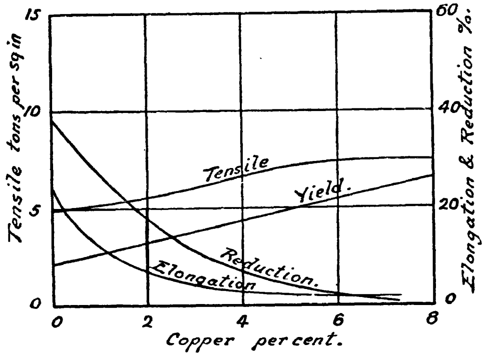


FIG. 186.—Tensile strengths of sand cast copper-aluminium alloys (Carpenter and Edwards).

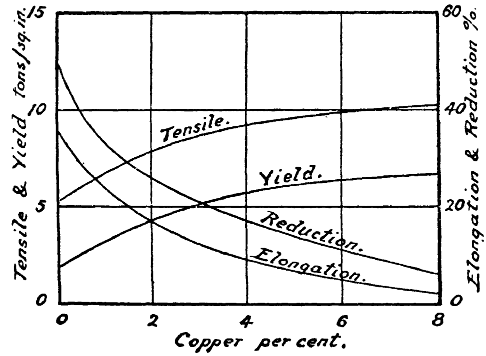


FIG. 187.—Tensile strengths of chill-cast copper-aluminium alloys (Carpenter and Edwards).

It will be seen that the strength of the alloys increases with the increase of copper, but that the ductility is reduced. All these alloys can be hot-rolled, while those containing less than 4 per cent. copper can be drawn. The effect of hot rolling and also drawing is to increase the tensile strength. This is shown by the following test figures given by Carpenter and Edwards on an alloy containing 3·76 per cent. copper :—

Condition.	Yield, tons per sq. in.	Ultimate Tensile, tons per sq. in.	Elongation in 2 ins. per cent.	Reduction Area per cent.
Chill cast	5·40	9·60	10·5	21·46
$1\frac{1}{4}$ inch hot-rolled bar ..	8·97	16·87	20·0	38·21
$\frac{13}{16}$ inch „ „ ..	11·60	16·96	21·0	49·76
$\frac{13}{16}$ inch drawn with annealing	15·44	16·90	8·0	21·79
$\frac{29}{32}$ inch cold drawn without annealing	18·53	20·04	7·5	20·84

The strength of hot-rolled bars within the range 0 to 8 per cent. copper is shown by Fig. 188.

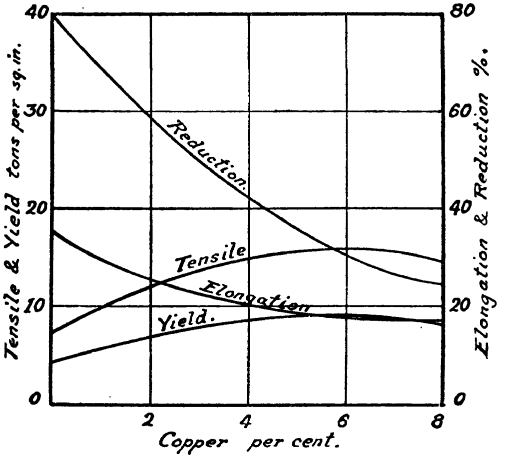


FIG. 188.—Strength of hot-rolled copper-aluminium alloys (Carpenter and Edwards).

The conclusion of Carpenter and Edwards is that there is no gain by adding more than 4 per cent. copper, but in practice it is common to use alloys containing 8 per cent. and even more copper.

The principal aluminium-copper alloys in general use are given in the following table :—

	No. 1.	No. 2.	No. 3.	No. 4.
Copper ..	3–4 per cent.	6–8 per cent.	9–11 per cent.	11–13 per cent.
Aluminium ..	95–94 per cent.	92–90 per cent.	89–87 per cent.	87–85 per cent.
Other elements	2 per cent. max.	2 per cent. max.	2 per cent. max.	2 per cent. max
Density—				
Sand-cast ..	2·84 max.	2·89 max.	2·98 max.	3·00 max.
Die-cast ..	—	—	2·95 „	2·97 „
Melting range	—	635–540° C.	630–540° C.	630–540° C.
Shrinkage ..	0·156 in. per ft.	0·156 in. per ft.	0·156 in. per ft.	0·156 in. per ft
Tensile strength, Sand-cast	6–7 tons per sq. in.	9–12·5 tons per sq. in.	—	8–8·5 tons per sq. in.
Elongation in 2 ins., sand-cast	5–3 per cent.	1·5–4·0 per cent.	—	Less than 1 por cent.
Tensile strength, die-cast	—	12–13 tons per sq. in.	12–13 tons per sq. in.	9–12 tons per sq. in.
Elongation in 2 ins., die-cast	—	About 1 per cent.	About 1 per cent.	Less than 1 per cent.

No. 1 alloy is used for sand castings where strength is not very important. As a rule, it is more ductile than the other copper alloys, and is used for the making of rolled bars and sheets and for drawing into wire.

No. 2 alloy is a very common alloy in the U.S.A., and is used for many automobile parts such as crank cases, brackets, and for general castings. It is also used for die castings with considerable success.

No 3 alloy is really a die-casting alloy, but is sometimes used for sand castings. It is a useful alloy for high temperatures, and pistons for aero and automobile engines are very frequently made from it.

No. 4 alloy is also a die-casting alloy, but can be cast in a sand mould. It is a useful alloy for parts which have to withstand pressures, as in the case of pumps. It is also used for aero-engine cylinders (fitted with steel liners).

The following is a typical analysis of such an alloy * :—

ANALYSIS OF AERO-ENGINE CYLINDER CASTING

Copper	11·48 per cent.
Aluminium	87·00 ,,
Iron	0·91 ,,
Silicon	0·28 ,,
Tin	0·32 ,,
Manganese	0·01 ,,

A typical aluminium alloy for die-casting is described by Livermore,† and as an example of such an alloy the following particulars are given herewith :—

Composition	Aluminium 92 per cent. Copper 8 per cent.
Weight per cubic inch	0·115 lb.
Melting point	622° C.
Tensile strength	9 tons per square inch.
Elongation	1·5 per cent.

CASTING LIMITS

Maximum weight of casting	10 lbs.
Minimum wall thickness	$\frac{1}{16}$ inch
Variation from dimensions (on drawing) per inch of diameter or length	0·0025 inch.
Cast threads, minimum number (external)	20 per inch.
Internal threads rarely cast	
Holes, minimum diameter	0·093 inch and not deeper than 1 inch.

The threaded portions (external) are cast oversize (by 0·01 inch) and are screwed to size. The draft allowed (on the various portions of the pattern) should be 0·015 inch per inch of diameter or length for cores, side walls 0·005 inch, small cores of less than $\frac{1}{4}$ inch diameter 0·005 inch per inch.

This particular alloy is used extensively for automobile and aeroplane parts such as pistons, cylinders, covers, magneto parts, carburettor parts, etc.

The copper content can be varied without unduly increasing the difficulties in die-casting, and a harder or a softer alloy may be obtained.

The addition of 1 per cent. manganese to these alloys improves the tensile strength, and the ductility at the solidification temperature, thus reducing the risk of cracking during cooling. Unfortunately, for parts such as pistons, manganese has the property of reducing the heat conductivity of the alloys. This may be lowered to half its original value.

---

* For further information on this subject see "Aluminium Alloys for Aeroplane Engines," by Professor F. C. Lea, D.Sc., read before the Aeronautical Society of Great Britain, April 16, 1919.

† "Aluminium and its Alloys," by F. A. Livermore, F.I.C., *Metal Industry*, vol. XX, No. 2, Jan. 13, 1922.

There does not appear to be much scope for heat treatment with aluminium-copper alloys, although according to Rosenhain the prolonged annealing of a 4-per-cent. copper, 96-per-cent. aluminium alloy * resulted in a considerable improvement of its mechanical properties, due no doubt to the gradual solution of the copper-aluminium compound. The tensile strength of this alloy was increased from 10 tons per square inch to 14·5 tons per square inch, whilst the elongation (on 2 inches) was increased from 10 per cent. to 20 per cent. The annealing operation covered a period of 3 days at a temperature of 450° to 520° C., but owing to its length such a treatment cannot be considered a commercial one.

Aluminium-Zinc Alloys

Alloys containing zinc are used very extensively, and the common impression that they were subject to spontaneous disintegration has been proved to be incorrect by the work of Rosenhain and Archbutt, who tested bars after an interval of 15 months and found no sign whatever of any change. Thus, this so-called ageing defect does not exist so far as these particular alloys are concerned.

The effect of adding zinc to aluminium is shown by Figs. 189 and 190.

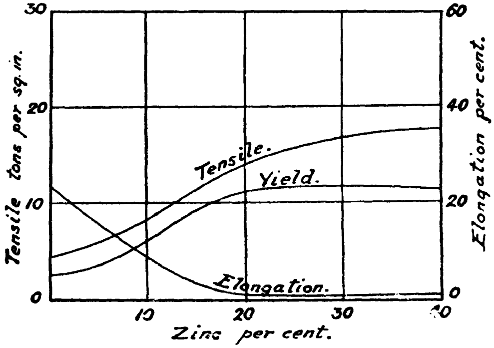


FIG. 189.—Strengths of sand-cast aluminium-zinc alloys (Rosenhain and Archbutt).

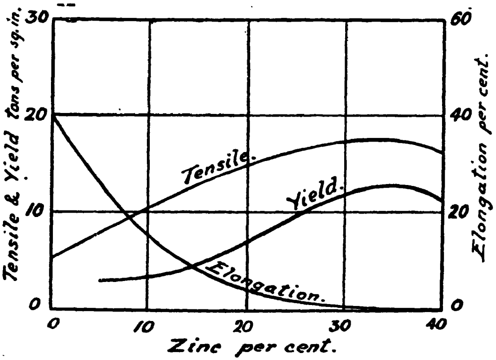


FIG. 190.—Strengths of chill-cast aluminium-zinc alloys (Rosenhain and Archbutt).

---

* Dr. Rosenhain, *Royal Soc. Arts*, April, 1920.

These results (Fig. 189) were obtained from sand castings 7 inches long by ⅝ inch diameter, all cast at temperatures below 800° C. The tensile strength increases with the increase in zinc. The effect of casting in chill moulds 7 inches long by ¾ inch diameter is shown by Fig. 190, from which it will be seen that the strength is only slightly greater than the sand castings, due, no doubt, to the greater density of the alloys.

Alloys containing up to 25 per cent. zinc can be hot-rolled, while those up to 20 per cent. can be drawn satisfactorily. The effect of hot rolling is shown by Fig. 191.

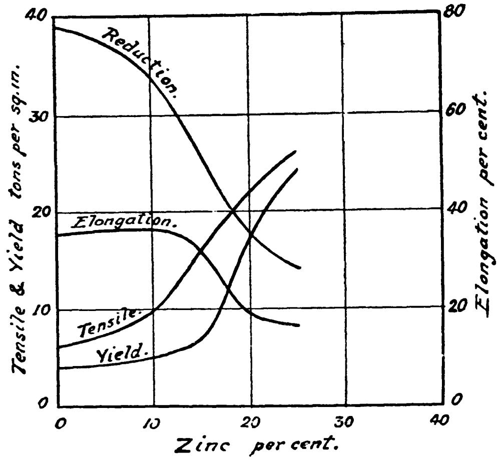


FIG. 191.—Strengths of hot-rolled aluminium-zinc alloys (Rosenhain and Archbutt).

Rosenhain and Archbutt found that those alloys containing more than 15 per cent. zinc appear to deteriorate when a large amount of work is put into them. The rolling of the 1¼ inch bars down to ⅞ inch had the effect of increasing the strength of the alloys containing less than 15 per cent. zinc, but for amounts exceeding this the strength was reduced. Thus, drawing the metal into wire only brings about an increase in strength for the lower percentages.

The principal defect of these alloys is their sensitiveness to rise in temperature. Thus, the tensile strength of the 25 per cent. alloy falls off by 33 per cent. in the change from 20° to 100° C.

Newly made castings are not easily machined, owing to the tendency of the material to " drag," but by allowing them to " age " for a few weeks the machining qualities improve very considerably. Copper is usually added to the alloy to improve it in this respect, but this alloy will be considered in the succeeding paragraphs.

The zinc base aluminium alloys are unsuitable for die-casting (especially if commercial spelter is used) due to the low elongation figure at the higher temperatures, and the consequent cracking during cooling when metal cores or other parts tend to hold the casting in position.

Aluminium-Zinc-Copper Alloys

In a preceding paragraph mention was made of the addition of copper to the zinc alloys to improve their machining properties. Copper in the alloy also helps to eliminate the porous nature of the plain zinc-aluminium alloy, improving its fluidity with the result that sharper and sounder castings are obtained.

Most of the zinc alloys now contain copper, usually in small amounts up to 4 per cent. The principal alloy used in England is one containing about 12 to 15 per cent. zinc, 2 to 3 per cent. copper, and about 1 per cent. impurities, the remainder being aluminium.

The following are a few typical analyses :—

Constituents.	No. 1.	No. 2.	No. 3.
Copper	2·12	3·06	5·87
Zinc	12·53	9·60	8·60
Aluminium	84·10	86·14	82·30
Iron	0·63	0·74	2·45
Silicon	0·30	0·34	0·51
Tin	Nil	Nil	Trace
Lead	Nil	0·10	0·16
Manganese	Trace	0·02	0·07
Magnesium	0·30	Nil	—

No. 1 alloy is the best, and gave on test the following figures :—

	No. 1 Alloy.	No. 3 Alloy.
Yield, tons per square inch	9·2	—
Ultimate Tensile ,, ,, ...	10·8	8·5
Elongation in 2 inches, per cent. ..	3·0	1·0
Reduction of Area, per cent. ..	4·0	—

No. 2 alloy is inferior, but is still a good quality material. No. 3 alloy is distinctly poor, but it represents the "common run" of much of the metal supplied for ordinary castings, and is used even in crank cases for car engines.

These alloys are all intended for sand castings, but No. 1 has been used for die castings with success.

Alloys containing higher percentages of zinc are also in use. Rosenhain and Archbutt describe one containing 25 per cent. zinc and 3 per cent. copper, which has a tensile strength of 18 tons per square inch when cast in sand, and 20 tons per square inch when chill cast. This alloy can be rolled with difficulty, when it gives a much higher tensile strength combined with a high elongation figure. This alloy would appear to be a good substitute for the well-known alloy duralumin.

Duralumin

This remarkable alloy is the strongest and most ductile of all the aluminium alloys. It is really a copper-aluminium alloy containing small percentages of magnesium and manganese. The following analyses show what its composition is in practice :—

ANALYSES OF DURALUMIN

	Bar No. 1.	Bar No. 2.
Copper	4·90	5·66
Aluminium	93·40	92·61
Magnesium	0·33	0·32
Manganese	0·58	0·54
Iron	0·50	0·55
Silicon	0·30	0·32
Zinc	Nil	Nil
Lead	,,	,,
Tin	,,	,,

strength of this alloy is equal to that of ordinary mild steel, and for ason it has been extensively used in aeronautical work for the metal ure of airships and aeroplanes. The following tests are representative e commercial bar material.*

	Bar No. 1.	Bar No. 2.
Yield, tons per square inch	23·6	25·4
Ultimate, ,, ,, ,, ...	29·9	23·9
Elongation, per cent.	17·5	15·5
Reduction of Area, per cent. .	26·0	20·0

In the annealed condition duralumin has a tensile strength of about 16 to 18 tons per square inch with 17 per cent. elongation on 2 inches. When hardened by heating it to 480° C. (not more than 490° C.) and quenching the tensile strength gradually increases until after a period of about 2 days it may reach 36 tons per square inch. The elongation is reduced considerably by this treatment. This hardness is partly removed when the alloy is subjected to quite low temperatures and for this reason it is necessary to take practical conditions into account when using duralumin in the hardened state. The reduction in strength amounts to about 10 per cent. after heating to 100° C. and about 25 per cent. after heating to 250° C.

Duralumin is obtainable in the form of plates, bars in various sections, tubes and wire. It can be forged and stamped and therefore commands a wide application in those directions where strength and lightness are essential. The operation of rolling and drawing increases the tensile strength, and this in the case of thin sheets may be as high as 35 tons per square inch. The specific gravity of duralumin is about 2·8.

Other Aluminium Alloys

The principal commercial alloys have been described, but there are a few more alloys † which are of interest, and, in view of the vast amount of work that has been done during the war on these alloys and the further developments that are likely to come, it will not be out of place to mention these.

Magnesium-Aluminium.—Alloys containing up to 6 per cent. of magnesium can be rolled hot or cold. Above this the alloy becomes too brittle. So far these alloys have not been used commercially. Their strength does not exceed that of alloys already in use, but they have the advantage of being lighter than aluminium itself, and therefore deserve attention.

Castings containing more than 15 per cent. are hard and brittle, but alloys containing as much as 30 per cent. are used for mirrors, the metal casting well and taking a high degree of polish.

The effect of magnesium on the strength of sand castings is shown in Fig. 192.

Magnesium is also employed in the making of the alloys known as magnalium and zimalium. Magnalium contains only a small proportion of magnesium, and generally has small amounts of copper, nickel, lead, and tin. The commercial alloys are known as "X," "Y," and "Z." They all contain less than

---

* For further information see "Non-Ferrous Metals in Aeroplane Construction," being a translation of "German Technical Report," by E. Unger and E. Schmidt, *Metal Industry*, June 11, 1920.

† See the Eleventh Report of the Alloys Research Committee: "On Some Alloys of Aluminium" (Light Alloys).

2 per cent. of magnesium and from 0·2 to 1·8 per cent. of copper. In addition, "X" contains about 1·2 per cent. of nickel. The alloy "Y" does not contain nickel, but has small amounts of tin and lead, while "Z" contains as much as 3 per cent. of tin and 0·75 per cent. of lead.

The alloy "X" is only used for castings of considerable strength, and "Y" for ordinary castings of 8 to 10 tons per square inch tensile. Alloy "Z" is intended for rolling and drawing, and in the rolled state has a tensile strength varying from 14 to 21 tons per square inch. This last alloy is exceedingly ductile and can be drawn into the finest wires. Annealing is carried out by heating and suddenly cooling (slow cooling hardens).

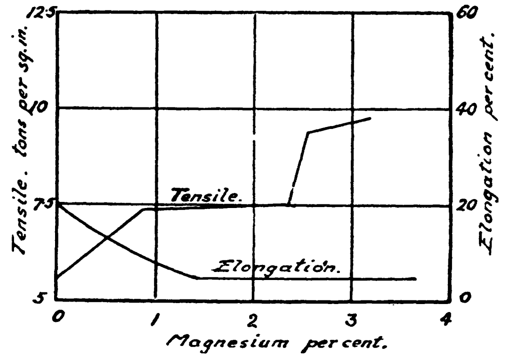


FIG. 192.—Strengths of sand-cast aluminium-magnesium alloys (Lane).

All the alloys cast well and machine well; excellent screw threads can be cut. The allowance for contraction should be about 2·5 to 4 per cent.

Zimalium contains up to 10 per cent. magnesium and up to 20 per cent. of zinc. It is harder and more easily worked than aluminium and has about twice its tensile strength.

Copper Alloys

The principal alloys of copper are classified as follows :—

(1) Bronzes or tin-copper alloys.
(2) Brasses or zinc-copper alloys.
(3) Special alloys, nickel-copper alloys, etc.

These, of course, are capable of subdivision, depending on the presence of other elements such as lead, aluminium, arsenic, phosphorus, manganese, silicon, nickel and iron, which are added in certain cases to improve the alloy in certain respects, as, for example, soundness of castings, machinability, strength, hardness, wearing qualities, ductility, etc. The influence these different elements exert is explained in Chapter IX.

Bronzes.—The bronze alloys in general use are tabulated below :—

Gunmetal	Zinc-tin-copper
Plain bronze	Tin-copper
Phosphor bronze	Phosphorus-tin-copper
Manganese bronze	Iron-manganese-zinc-copper
Aluminium bronze	Aluminium-copper

Gunmetal

This well-known alloy, originally used for ordnance work, is perhaps best considered on the basis of the Admiralty specification, which calls for a composition as follows :—

Copper	88 per cent.
Tin	10 ,,
Zinc	2 ,,

A maximum variation of one per cent. of any of its component metals is allowed, and the alloy should comply with the following mechanical tests :—

Ultimate tensile strength	14 tons per square inch (min.)
Elongation on 2 inches	7·5 per cent.

Although this is adhered to so far as Admiralty work is concerned, in practice it will be found for ordinary work that many foundries supply metal containing more than 2 per cent. of zinc, and in addition a considerable amount of lead. Such alloys are cheaper and are more easily cast, and give fairly satisfactory test results. A few actual examples of these variations from standard gunmetal are given here.

	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Copper	84·60	85·04	87·95	83·55	82·92	80·00
Tin	11·23	7·94	8·74	5·05	9·14	8·10
Zinc	4·07	4·77	1·35	7·05	3·41	5·58
Lead	0·10	2·29	1·95	4·27	4·51	5·60
Iron	Trace	Nil	Nil	0·08	0·01	Trace
Nickel	Nil	Nil	Nil	Nil	0·01	0·68

The remarkable variations in the above compositions would give the impression that almost any combination would meet the requirements. This, of course, is not the case, but, instead, the alloys can be graded and then selected to suit the actual parts under consideration. Thus, classing the Admiralty alloy as the No. 1 alloy, two other but inferior alloys may be established as follows :—

No. 2 Alloy

Copper	80·0 to 84·0 per cent.
Tin	8·5 ,, 7·0 ,,
Zinc	5·5 ,, 4·5 ,,
Lead	6·0 ,, 4·5 ,,

This alloy will give about 10 to 12 tons per square inch tensile strength, and an elongation value of about 2 to 5 per cent. in 2 inches.

No. 3 Alloy

Copper	77·0 to 81·0 per cent.
Tin	5·5 ,, 4·5 ,,
Zinc	8·5 ,, 7·5 ,,
Lead	9·0 ,, 7·0 ,,

This alloy, which is much inferior to the No. 2 alloy, will give about 8 to 10 tons per square inch tensile strength and about 2 to 5 per cent. elongation in 2 inches.

The zinc is put in to harden the alloy and to counteract the effect of lead, which softens it.

The No. 2 alloy can be used for bearing purposes, the presence of the lead tending to reduce the wear, but it is probably best employed as a support for an anti-friction alloy or other white metal. It tins well, and thus takes such a lining very well.

The No. 3 alloy is suitable where the stresses are low and where there is little hammering action.

Form.—Gunmetal is only used in the form of castings and is not suitable for rolling and drawing. It is cast either in sand moulds or in chill moulds. It would be useless for the bearings of a high-speed connecting rod, but would answer the requirements of a white-metal lined bearing on a steady running shaft.

Heat Treatment.—The alloy free from lead can often be heat-treated with advantage, the best treatment for the No. 1 alloy being an annealing process. In this respect it differs from a plain bronze of 90 copper and 10 tin, which gives the best results when quenched. The zinc, although only a small amount, appears to alter the character of the alloy very considerably.

According to H. S. Primrose and J. S. G. Primrose, the best annealing temperature is 700° C., and at this temperature the best results are obtained after soaking for 30 minutes. Further details of the heat treatment are given in Chapter X, but the chief results of this treatment are an increase in the tensile strength and a considerable increase in the elongation figure, showing that the alloy is much more ductile. Another important result is the reduced porosity of the metal; castings which were porous to water or oil under pressure are quite impervious after the annealing treatment. The following results are those obtained by Messrs. Primrose :—

	Tensile Strength.	Elongation.
	Tons per sq. in.	Per cent.
Dry sand-casting as cast	17·2	24·0
After annealing 30 minutes at 700° C.	18·0	37·5
Chill-cast as cast	15·0	4·0
After annealing 30 minutes at 700° C.	20·0	30·0

Effect of Temperature on Strength of Gunmetal.—The investigations of Dewrance and of Longbottom and Campion show that the tensile strength of gunmetal (Admiralty specification) remains practically constant (at about 13 tons per square inch) at all temperatures up to 200° C., and then falls off suddenly, almost reaching zero at 750° C. The elongation rises to a maximum at about 150° C. and then falls rapidly, reaching a very low but nearly constant value between 350° and 550° C.

It is claimed by Dewrance that the addition of 0·50 per cent. of lead increases the initial tensile strength of gunmetal and also its resistance to the effect of high temperatures, but the latter claim is disputed.

The above figures show that gunmetal is not a suitable material for use at temperatures much above the normal. Thus, apart from any chemical action which superheated steam may have on the alloy, gunmetal is quite unsuitable for parts subjected to superheated steam.

Bronzes

The name bronze is applied rather loosely to a great variety of alloys, some of which are sold under other names, such as gunmetal and phosphor bronze. The original conception of bronze was an alloy of copper and tin, and, perhaps to distinguish this combination, it is advisable to describe such alloys as plain bronzes. When zinc is added in small amounts the alloy becomes gunmetal, although some Admiralty specifications for this material do not contain zinc at all, but might be classed as plain bronzes.

The addition of lead is very common, and if this metal is present in large amount, it is usual to call the alloy a "lead bronze." But zinc is also generally present, and it is not unusual to find an alloy containing both zinc and lead in addition to copper and tin, sold both as a bronze and as gunmetal. Now the latter name is so well known, and is universally regarded as belonging to a totally different alloy from that called bronze, that it is a pity for the two names to be applied in this unsatisfactory manner. Gunmetal should be regarded as belonging to the bronze group of alloys, and certain limits should be set as to its constituents and their amount. It should represent those alloys which, beside containing copper and tin as the base, also contain zinc and lead in definite amounts.

Phosphorus is now used very extensively as a deoxidiser in these alloys, and it has become common to refer to many of them as phosphor bronze. This again is confusing because in many instances the amount of phosphorus in the final alloy is nil, or only very small, due to it having been used up entirely in removing the dissolved oxides. Some of these bronzes on the market are practically identical with those sold as gunmetal, and it may be said—whichever alloy is chosen, that ordered as gunmetal or as phosphor bronze—the difference between the two is small, and generally speaking both are poor.

When phosphorus is added in such quantity that the final alloy contains definite amounts, say above 0·2 per cent., then the bronze might truly be described as phosphor bronze. Even then, however, many such alloys contain large amounts of lead and zinc. However, as the phosphorus exercises an important influence on the alloy so far as bearing surfaces are concerned, it is feasible to regard it as distinct from gunmetal.

The addition of aluminium to copper, forming what is known as aluminium bronze, is altogether a different matter because the alloy does not contain tin. It is simply an alloy of aluminium and copper.

The so-called manganese bronzes, again, are misleading, since the majority are really brasses, containing zinc in large amounts. They contain very little tin, and therefore have no relation to bronze, even in the widest sense.

Bronze and Phosphor Bronze.—The plain copper-tin alloy called bronze is seldom used now. The use of phosphorus as a deoxidiser has so improved the properties of the alloy, that its use is now almost universal, and manufacturers have in consequence sold the metal under the name of phosphor bronze.

Many of these so-called phosphor bronzes contain little or no phosphorus; they are simply ordinary bronzes from which the dissolved oxides have been removed by the reducing action of phosphorus. They may be regarded as "purified" bronzes. These alloys are dealt with first, while those that contain phosphorus in definite intended amounts are described later.

The plain alloys can be divided into two groups : (1) those that contain less than 8 per cent. of tin and are capable of being rolled into sheet or drawn into wire, and (2) those that contain more tin and can only be cast, being too brittle for rolling.

Influence of Temperature.—Rolled or drawn phosphor bronze of low tin content and only traces of phosphorus, can be used for high temperature work, such as firebox stays and plates. It does not fall off much in strength at temperatures up to 300° C. Material having a tensile strength of 28 to 30 tons per square inch will have a strength of about 25 tons per square inch at this temperature.

When the alloy contains more tin (not exceeding 8 per cent.) it commences to lose its strength at about 200° C. and at 300° C. the tensile strength is only about half the original value. Thus phosphor bronze which possesses a tensile strength of 15 to 16 tons per square inch at normal temperatures will have a strength of about 13 tons per square inch at 200° C. and about 8 tons per square inch at 300° C. The elongation of this particular alloy falls off in about the same order as the strength, and thus the metal is shorter at the higher temperatures.

Of the first group the usual alloy for rolled and drawn bar, sheet or wire is that represented by No. 1 alloy in the table on p. 398. Such material is very strong, wire having a tensile strength of 50 to 60 tons per square inch being used for long spans in telephone work in place of copper which is too weak. The bar and sheet approximate 30 tons per square inch tensile.

The second group of alloys is represented by Nos. 2, 3, and 4 in the table. These are generally used in the form of castings for very small pump bodies, bearings, and gearing. The addition of tin increases the hardness of the alloy and reduces its ductility very considerably. Those alloys intended for shock and vibration as with gearing, should contain from 88 to 92 per cent. of copper. For bearings care must be exercised as to the kind of steel used for the shaft ; for hardened steel (case-hardened) an alloy containing up to 20 per cent. of tin can be used, but this would be very harmful to a soft or medium soft steel shaft. The hard constituent "delta" formed by the tin will score most steels (unless hardened) very readily. The tin content should not exceed 9 or 10 per cent. for such unhardened steel. The value of annealing should not be overlooked in this application of bronzes because of the possible elimination of the hard delta constituent, and reference should be made to Chapter X, where this is dealt with.

True Phosphor Bronzes.—These are the alloys which contain phosphorus in definite and intended amounts. Their use is confined mainly to bearings for hardened steel. The phosphorus, when added only to purify the metal and not present in amounts above 0·05 per cent., increases the tensile strength, but above this it causes a rapid falling off which, however, becomes more gradual at about 0·5 per cent., and further amounts do not have such a large effect.

The machining qualities are much affected, and alloys containing 1 to 1·5 per cent. will be found difficult to cut rapidly.

As materials for bearings, these alloys are dealt with more fully in Chapter XVI on Bearing Metals, but for completeness a few typical alloys are given in the table on p. 398, Nos. 5 to 8. The following alloys represent common practice :—

BRONZES

No. of Alloy.	Copper Minimum. Per cent.	Tin. per cent.	Zinc. per cent.	Lead. per cent.	Phosphorus. per cent.	Tons per sq. in.		Elongation. per cent. 2 ins.	Reduction Area. per cent.	Brinell Hardness Number	Compression Test.		General Applications.
						Yield.	Ultimate.				Yield.	Per cent. Reduction Loading.	
1	95	5 *	—	—	Trace	—	—	—	—	—	—	—	Rolled and drawn bar, sheet, wire.
2	90	10	—	—	Trace	—	14–16	10–14	—	67–70	—	—	Pumps, collars, bearings.†
3	89	11	—	—	—	10–11	15·5–18	6–10	7–9	80	7·75	25–27	Gears and worm wheels.†
4	80	20	—	—	Trace	—	—	—	—	136	—	3·1	Dies, bells, bearings, etc.†
5	90	10 *	—	—	0·5	—	15	10	—	—	—	—	Hard bearing metal.
6	87	11	—	—	1·0	—	10	3	—	—	—	—	Extra hard bearing metal.
7	85	15	—	—	1·0 *	—	—	—	—	—	8·5–10	12–25	In bridges, for contact with soft steel at pressure below 1,500 lbs. sq. in.
8	80	20	—	—	1·0 *	—	—	—	—	—	11–18	6–10	Ditto, but hard steel pressure above 1,500 lbs. per sq. in.†
9	88	10	—	2	—	8·5–10	13·15	15–20	18–26	67–70	6·5	28–29	Gears under moderate service and for good machinability.†
10	88	8	—	4	0·2	9	14	15	15	—	—	—	Standard bearing metal for shafts of medium carbon steel and medium hardness.
11	84	9·5	—	6·3	0·2	—	13–14·5	8–10	—	59–61	—	—	Slide valves, bearings.†
12	84	8	—	8	Trace	—	—	—	—	—	—	—	
13	80	10	—	10	Trace	8·5–9·5	12·5–14·5	5–7	6–10	55–60	5–5·5	33–35	Standard for high speeds, heavy pressures, shock, and vibration.†
14	80	10	—	10	0·8	—	—	—	—	—	8	—	Bridge bearings.
15	79	14·5	—	6·5	—	—	—	—	—	—	—	—	Bearing metal.
16	78	7	—	15	—	7·5–8	12·5–13·5	12–18	17–23	48	4–5	38–39	Bearings for medium pressure and high speed.†
17	64	5	—	30	—	Also contains 1 per cent. nickel.			—	—	—	—	Railway waggon axles in U.S.A. for pressures less than 600 lbs. per sq. in.†
18	88	10	2	—	0·25 *	—	14·5	14	—	—	6	—	Gears, worm wheels, nuts.†
19	83	14	2	1	—	7·5	11·0	2	—	—	—	—	Bearings and bushings.†
20	80	9	2	8	1·0 *	9·0	15·0	18	—	—	—	—	Gun fittings.†

* Maximum limit.

† Metal Industry Handbook.

Phosphor bronze for strength and low brittleness (*i.e.* high ductility) :—

No. 1.—Chemical Composition

Copper	minimum 90 per cent.
Tin	8 to 10 ,,
Phosphorus	0·2 to 0·7 ,,

Mechanical Tests

Ultimate tensile ..	15 tons per square inch minimum
Elongation in 2 inches	10 per cent. minimum

Phosphor bronze for bearings for hardened steel shafts :—

No. 2.—Chemical Composition

Copper	minimum 87 per cent.
Tin	10 to 12 ,,
Phosphorus	0·6 to 1·0 ,,

Mechanical Tests

Ultimate tensile ..	10 tons per square inch minimum
Elongation in 2 inches	2 per cent. minimum

Phosphor bronze for exceptionally hard wear should be of the same composition, but the phosphorus content should be about 0·9 to 1·5 per cent.

These standard compositions are used mainly for the following purposes :—

No 1. Suitable for pumps, propellers, pinions, gears, valves, and steam fittings.

No. 2. Suitable for worms and worm wheels, gears and pinions, pumps, cylinders, bearings for hardened steel, and is intended for hard wear.

Impurities.—Both the plain and phosphor bronzes are likely to contain the following impurities : lead, iron, zinc, and manganese. These, in a good quality alloy, should not total more than 1 per cent., but in many of the usual commercial qualities this amount is exceeded. The following analyses represent actual examples :—

	1	2	3	4	5	6	7	8
Copper ..	88·39	87·90	88·80	87·34	87·45	87·90	87·60	87·27
Tin ..	10·58	10·37	10·54	11·95	10·40	10·00	11·22	11·22
Phosphorus	0·02	0·12	0·43	0·65	0·11	0·41	0·69	1·50
Lead ..	1·00	0·48	0·23	0·05	1·36	Trace	0·49	Trace
Zinc ..	Nil	1·15	Nil	Nil	0·59	1·69	Nil	Trace
Iron ..	Trace	Trace	Trace	Trace	0·09	Trace	Trace	Trace

The principal impurities are lead and zinc. The lead does not alloy with the metal, and will be found in the structure in the form of minute globules Up to 0·25 per cent. it has no injurious effect. In larger amounts it increases the brittleness and reduces the tensile strength. Zinc is often added to make the metal run easier and to increase the soundness of the casting. It alloys in small amounts and does not appear to influence the properties of the metal until it exceeds 2 per cent. It is then harmful for bearing metals, and reduces the tensile strength and hardness, and also the ductility of the alloy.

The presence of both lead and zinc, however, improves the machining qualities of the alloy in so far that the chips break off shorter and the tool clears itself more easily.

Iron alloys with the metal and makes it harder and stronger. It should not exceed 0·3 per cent.

Bronzes containing Lead.—Lead is added in large and definite amounts to bronzes to form bearing metals. In Chapter XVI these alloys are dealt with fully, but a few points about them here will be of service. The lead does not alloy (except for a little which goes into solution), but exists in the form of small globules distributed over the mass. From this it is evident that owing to its low melting point (330° C.), it will be the last to solidify, and will therefore tend to collect in large areas towards the centre or lower portion of the casting. The tendency to liquate or segregate is one of the difficulties in casting, and there is always some uncertainty as to the amount of lead on the surface of a bearing.

In the case of high percentages of lead, Henrickson and Clamer in America have found that nickel prevents the liquation, probably because it forms a network enclosing the grains and thus maintains the lead in position until it solidifies. By this means alloys containing as much as 30 per cent. of lead are made, and are found to be homogeneous. Such an alloy is given in the table on p. 398 (see No. 17).

A few of the more common lead bronzes are given in the table on p. 434.

Bronzes with Zinc.—Zinc added to a bronze really forms the alloy known as gunmetal, and this alloy has been dealt with already. It is, however, a very common constituent in bronzes since it tends to promote sound castings and also improves the machining quality of the alloy. A few typical zinc and zinc-lead bronzes are represented by alloys 18, 19, and 20 in the table on p. 398.

Manganese Bronze

This so-called bronze is the result of many efforts to produce a strong, tough alloy that will resist corrosion. It is really a brass to which small percentages of manganese, iron, and aluminium are added, all with the definite object of making the alloy dense and close-grained, and also increasing its strength.

The average composition of commercial manganese bronzes is as follows :—

Copper	56·00 to 59·0 per cent.
Zinc	38 00 „ 41·0 „
Tin	0·25 „ 1 0 „
Manganese	0·25 „ 2·0 „
Iron	0·25 „ 1·25 „
Aluminium	0 25 „ 1·0 „
Lead	Trace to 0·5 „

The average mechanical strength of such alloys is as follows :—

Yield	17 tons per square inch
Ultimate tensile ..	30 „ „ „
Elongation in 2 inches	25 per cent.
Reduction of area ..	30 „

Some typical analyses of castings, together with the mechanical test results obtained, are given in the following table :—

	1	2	3	4	5
Copper	58·50	58·97	57·85	57·20	57·76
Zinc	38·96	39·00	39·18	39·52	38·86
Tin	0·45	0·98	0·38	0·54	1·18
Manganese	0·20	0·44	0·77	0·94	1·62
Iron	1·24	0·10	0·81	1·01	0·06
Aluminium	0·36	0·30	0·61	0·46	0·31
Lead	0·20	0·20	0·39	0·33	0·20
Nickel	Nil	Nil	Nil	Nil	Nil
Phosphorus	Trace	Trace	Nil	Nil	Trace
Yield, tons per square inch ..	13·4	19·4	20·7	22·5	24·6
Ultimate, ,, ,, ...	29·5	31·6	30·2	32·2	36·8
Elongation in 2 inches	26·2	31·2	23·2	21·3	25·0
Reduction of area	31·6	41·4	30·1	29·7	30·0

Effect of Manganese.—Many alloys contain only a trace of manganese, or perhaps none at all, from which it is evident that it has been entirely used up in performing its function as a deoxidiser. When present it increases the tensile and the yield strength, but without lowering the elongation, and makes the alloy harder.

Effect of Iron.—This metal is either added with manganese in the form of ferro-manganese or with cupro-manganese, in which it also exists. It tends to increase the tensile strength and to harden the alloy.

Effect of Aluminium.—Aluminium is added to increase the fluidity of the metal during casting, to eliminate blowholes and render the alloy denser and more uniform.

Heat Treatment.—Manganese bronze castings possessing a low elongation percentage (*i.e.* ductility) can be improved by slow annealing at temperatures between 700° and 800° C. The tensile strength is reduced slightly by this treatment. Rapid cooling by quenching in water reduces the ductility of the alloy to almost nil, and in consequence this treatment is useless. Slower cooling (in air) will sometimes raise the tensile strength without affecting the elongation percentage very seriously. Thus variations in the treatment can often be applied to correct any falling off in the strength or ductility of manganese bronze castings.

Rolling and Forging.—Manganese bronze containing about 60 per cent. of copper is suitable for rolling and forging. Drop stampings are made also from the same class of alloy, and as a rule these are very well finished and true to shape.

In the forged or stamped condition the tensile strength of manganese bronze ranges from 25 tons per square inch to about 35 tons per square inch, according to the composition. The corresponding yield points are about 11 and 20 tons per square inch, whilst the elongation ranges from about 40 per cent. down to 15 per cent.

Manganese bronze is rolled cold into bars and sheets and is drawn into tubes and wire. In the cold rolled state the tensile strength may be as high as 50 tons per square inch (usually 40 to 45 tons per square inch). Thus this material may be used for bolts, nuts, and studs, whilst it is particularly suitable for hydraulic plant and other work where corrosion is the principal source of trouble. The tubing can be bent easily (hot or cold), and the metal is less prone to seepage than most of the other alloys, and of course is much stronger than copper or brass and therefore withstands higher pressures.

The cast material is used largely in connection with marine work for parts such as propellers, pump spindles, valves, and hydraulic rams.

Effect of Temperature on the Strength of Manganese Bronze.—The strength of manganese bronze, in common with other alloys, falls off considerably at the higher temperatures. According to some tests recently published,* Lea obtains the following results :—

Composition.							15° Cent.			300° Cent.		
Cu.	Zn.	Sn.	Pb.	Fe.	Al.	Mn.	Ult. tensile.	Elongation per cent.	Brinell hardness.	Ult. tensile.	Elongation per cent.	Brinell hardness.
58·15	39·94	1·05	0·63	0·25	—	0·98	35·70	24·0	143	17·70	62·0	105
59·5	36·72	0·63	0·90	0·56	1·06	0·63	37·48	25·0	137	10·42	78·0	114

Aluminium Bronze

The aluminium bronzes may be divided into two groups : (1) those that are very ductile and can be drawn cold ; (2) those that are only moderately ductile, and can only be rolled while hot.

The first group does not contain more than about 7 per cent. of aluminium, and the second group contains between 7 and 11 per cent. Above 11 per cent. the alloy is too brittle for service.

The effect of aluminium is to increase the tensile strength, although this is not very marked until the amount rises above 7 per cent., and then the increase is quite considerable. The ductility also increases, but at about 7 per cent. commences to fall off rapidly. The extent of this is shown in Fig. 193, which represents the results of some experiments carried out by Carpenter and Edwards.

Rolling and Forging.—As explained above, the lower percentages of aluminium give very ductile alloys, and these can be drawn into wire. The results obtained by rolling and also cold drawing are shown in Fig. 194, from which it will be seen that in the case of the 7-per-cent. aluminium alloy, the tensile strength is raised from about 19 tons per square inch in the cast condition, to about 27 tons per square inch when rolled, and to about 32 tons per square inch when drawn cold from $\frac{7}{8}$ inch to $\frac{13}{16}$ inch diameter. The ductility is increased by the rolling, but of course falls off during drawing.

The figures are likely to be modified by the amount of "working," and must depend on the reduction during drawing. The importance of gradual

---

* "The Effect of Temperature on Some of the Properties of Metals," by Professor F. C. Lea, O.B.E., D.Sc., *Inst. Mech. Eng.*, June 15, 1922; *Engineering*, June 30, 1922.

reduction is the same for these alloys as for brass, and if too great a "pinch" is given the usual troubles common to brass will occur, such as "season cracking."

Heat Treatment.—Those alloys containing less than 7 per cent. of aluminium are not much affected by heat treatment, whether cooled slowly or quenched, but the effect of annealing is much the same as with brass, and prolonged heating causes the grain-size to increase with a consequent reduction in strength and a very marked falling off in the yield point (see Chapter X).

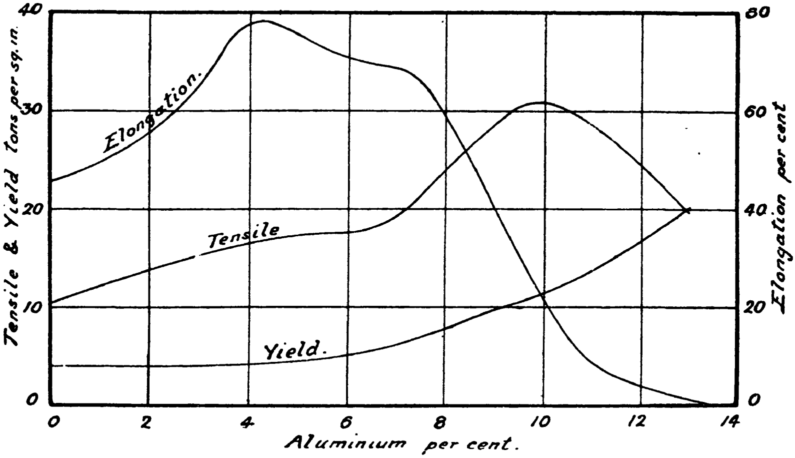


FIG. 193.—Strengths of Aluminium Bronze Alloys (Sand Castings).

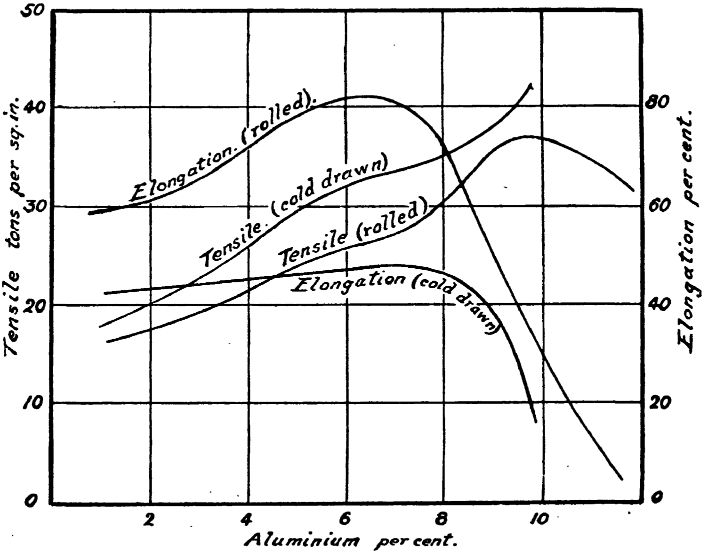


FIG. 194.—Strengths of Rolled and Drawn Aluminium Bronze Alloys.

In the case of the alloys containing over 7·5 per cent. aluminium the effect of quenching is quite considerable, especially with the 10-per-cent. alloy, in which the tensile strength is raised from about 32 tons per square inch to about 50 tons per square inch by quenching in water from a temperature of 800° C. This important property is dealt with in Chapter X, under "Heat Treatment," and reference should be made to that section.

Castings—Sand, Chill and Die.—The principal feature of aluminium bronze castings is their high shrinkage and contraction. For the shrinkage it is necessary to provide large gates and a good head of metal, otherwise the castings will be porous and spongy. The contraction to be allowed for amounts to about 0·20 inch per foot.

Casting in chill moulds does not greatly increase the tensile strength of the 7-per-cent. alloy, but with the higher percentage alloys the improvement is more marked, although even then the gain is not much, the 10-per-cent. alloy being about 4 tons per square inch better.

An important advance in die castings is announced by Rix and Whitaker,* who are using a modified aluminium bronze with success in die castings. The alloy they are using is one of the series containing 7 to 10 per cent. aluminium, and from 1 to 4 per cent. of iron. The addition of iron is highly important, and the results obtained from 24 test bars cast in 1-inch chill moulds and cooled in air average out as follows :—

Yield	14·7 tons per square inch
Ultimate tensile	35·5 " " "
Elongation on 2 inches ..	24·0 per cent.
Reduction of area	21·8 "

These two workers are employing this alloy for very complicated parts, such as dynamo brush rockers, and the results appear to be highly satisfactory.

The strongest alloy in the form of sand castings is that containing about 10 per cent. aluminium. The tensile strength is about 30 tons per square inch and the elongation about 20 per cent. When cast in a chill mould the tensile strength is increased to about 35 tons per square inch and the elongation to 25 per cent.

Brass

Essentially, brass is a copper-zinc alloy, but there are many special brasses containing other elements, added purposely to improve the properties of the alloy. Thus, to commence with, the brasses might be divided into (1) ordinary plain brasses, and (2) special or high tensile brasses. Some of the latter alloys are very complex, and before attempting to deal with them it is advisable to consider the plain or simple brasses consisting only of copper and zinc.

The effect of varying the proportions of these two metals is shown in Fig. 195. From this it will be seen that as the zinc content is increased so the tensile strength is raised until at about 45 per cent. zinc it reaches a maximum of 30 tons per square inch. The ductility, however, as shown by the elongation, reaches a maximum at 30 per cent. zinc, and then falls off rapidly. The alloys

---

* "Die Castings of Aluminium Bronze," by H. Rix and H. Whitaker, M.Sc., *Inst. Metals*, March, 1918.

containing more than 45 per cent. of zinc are of no commercial value, as will be seen by the rapid falling off in strength. All the principal brasses in use contain between 55 and 70 per cent. of copper, and the constitution of these is very simple. Those containing more than 64 per cent. of copper consist of a single solid solution, "alpha," and those containing between 64 and 55 per cent. are composed of two different solid solutions, "alpha" and "beta." The single constituent brasses can be rolled and drawn cold, while those with two constituents are rolled hot. The division between the two is not sharply defined, as some of the double constituent alloys can also be rolled cold.

Commercial Brasses.—In most cases brass contains a number of added metals together with certain impurities, and it is necessary therefore to take these into account when considering the different grades now in use.

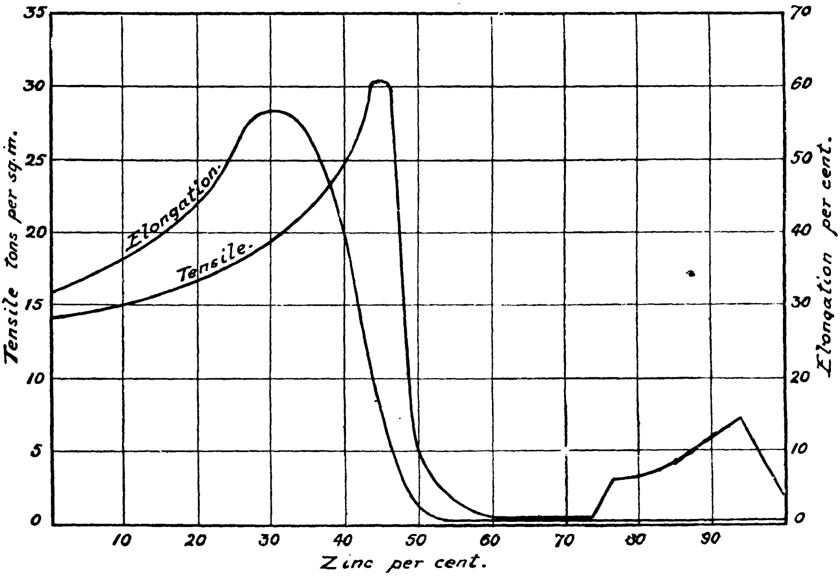


FIG. 195.—Strengths of Copper-zinc Alloys. After mechanical and thermal treatment.

Lead.—This metal is nearly always present in brass, being introduced in the zinc, which always contains a small amount. Very often it is added intentionally because it improves the machining qualities of the alloy, a fact which is due to it not alloying properly but remaining in the free state distributed throughout the mass in very minute globules or films which separate the crystal grains, and thus render the metal less tenacious. The turnings, therefore, instead of being long and tough are short chips breaking off through the lines of weakness produced by the lead. It also appears that the lead acts in the manner of a lubricant, and thus enables higher speeds to be employed and a better finish to be secured.

Since, however, lead reduces the tensile strength and ductility of the alloy, its amount must be limited in good quality brasses, and it is usual therefore, to limit it to about 0·10 per cent

Tin.—Tin is added to brass to reduce corrosion, and for this reason is specified as a definite constituent by the Admiralty, the alloy (which is of special composition) being known as "Naval" brass. It increases the hardness and strength of the alloy, but beyond 1 per cent. the metal rapidly becomes too hard and brittle, and with 2 per cent. is practically useless.

Iron.—This metal is added to brass to form a stronger alloy, and is one of the constituents of the well-known Delta Metal which is described later. It is not usually present in large amount in ordinary brasses although it is a common impurity. It increases the strength and hardness.

Arsenic.—This element is an impurity originally contained in the copper, and has an injurious effect upon the alloy since it tends to cause brittleness when present in amounts exceeding 0·5 per cent. Small amounts dissolve in the copper, and have a hardening effect, and in some cases, therefore, its presence is helpful.

Antimony.—This metal is also an impurity imparted by the copper, but is much more injurious than arsenic. It affects the rolling very much, since it causes the metal to crack. This will be easily understood because antimony is almost insoluble in copper, and therefore during the cooling of the ingot it separates out either as free metal or with a little copper, and having a low melting point remains liquid, and finally solidifies between the grains of the brass itself. Thus each grain is separated by a thin film of brittle and weak material, and the alloy during rolling easily cracks along this plane of weakness. Sperry found that 0·02 per cent. would cause trouble, and therefore in good brasses antimony should be limited to 0·01 per cent. as a maximum.

Bismuth.—In some instances bismuth is found in copper alloys, being introduced through this metal. Its effect on brass is similar to antimony, but it does not appear to be quite so injurious. In a good brass it should not exceed 0·01 per cent., but in some cases it may be allowed to approach 0·02 per cent. without serious trouble occurring.

Composition.—The table on p. 407 contains a few of the more common alloys, but it should be remembered that the composition of most commercial brasses is very varied, particularly the cast brasses. The first three alloys are termed "basis" alloys, and represent the standard compositions for the three purposes, cold rolling, casting, and hot rolling respectively.

Cast Brass.—Brass castings are usually of the following approximate composition: Copper 66 per cent.; zinc 34 per cent.

There are, however, many other compositions, and usually very large amounts of impurities such as lead, tin, and iron. These are mainly due to the employment of scrap metal, a very common practice in brass foundries, and, except when the metal has to be particularly reliable, these compositions are usually satisfactory. Common yellow brass of 70 copper, 30 zinc is often used, while the 60 copper, 40 zinc is another alloy.

Sometimes smaller and more delicate castings are made from alloys containing from 75 per cent. to 90 per cent. of copper. Thus cocks and taps are often made from an alloy containing about 78/79 copper, 14/15 zinc, together with 2 to 3 per cent. of both lead and tin. Red brass contains up to 90 per cent. of copper, whilst jewellery is generally made from 85 copper, 15 zinc alloy.

Very large castings may contain a comparatively large amount of zinc.

BRASSES

No. of Alloy.	Copper, per cent.	Zinc, per cent.	Tin per cent.	Lead, per cent.	Iron, per cent.	Manganese, per cent.	Aluminium, per cent.	Tensile, tons per sq. inch.		Elongation. in 2 ins. per cent.	Reduction of area, per cent.	Brinell Hardness No.	Compression Test.		General Applications.
								Yield.	Ultimate.				Yield.	Per cent. reduction, loading 100,000 lbs. per sq. in.	
1	70	30	—	—	—	—	—	6·5	16	55	55	—	—	—	Basis alloy for cold rolling and drawing (cast state).
2	66	34	—	—	—	—	—	6	14	40	—	—	—	—	Basis alloy for cast brass.
3	58–62	38–42	—	—	—	—	—	—	—	—	—	—	—	—	Basis alloys for hot rolling.
4 *	74·5–77·5	21–23·3	0·8–1·2	0·3–1·2	0·2†	—	—	3–4	10–12·5	23–33	15–25	40–60	—	—	Castings.
5 *	70	27	1	2	—	—	—	4–4·5	12·5–14·0	22–28	27–30	50–55	2 5	40	Light castings and other work not requiring strength.
6 *	55	45	—	—	—	—	—	—	17–20	9–13	—	80–93	—	—	Low grade bearings.
7 *	55–62	30 remainder	1–1·5 †	0·4 †	0·5–2·0	0·5–3·5	1·5†	—	27 min.	15 min.	—	—	—	—	For strength in heavy work, substitute for steel in intricate work—high resistance to corrosion.
8	70	29	1	—	—	—	—	—	—	—	—	—	—	—	Admiralty brass.
9	62	37	1	—	—	—	—	—	22 min.	30 min.	—	—	—	—	Naval brass for stanchions, spindles, tube-plates, bolts, etc.
10	60	38	nil	2	—	—	—	—	24–29	15–26	50–60	—	—	—	Screwing brass for rapid machining.
11	60	40	—	—	—	—	—	—	—	—	—	—	—	—	Muntz metal — high resistance to corrosion.
12 *	85	9	3	3	—	—	—	—	10–11	16–18	—	—	—	—	Oil and water pumps castings (red brass).
13 *	83	7	4	6	—	—	—	6–7	12·5–14·5	15–20	20–26	55–60	4–45	37–39	Valves, cocks, and pipe fittings (red brass).

* "Metal Industry." † Maximum.

Thus, hydraulic pump parts are made from an alloy containing 58/59 copper, 37/39 zinc, with tin and lead each under 2 per cent.

The mechanical properties of the cast brasses depend not only on the proportions of copper and zinc, but also on the impurities present. Further, the addition of certain other metals will affect the strength and ductility of the alloys. The tensile strength and elongation per cent. for those alloys that have been made from comparatively pure copper and zinc are shown in Fig. 195. Other figures are given in the table on p. 407.

It is important to note that the elastic limit (or the yield point) is very low as compared with the ultimate breaking stress, and this fact must be considered when using brass castings for parts that are subjected to comparatively high stresses.

Pouring Temperatures.—The casting temperature depends mainly on the type and size of casting. It is also controlled by the composition of the alloy. The best commencing temperature for casting with a 60/40 brass is about 980° to 1,000° C., and for a 70/30 brass about 1,030° to 1,040° C., while for alloys containing more copper the temperature should be about 1,100° C.

The difficulty with higher temperatures is the absorption of gases by the metal, and this grows more serious as the temperature is increased. These gases, of course, are absorbed while in the furnace, and unless the latter is electrically heated this source of trouble cannot be entirely prevented. If the metal is poured at such high temperatures and while still charged with gases, the resulting casting is generally full of blowholes caused by the gases liberated during cooling not being able to escape. Such metal is described as " spuey."

With low temperatures dross is apt to be carried in by the metal, and this causes a non-coherent structure. What is termed " spilly " metal is often produced by the immediate freezing of the metal as it touches the mould; subsequent layers do not adhere.

Hot-rolled Brass.—Nearly all the rolled metal is worked while hot, whatever its composition may be, but as some can be rolled and drawn cold a division is made here, and the latter alloys are dealt with later. The hot-rolling alloys contain from 58 to 62 per cent. of copper; the most common of these is Muntz metal, of about 60/40 composition. Such alloys, as explained already, consist of the two constituents alpha and beta solid solutions, and in the cast state these are found separated in fairly large patches, causing the structure to be very coarse. By hot working, however, these patches are reduced, and the structure becomes much finer, but the temperature should be higher than 600° C., otherwise the grains are simply distorted and annealing becomes necessary to restore the metal. The mechanical characteristics of the hot-rolled brasses are somewhat similar to those of the forged material referred to below.

Hot-forging Brass.—Some brasses can be forged under the drop hammer, and very satisfactory drop stampings are made this way. The alloys coming within the range 57 to 63 per cent. copper are those generally employed. The mechanical properties of these alloys depend on the amount of work put into the metal and the thermal treatment. If the stampings are quenched in water instead of being allowed to cool slowly they will be harder and stronger, but not so ductile as the slowly cooled material.

According to Ellis, the following results may be expected from stampings that have been fully annealed :—

Copper, per cent.	Yield, tons per sq. in.	Ultimate, tons per sq. in.	Elongation, per cent.
57	12·5	27·5	25
60	11·0	25·0	40
63	8·5	19·0	40

The above figures show that the 60/40 alloy is the best all-round one in this range. Ellis also shows that the best results for machining are to be obtained with between 59 and 60 per cent. copper. The 60/40 mixture has the fastest machining time. With these mixtures the turnings are short and chippy, whilst above 60 per cent. and below 59 per cent. copper, the turnings have a more ribbon-like nature.

"Naval brass" is an alloy specified by the Admiralty and consists of 62 per cent. copper, 37 per cent. zinc, and 1 per cent. tin. The copper content must not be less than 61 per cent., and the impurities must not exceed 0·75 per cent. This alloy can be forged or rolled hot into bars and sheets. It is employed by the Admiralty for bolts, spindles, tube plates, and for stanchions. The addition of tin reduces corrosion and therefore makes the alloy serviceable for marine work. Thus, for parts that are subjected to the action of sea water, the amount of tin is specified at 1 per cent. minimum.

The tensile strengths of naval brass as specified by Government Departments are given in the following table :—

——	Ultimate (min.), tons per sq. in.	Elongation (min.), per cent.	Bending test (cold).
Sheets, $\frac{3}{8}$ inch and under (annealed) . .	26	30	180°
,, $\frac{3}{8}$ inch and under (hard rolled)	26	25	135°
,, $\frac{3}{8}$ inch to $\frac{1}{2}$ inch	26	20	135°
,, $\frac{1}{2}$ inch to $\frac{3}{4}$ inch	24	20	120°
,, above $\frac{3}{4}$ inch	22	20	90°
Bars, $\frac{3}{4}$ inch diameter and under . .	26	30	75°
,, above $\frac{3}{4}$ inch diameter	22	30	75°
,, square	22	30	75°

The elongation percentage is taken on gauge points 2 inches apart. The bending test (cold without annealing) is over a radius equal to the thickness or diameter of the test piece (which is placed on supports 10 inches apart and a die of the correct radius applied to the centre).

Cold-rolled Brass.—The alloys generally employed for cold rolling or drawing contain more than 63 per cent. of copper. The No. 1 alloy in the table on p. 407 is the best of these since it possesses the maximum ductility, and is still fairly strong. Its structure is the homogeneous solid solution alpha, but the cold working produces grain distortion, and it is necessary to resort to annealing at intervals during the reduction. This procedure is important, for if attempts are made to leave out some of the annealing treatments, or rather to do too much cold work on the metal, a trouble known as "season cracking" occurs. This is a spontaneous splitting of the metal, which may take place some little time after the metal is finished. This is very common with brass tubing, where the "pinch "or reduction has been too great, and the annealing insufficient. This defect rarely occurs in the rolled material and is almost confined to the drawn product.

The 70/30 alloy mentioned above (No. 1 in table), when cold-rolled into sheets or strips and correctly annealed, possesses the following mechanical properties :—

Yield, tons per square inch	4 to 6
Ultimate, tons per square inch	20 „ 23
Elongation, per cent. (2 inches)	55 „ 60

This same alloy is used for boiler and condenser tubes, for which the Engineering Standards Committee have drawn up a specification. The principal tests applied are as follows :—

(1) *Bulging or Drifting Test.*—The tubes must stand an increase of 25 per cent. in diameter without showing either crack or flaw.

(2) *Flanging Test.*—The tubes must stand flanging, without showing either crack or flaw, until the diameter of the flange measures not less than 25 per cent. greater than the original diameter of the tube.

(3) *Flattening and Doubling-over Test.*—A piece of the tube is flattened down until the interior surfaces meet and is then doubled over (lengthways) on itself, that is bent through an angle of 180°, and flattened. No crack or flaw should show up. This test is carried out in the cold state.

(4) *Hydraulic Test.*—All boiler tubes must stand an internal pressure of at least 750 lbs. per square inch.

The American Society for Testing Materials have issued a similar specification for boiler tubes, and in this they state the composition as follows :—

Copper	not under 69·00 per cent.
Lead	not over 0·50 „
Iron	„ „ 0·10 „
Materials other than copper or zinc	„ „ 0·50 „
Zinc	remainder.

Thus, the total of the materials other than copper or zinc does not exceed 0·50 per cent. In the British specification the maximum limit is 0·75 per cent. The Admiralty specify the addition of 1 per cent. of tin, the composition being 70 : 29 : 1. An alternative composition to the above is that containing copper and zinc in the ratio of 2 to 1. The copper should not be less than 66·7 per cent., and the maximum limit for materials other than copper or zinc is 0·75 per cent.

Effect of Temperature on the Strength of Brass.—The strength of the copper-zinc alloys becomes less as the temperature increases, but some of the alloys do not diminish in strength so rapidly as others. Thus Muntz metal is superior to most of the other brasses. The tensile strength of Muntz metal falls off approximately 16 to 18 per cent. during the change from the normal temperature to 200° C., and at 300° C. the decrease in strength is about 30 per cent. The ductility does not fall off seriously until 200° C. is reached, and at 300° C. the elongation percentage is about half of the normal value.

Special Brasses

The special brasses are often complex alloys having as a basis one or other of the common brasses but modified by the addition of one or more special metals such as iron, aluminium, tin, lead, manganese, or nickel. These are added chiefly with the object of increasing the strength and hardness of the alloy, although other objects are sought after, such as resistance to corrosion and improved machinability.

There is still some uncertainty as to the effects of these different metals on the mechanical properties of the alloys, but in general the results can be summarised briefly as follows :—

Iron.—This metal increases the hardness and strength of brass. It forms one of the principal controlling elements in such well-known alloys as " Delta " metal, " Durana " metal, " Tobin " bronze, " Aich " metal, and " Sterro-metal." Of these, " Delta " metal is the one that is chiefly used in England, " Durana " metal being of German origin. The others are not used to any great extent.

Some tests made by Smalley * show that the addition of 1 per cent. of iron to a 70/30 brass raises the yield point from 6·5 to 10·7 tons per square inch and the ultimate tensile strength from 16·7 to 24·5 tons per square inch. The ductility of the brass is practically unaffected. These are results obtained in the cast condition. After cold rolling and annealing, the yield point is raised (due to the iron) from 8 to 11 tons per square inch, and the ultimate tensile strength from 21·5 to 26·5 tons per square inch. The ductility remains about the same.

The addition of 1 per cent. of iron to a 59/41 brass does not improve the alloy to the same extent as with the 70/30 brass mentioned above. The greatest improvement is in the yield point of the forged material, and this is raised from 9 to 13·9 tons per square inch, the tensile strength being increased by 2·8 tons per square inch from 26·0 tons per square inch. The improvement in the cast metal is only small.

Aluminium.—Brass containing small quantities of aluminium is put on the market, although there does not appear to be any great demand for it. Other alloys, such as manganese bronze and " Delta " metal, are more in favour. The maximum amount of aluminium is 4 per cent., alloys containing more being difficult to work. It appears to have the same effect as zinc, but in a greater degree, and the structure of the alloy is very similar to an ordinary brass.

The strength of the alloy increases with the proportion of aluminium, and with 3 per cent. is about 20 tons per square inch, with 50 per cent. elongation. The proportions of copper and zinc are about 70 and 27 per cent. respectively. With less copper and more zinc, say 59 Cu, 38 Zn, the tensile strength is about 28 tons per square inch, with 12 per cent. elongation.

These alloys cast well, and can be rolled and forged while hot. They can take the place of manganese bronze for pumps, small gears, marine work, etc.

According to Smalley's investigations,† the ductility of a 70/30 brass in the cast state falls off considerably as the percentage of aluminium is increased. The 59/41 brasses are affected in the same manner but not to the same extent.

---

* " The Development and Manufacture of High Tenacity Brass and Bronze," by O. Smalley, M.Inst.M., read June, 1922, Inst. Brit. Foundrymen.

† *Ibid.*

The table below contains some of the results obtained by Smalley. The increase in the yield point and in the strength of both kinds of brass is very considerable.

TESTS TAKEN ON CHILL CASTINGS.

Composition.			Yield point, tons per sq. in.	Ultimate, tons per sq. in.	Elongation, per cent. (2 ins.).	Reduction of area, per cent.
Copper.	Zinc.	Aluminium.				
69·79	26·67	3·54	13·60	29·30	26·00	27·60
69·13	26·32	4·55	17·6	31·9	8·00	11·7
69·42	24·68	5·90	28·10	38·00	3·00	1·50
59·48	39·52	1·00	14·80	32·00	30·00	33·50
58·35	40·11	1·54	16·4	35·20	17·00	18·50
58·26	38·56	2·18	16·00	36·40	16·00	21·50
59·85	37·13	3·02	22·30	42·00	18·50	21·50

The 70/30 alloys when forged give even better results, but the 59/41 alloys are not improved except in regard to ductility. These results are given in the following table. The 70/30 brasses are on the whole the best alloys for forging, rolling, or extruding, and are not so liable to develop a coarse crystalline structure and thus become brittle.

TESTS TAKEN IN FORGED CONDITION.

Composition.			Yield point, tons per sq. in.	Ultimate, tons per sq. in.	Elongation, per cent. (2 ins.).	Reduction of area, per cent.
Copper.	Zinc.	Aluminium.				
69·79	26·67	3·54	23·40	37·10	34·00	41·90
69·13	26·32	4·55	20·30	38·60	17·00	20·00
69·42	24·68	5·90	32·50	42·30	6·00	8·40
59·48	39·52	1·00	11·10	31·30	41·00	44·60
58·26	38·56	2·18	11·70	37·40	27·00	33·50
59·85	37·13	3·02	19·00	40·30	24·50	30·60

Tin.—Alloys containing copper, zinc, and tin have been already dealt with under "Gunmetal." This metal added to brass increases the resistance to corrosion, but if more than 1 per cent. is added the alloy tends to become brittle.

Lead.—This metal is added to improve the machining qualities of brass, and its effects are explained on p. 405.

Manganese.—As explained on p. 154, this metal forms part of an alloy which is really brass, but is generally referred to as a bronze. In such cases iron and aluminium are usually associated with it, forming the commercial alloy manganese bronze.

Delta Metal.—Several alloys are now sold under this name, but the original alloy patented by Dick was simply a brass containing about 55 per cent. copper. 41 per cent. zinc, to which was added about 2 or 3 per cent. of iron. The commercial product, however, contains other metals in varying quantity, such as aluminium, tin, and manganese, and in consequence the analyses obtained from time to time do not always agree.

These various alloys have been developed to suit varying requirements, and must therefore be recognised as such.

Of the full range of alloys sold by the Delta Metal Company, Ltd., that known as No. IV is the one in greatest demand. This alloy can be cast in sand or chill moulds, and may be forged. Sand castings have a tensile strength of 20 to 24 tons per square inch, and an elongation figure of 30 to 40 per cent. Chill castings are slightly stronger by about 2 or 3 tons per square inch, the elongation value being a little less.

At a temperature of about 530° C., this alloy is quite malleable, and can be forged, stamped, or pressed into any required shape. A large quantity is put on the market as extruded bars in various sections. In this state, and also when forged, the metal is stronger than the cast, and is less liable to suffer from defects, such as blowholes. The tensile strength will vary from 32 to 36 tons per square inch with about 20 to 28 per cent. elongation.

The effect of temperature on its strength is less than in the case of brass, gunmetal, and phosphor bronze, and this of course is valuable for steam fittings and other parts exposed to high temperatures. The falling off in strength at a temperature of 260° C. of a few of the common alloys is given as follows :—

Delta metal IV	17·5 per cent.
Ordinary brass	38·0 ,,
Phosphor bronze	31·0 ,,
Gunmetal	33·0 ,,

Professor W. C. Unwin * gives a series of test results showing the variation in strength of both cast and rolled delta metal with increase in temperature. These results are given here :—

Cast Delta Metal.

Temperature.		Ultimate, tons per sq. in.	Elongation, in 2 in., per cent.	Reduction of area, per cent.
Degs. Fahr.	Degs. Cent.			
Atmos.	Atmos.	20·15	4·5	6·3
,,	,,	18·25	4·0	7·0
310	154	23·36	7·0	11·8
410	210	22·48	9·0	13·0
506	263	19·68	16·0	22·3
590	310	16·00	4·0	9·4
635	334	12·70	45·0	45·7

Rolled Delta Metal.

Atmos.	Atmos.	31·16	20·0	55·0
260	126	28·30	22·0	47·0
400	204	26·58	25·0	53·0
500	260	23·83	27·9	59·0
570	299	19·32	38·5	60·0
650	343	16·04	33·0	48·0

---

* "Strength of Alloys at Different Temperatures," Unwin, *Report of the British Association*, 1899.

A few of the principal special brasses are given in the following table :—

SPECIAL BRASSES

No. of Alloy.	Copper, per cent.	Zinc, per cent.	Tin, per cent.	Lead, per cent.	Manganese, per cent.	Aluminium, per cent.	Iron, per cent.	Nickel, per cent.	Tensile, tons per sq. in.		Elongation, per cent.	Reduction of area, per cent.	Brinell hardness number.	Name of Alloy
									Yield.	Ultimate.				
1	55	41	—	—	1	—	3	—	—	19·6	30–40	—	—	Delta metal as cast. } See text.
2	55	42	—	—	0–1·0	0–1·0	0·5–1·0	—	—	—	—	—	—	Delta metal. } See text.
3	64–78	29·5	2·2 with antimony	—	—	1·70	1·5	—	30–32	35–37	14	—	—	Durana metal.
4	60	38	—	—	—	—	2	—	—	22–31	11–39	—	—	Sterrometal.
5	59	38·4	2·16	0·31	—	—	0·11	—	—	35	15	—	—	Tobin bronze.
6	70	27	—	—	—	3	—	—	—	20	50	—	—	Aluminium brass.
7	59	38	—	—	—	3	—	—	—	28	12	—	—	Aluminium brass.

Cupro-Nickel Alloys

There are many alloys containing copper and nickel with and without other metals, but very few are used in general engineering work. Alloys of copper and nickel only are used for pumps, valves, and other plant, where corrosion is an important factor, while coins and bullet cases claim a large proportion of the output. Other alloys, such as nickel silver or German silver, find a use in the manufacture of spoons and forks, and for reflectors.

The most important alloy is that containing 85 per cent. copper and 15 per cent. nickel, used for bullet cases. This, in the annealed state, has a tensile strength of 18 to 20 tons per square inch, with an elongation value of 28 to 30 per cent. When drawn or rolled hard its strength is about 29 to 31 tons per square inch, with an elongation value of about 5 per cent.

Another alloy is that known as Monel metal, containing approximately 30 per cent. copper and 66 per cent. nickel, with small proportions of manganese, iron, and silicon. This alloy is prepared from ore which contains practically the same proportions of the two main metals ; the ore is found in Sudbury, Canada, but the alloy is named after its inventor, Ambrose Monel.

Two alloys are put on the market : one suitable for castings, containing from 1 to 1·5 per cent. silicon, and the other for rolling or forging, containing about 0·1 per cent. silicon. The casting is a difficult operation, and it is the rolled metal that has found most use.

The strength in the normal rolled condition is about 38 or 41 tons per square inch, with 38 to 45 per cent. elongation, and when annealed is about 33 to 35 tons per square inch, with 40 to 50 per cent. elongation. It is extremely tough and in the forged or hot-rolled condition will not break on the impact testing machine (Izod).

The chief characteristic of Monel metal is its strength at high temperatures, and in this respect it is superior to almost all the other copper alloys. The following figures are given by John Arnott.* Compared with mild steel at a

---

* "Note on Monel Metal," by John Arnott, *Engineering*, October 25, 1918.

temperature of 600° C., Monel metal has a tensile strength of 20 tons per square inch as against 8 or 9 tons per square inch for steel.

Temperature.	Monel Metal.	Naval Brass.	Manganese Brass.
	Tons per sq. in.	Tons per sq. in.	Tons per sq. in.
Normal	41·4	26·0	29·0
295° C.	39·1	18·3	14·5
340° C.	38·2	13·5	9·5
410° C.	33·8	5·4	4·4
500° C.	28·7	Nil	Nil

The alloy has found considerable use for valves, pump rods, pump liners, springs, turbine blading, etc., in which it stands up much better than manganese brass. Its corrosion-resisting properties make it useful for marine purposes and for fittings on motor cars, etc.

Other alloys containing copper and nickel are given in the following table :—

Name of Alloy.	Copper, per cent.	Nickel, per cent.	Zinc, per cent.	Iron, per cent.	Manganese, per cent.
Bullet case (foreign)	85	15	—	trace	trace
Bullet case (British)	80	20	—	—	—
Monel metal	28	66-67	—	3	2
Constantan	60	40	—	—	—
Manganin	84	4	—	—	12
Nickel silver	61	19	19	—	—
,, ,, ...	57	24	19	—	—

Manganin and constantan are used in electrical apparatus because of their high electrical resistance and low resistance temperature coefficient. Both alloys are made in the form of sheet, strip, and wire.

Nickel silver (German silver) is an alloy of copper, zinc, and nickel, and is made up in various proportions for the manufacture of electrical resistances, lamp reflectors, spoons, forks, and electro-plate ware. The strength of these alloys is generally greater than that of ordinary brasses. The nickel silver alloy first mentioned in the above table has a yield point of about 8 tons per square inch, and an ultimate strength of approximately 18 tons per square inch, whilst the elongation is about 30 per cent. Nickel tends to increase the strength, and also the resistance to corrosion, of the alloys. A good alloy for casting is one containing 40 per cent. copper, 30 per cent. zinc, and 30 per cent. nickel. Alloys containing more copper and fairly free from impurities can be rolled or drawn into sheets and wire.

Miscellaneous Alloys

Nickel Chromium.—These two metals form alloys that resist corrosion to a remarkable extent. Alloys containing nickel and chromium are now used for case-hardening pots, annealing pots, and pyrometer protecting tubes. These do not oxidise at temperatures up to 1,100° C., and appear to be indestructible. Other alloys are made and drawn into wire and strip for electrical heating apparatus, etc. One such alloy is known under the trade name of " Nichrome."

Fusible Alloys.—Certain low-temperature melting-point alloys are used for boiler safety plugs, fire sprinkler valves, etc. Such alloys contain lead, tin, bismuth or cadmium, and the melting-point depends on the proportions of these metals. A few of the more important are given in the following table :—

Fusible Metals

Melting point.	Composition.				Remarks.
	Bismuth.	Lead.	Tin.	Cadmium.	
Degs. C.	Per cent.	Per cent.	Per cent.	Per cent.	
65·5	50·0	25·0	12·5	12·5	Specially low melting-point.
60·0–68·0	50·0	26·7	13·3	10·0	Lipowitz's alloy.
71·0	38·4	30·8	15·4	15·4	Woods' alloy.
75·0	27·6	27·6	10·3	34·5	" Fusible metal."
80·0	35·3	35·1	20·0	9·5	,, ,,
93·0	50·0	25·0	25·0	—	Darcet's alloy.*
95·0	50·0	31·25	18·75	—	Newton's alloy.*
95·0	50·0	—	25·0	25·0	"Fusible metal."
100·0	50·0	28·0	22·0	—	Rose's alloy.*
108·0	42·1	42·1	15·8	—	" Fusible metal."
117·0	36·5	36·5	27·0	—	,, ,,
124·5	57·4	42·6	—	—	,, ,, *
137·0	56·7	—	43·3	—	,, ,, *
151·0	23·5	47·0	29·5	—	,, ,,
177·0	—	—	48·0	52·0	,, ,, *
180·0	—	36·5	63·5	—	,, ,, *

Solders.—The solders used in general engineering work may be divided into two distinct classes : " hard " and " soft " The hard solders are used for the operation known as " brazing," and, as would be expected from their name, they are harder and stronger than the soft solders.

The more common hard solders are " spelter " solders, consisting of zinc-rich brasses, and of these the one that is generally used contains about 50 per cent. of zinc. This is suitable for brazing brass articles. Spelter solder containing about 35 to 40 per cent. zinc is used for copper, steel, and iron articles. Occasionally an alloy containing less zinc (30 per cent.) is used, but owing to the high melting point of this alloy the brazing operation becomes a difficult one.

Other alloys are used, some containing silver and others nickel. A few of these are given in the following table :—

Composition (approx.).				Applications.
Copper.	Zinc.	Silver.	Nickel.	
Per cent.	Per cent.	Per cent.	Per cent.	
90	—	10	—	Silver solder for thin steel articles.
55	—	45	—	Electrical instruments, etc.
50	20	30	—	Copper and brass work.
38	50	—	12	Hard " white " solder for iron.

---

* These alloys expand considerably on cooling, and are useful for taking impressions of dies, coins, and other objects from which accurate " casts " are required.

Borax is used as a flux when working with the hard solders described above. Powdered glass may be used for the very hard solders.

The so-called "soft" solders generally consist of lead and tin. These vary considerably in composition, depending on the purpose for which they are required. Thus tinmen's soft solder consists of 35 to 45 per cent. of lead, the remainder being tin. The solder used by plumbers contains from 65 to 75 per cent. of lead.

The "fine" solder used by tinmen contains 35 per cent. of lead and melts at 180° C. When more lead is present the alloy passes through a pasty condition before solidifying, and it is because of this that plumbers use a lead-rich alloy for "wiped" joints.

The following list gives brief particulars of the lead-tin solders :—

Plumbers' "coarse" solder	75 per cent. lead; pasty stage commences at 270° C. (approx.).
Plumbers' "fine" solder	65 per cent. lead; pasty stage commences at 245° C. (approx.).
Tinmen's "coarse" solder	45 per cent. lead; pasty stage commences at 205° C. (approx.).
Tinmen's "fine" solder	35 per cent. lead; does not pass through a pasty stage.

All the above soft solders solidify finally at 180° C.

Various fluxes are used with the lead-tin solders, the most common being zinc chloride, resin, tallow, and ammonium chloride (sal-ammoniac). Zinc chloride solution ("killed spirits") is corrosive and should not be used for electrical connections (cables and fuses, etc.); resin is much safer. Tallow is used on lead work, wiped joints, etc. Ammonium chloride is useful for copper and iron.

Extruded Metals and Alloys

The extrusion process referred to in the earlier portion of this chapter has been applied to a number of metals and alloys with considerable success. The improvement in the mechanical qualities of non-ferrous metals and alloys is somewhat similar to that obtained with forging processes. This is due to compressive action on the material and the absence of blowholes, etc. The various important metals and alloys that are extruded are described below.

Aluminium.—This metal when extruded possesses a tensile strength of about 16 to 17 tons per square inch and an elongation value of 4 or 5 per cent.

Copper.—Extruded sections of copper have a tensile strength of approximately 15 tons per square inch and an elongation value of about 40 per cent.

Zinc.—Zinc is extruded at comparatively low temperatures (35° to 80° C.), and in the extruded form possesses a tensile strength of 12 or 13 tons per square inch and 20 to 25 per cent. elongation.

Brass.—Alloys containing from 57 to 63 per cent. of copper with zinc as the balance are used in the extruding process. In many cases, however, other metals are added, some to improve machinability and others the tensile strength.

The plain alloy, containing 60 per cent. copper and 40 per cent. zinc, when extruded possesses the following properties: Yield point, 9 tons per square inch; ultimate strength, 25 tons per square inch; elongation, 40 per cent.; reduction

Fusible /
for boiler saf
tin, bismuth
these meta

50 per cent. Lead is added to improve the machining qualities, and an ntaining 59·5 per cent. copper, 39 per cent. zinc, and 1·5 per cent. lead ve results approximating to : Yield point, 8 tons per square inch ; ultimate ngth, 20 tons per square inch ; elongation, 20 per cent. The cutting speed this extruded alloy will be about 280 feet per minute.

Mr The tensile strength of the 60/40 alloy is increased by adding tin and manganese while still retaining some lead to maintain a fair machining speed. Thus an alloy of the following approximate composition will give the results specified :—

Composition.		Mechanical Properties.	
Copper	58·0 per cent.	Yield point ..	20 tons per square inch.
Zinc	39·5 „	Ultimate ..	30 „ „
Lead	1·3 „	Elongation ..	20 per cent.
Tin	0·5 „		
Manganese	0·5 „		
Iron	0·2 „		

Naval brass is extruded with success and gives results in accordance with the Government specifications.

The Delta Metal Co., Ltd., who probably are the largest manufacturers of extruded metals and alloys, make up various rods and sections in the well-known "Delta" bronzes, manganese and aluminium bronzes, and all the usual brasses mentioned above. The following results are typical of the "Delta" bronzes :—

	Delta Bronze No. I.	Delta Bronze No. IV.
Ultimate strength (tons per square inch)	49·82	37·1
Elongation (per cent., 2 inches)	26·0	27·0
Reduction of area (per cent.)	24·9	20·0

CHAPTER XVI

BEARING METALS

CONSIDERING the importance of bearing metals in engineering work it is surprising how little really systematic work has been done to clear up the many doubtful points that still trouble the designer. The ideal conditions, as Osborne Reynolds shows, where the friction is only that between a solid and the lubricant, are scarcely ever attained in practice. The journal or other moving portion must on occasions come into actual contact with the bearing, and what then happens must depend on the nature of the materials in contact.

The ordinary physical tests fail to give information that is sufficient to judge the quality of a material for bearing purposes. Actual tests under running conditions are, of course, the only reliable ones, but they are of necessity prolonged and at the best are not of much assistance in solving problems on machinery which may happen to be of a different class. For example, comparative tests on railway axle bearings are not of much assistance to the designer of automobile engines. Laboratory tests for wear are not strictly comparable, since the results must depend on such variable factors as bedding in, kind and quantity of lubricant, and also temperature.*

There can be no doubt that these difficulties, in obtaining comparative information which will be of general service, are responsible for the meagre supply of literature. This, combined with the "trade jealousy" of the anti-friction metal manufacturer, forces the commercial engineer to remain conservative to those few materials that have proved satisfactory under the conditions he is interested in.

Requirements of Bearing Metals.—In general the requirements of a bearing metal can be summed up under the following headings :—

(1) Low coefficient of friction.
(2) Sufficient compressive strength (and hardness).
(3) Durability—*i.e.* small amount of wear (in bearing).
(4) Low temperature of running.
(5) Minimum wear of journal.
(6) Good behaviour under irritating circumstances (*i.e.* dust or grit).

---

* There are other variables, such as pressure, surface velocity, intermittency of loading, position of maximum pressure, inertia effects which vary with alteration in speed of reciprocating parts, and heat conduction due to the housing. Temperature and lubricant differences may be investigated in the laboratory, but the above and also the cooling effect of the air, etc., when running cannot be assessed.

(7) Ease of fixing and replacing.
(8) Resistance to corrosion by the lubricant.
(9) Low cost.

This summary of the properties required of a bearing metal is due to Hague.*

Before dealing with these requirements in detail, however, a few general considerations are necessary, both as to the lubricant used and the nature of a bearing surface. With fatty oils (vegetable or animal) the degree of " oiliness " or " greasiness " is much more marked than with mineral oils, and when bearings are lubricated with such oils there is very little risk of injury unless the load is very excessive. But with mineral oils as lubricants more care must be bestowed on the materials used for the journal and bearing. In many instances lubrication is not possible or is not efficient, as for example, in some textile machines, knitting machines, and clock mechanism, and then it becomes a question of hardness of the bearing surfaces and their suitability for working in contact with each other.

It is well known that the harder the surfaces are, the less will be the friction and the amount of heat developed, but to obtain satisfactory results it is essential that the rubbing parts should be well fitted. Even then, the two surfaces can only touch at a few points, and it is these that must carry the load. Thus with hardened steel rubbing on hard steel it will be found that the speed must be kept low, otherwise excessive heating will take place From this it is evident that another property must be made use of (in addition to hardness), and that is the ability of the material to deform sufficiently so as to offer a large number of points, to carry the load, and thus reduce the intensity of loading per point. This second property is referred to as plasticity, and, as will be seen later, it is one of the most important properties of a bearing metal.

Therefore two essentials are known : the first of which is hardness, and the second plasticity. These, unfortunately, are not usually associated in the same metal, and it is for this reason that certain metals are alloyed in order to produce the desired structure. This structure should consist of a large number of small hard points or areas embedded in a tough yet plastic body. Then the body or matrix will mould itself to the journal, and correct for any slight lack of alignment, whilst the load will actually be carried by a large number of hard particles supported in the matrix. The pressure on each hard particle (or bearing point) is reduced, and consequently there is less heating.

It is the formation of this particular structure that the metallurgist works for when producing anti-friction alloys, and, as will be seen later, this is the chief characteristic of the most successful bearing metals or alloys.

Steel

The most common mechanism is a shaft rotating in a bearing, and as a rule this shaft is made of steel. For this reason it is advisable to know what the wearing properties of steel are before proceeding to deal with the different kinds of bearing metals in which such shafts are run.

---

* *Engineering,* June, 1910, pp. 826–29.

It is the usual practice to make the bearing of a softer material than the shaft or other moving part in order to concentrate the wear on the bearing rather than on the shaft, since it is usually easier to replace the bearing than the shaft. Hence the kind of bearing metal employed will depend to some extent on the hardness of the steel shaft.

The hardness of the shaft depends on the class of steel, its carbon content, and on the treatment it has received. The different conditions are dealt with as follows.

Mild Steel.—Low carbon steels (up to 0·25 per cent. carbon) do not run so well as the medium and high carbon steels. When run in gunmetal or bronze bearings the steel, owing to its softness, "picks up" particles of the copper constituent and this becomes embedded in the steel. This, of course, aggravates the trouble and each revolution attracts more particles. If the steel has been toughened by water quenching this fault is minimised to a great extent.

Mild steel can be run with success in soft grey iron, white metal, and to some extent in gunmetal bearings. It should not be run in bronze unless this contains a considerable amount of lead, and certainly not in phosphor bronze (with phosphorus over 0·15 per cent.) even when the proportion of lead is high.

Medium Carbon Steel.—30-ton (0·25 to 0·35 per cent. carbon) and 40-ton (0·35 to 0·45 per cent. carbon) steels are usually chosen for running parts. According to Robin a 0·4 per cent. carbon steel offers the greatest resistance of all the carbon steels to abrasive action.

When heat treated these steels can be run with success in soft grey iron, white metal, gunmetal, lead bronze, and low phosphorus (0·1 per cent.) phosphor bronze bearings.

Hardened Carbon Steel.—High carbon steels are not used to any extent except for small parts like catch plates, trip gear, etc. When hardened and tempered they will give good service against similarly treated steel at slow speeds and when lubricated well with a viscous oil or grease.

In general practice, however, hardened steel parts are generally case-hardened.

The great hardness of such parts makes it possible to employ the hard bronzes as bearing material. Phosphor bronze containing up to 1·5 per cent. phosphorus can be used with remarkable success; in fact this is the only possible application of this bronze. Other good materials are grey cast-iron, and the bronzes and white metals. Some of the aluminium alloys also run well.

The structure desirable in bearing metals can also be obtained in case-hardened steel (see p. 223) by retaining the free cementite in the spheroidal form. With alloy case-hardening steels this is especially so because the hardening produces a partly austenitic structure which, while not strictly hard, is very tough and plastic, and which supports the hard granules of cementite. This particular structure is not usually obtained, but there is much in its favour, and no doubt in the future the tendency will be to develop the case-hardening process in this direction.

Alloy Steels.—For the same carbon content alloy steels wear better than carbon, and the harder bronzes can be used with them without risk of scoring. At the same time the high phosphorus bronzes are likely to lead to trouble at high speeds, and where the lubrication is not quite efficient.

The presence of chromium adds greatly to the wearing properties, and in the case of case-hardening steels, chromium should be included in the composition together with nickel, when very severe conditions prevail.

Cast-iron

Soft grey cast-iron makes an excellent bearing surface. This, no doubt, is mainly due to the presence of particles of graphite in the iron and to its porosity, which holds the lubricant and allows it to ooze out to the surface. It gives good service in contact with any of the steels, and is even satisfactory with wrought iron. It also runs well against itself, as, for example, cast-iron piston rings in petrol engines are regularly used to work against cast-iron cylinders. The surface after running some time develops a beautiful, smooth, glossy appearance, and even when heated does not seize readily. It will continue working under bad conditions, the metal simply grinding to a powder, leaving the parts free to move over each other so long as any solid material remains.

Chilled cast-iron is often used in place of steel, whether case-hardened or not, and gives better service. Castings are made with suitable chills placed at those points which are to form the bearing surfaces, and these surfaces are carefully ground. The chief difficulty lies in the distortion of the castings, and this must be allowed for in the patterns. Of course, in many instances the bearing surfaces can be cast separately and then attached to the main portion of the structure. The effect of chilling is to prevent the carbon separating out as graphite, thus producing iron rich in combined (hardening) carbon and which, in consequence, is very hard. Such iron on fracture has the characteristic white, bright glistening appearance of white cast-iron.

Bronze

Bronzes are used mainly on account of their toughness and ability to withstand heavy blows and stresses without fracture. Copper alone is unsuitable because of the difficulties in casting and machining, but when tin is added a strong machinable alloy is produced which forms a good bearing metal. The addition of lead, however, due to Dick, makes this alloy much more satisfactory, and the majority of the bearings, however used, now contain fairly large proportions of this metal. Dick also added phosphorus, which, acting as a powerful deoxidiser, purified the alloy of oxides and dross, etc., making much sounder castings. Lead weakens the alloy, but greatly increases its plasticity and reduces the wear.

Archbutt and Deeley * quote some results obtained by Dr. Dudley,† who

---

* "Lubrication and Lubricants," 1912, pp. 425.

† *Journal Franklin Inst.*, 1892, pp. 81–93 and 161–72.

very carefully investigated the effect of adding lead and phosphorus to the standard copper-tin alloy. These results are given below :—

RELATIVE WEAR OF BRONZE BEARINGS

Alloy Tested.	Composition.					Relative wear.
	Cu	Sn	Pb	P	As	
Standard lead (phosphor) bronze S ..	79·7	10·0	9·5	0·80	—	1·0
Ordinary bronze	87·5	12·5	—	—	—	1·49
Arsenic bronze A	89·2	10·0	—	—	0·80	1·42
,, ,, B	82·2	10·0	7·0	—	0·80	1·15
,, ,, C..	79·7	10·0	9·5	—	0·80	1·01
Bronze "K"	77·0	10·5	12·5	—	—	0·92
,, "B"	77·0	8·0	15·0	—	—	0·86

These tests were carried out by taking a certain number of bearings made of ordinary bronze, and an equal number made of the experimental alloy and placing these on locomotive tender or car axles in pairs, an ordinary bronze and an experimental bearing being placed on opposite ends of the same axle. The relative rates of wear were ascertained by weighing the bearing at intervals. The ordinary bronze not only wore half as fast again as the standard lead bronze, but a much larger percentage heated of the bearings made of it.

Arsenic gave the same result as phosphorus. Like phosphorus it merely promotes sound castings, while both have little, if any, influence upon the rate of wear.

These results of Dudley's were confirmed later by Clamer,* who used a specially designed friction-testing machine and obtained the results given below.

RELATIVE FRICTION AND WEAR OF LEAD BRONZES (CLAMER).

	Copper.	Tin.	Lead.	Friction factor.	Temperature above room.	Wear in Grams.
				lbs.	Degs. F.	
1	85·76	14·90	—	13	50	0·2800
2	90·67	9·45	—	13	51	0·1768
3	95·01	4·95	—	16	52	0·0776
4	90·82	4·62	4·82	14	53	0·0542
5	85·12	4·64	10·62	18½	56	0·0380
6	81·27	5·17	14·14	18½	58	0·0327
7	75·0	5·0	20·0	18½	58	0·0277
8	68·71	5·24	26·67	18	58	0·0204
9	64·34	4·70	31·22	18	64	0·0130

It was found that the rate of wear diminished, though the friction and temperature increased, as the percentage of tin in the bronze was decreased and the percentage of lead increased.

The practice of using so much lead is not adopted generally in England. Very few of the bronzes used contain more than 10 per cent. lead, it being more usual to employ white metals instead of high lead bronzes. Segregation is one

---

* *Journal Franklin Inst.*, 1903, pp. 49–77.

of the most common troubles, and with high percentages of lead it is found necessary to limit the amount of tin to about 6 per cent. Even then great care is required to secure sound castings. Nickel is added (about 1 per cent.) to overcome this difficulty, but its action is not thoroughly understood.

Lead does not alloy with the copper and tin, but separates out as small globules which, in a good casting, should be uniformly distributed. These soft areas make the alloy plastic. The copper and tin, however, form the compound $SnCu_3$ (about 9 per cent. tin, 91 per cent. copper), which is hard and resists the wear. The matrix or mass of the alloy is a solid solution of tin in copper, which is also hard ; thus these bronzes do not fulfil exactly the conditions specified in the early part of this chapter, *i.e.* the metal should have hard particles embedded in a softer and tougher matrix. For this reason bronzes are liable to cut and score such soft materials as mild steel and wrought iron.

Charpy, who has carried out an immense amount of work on bearing metals, finds that the plasticity or compressive strength increases as the percentage of tin is increased and decreases as the percentage of lead is increased. Law * quotes some of his results as follows :—

Composition.						Load corresponding to a compression of 0·2 mm.	Compression produced by a load of 5000 kg.
Cu	Sn	Pb	Sb	P	Zn	Kilograms.	Millimetres.
89·45	9·05	0·68	0·25	0·107	0·44	1925	3·7
88·55	10·32	0·25	0·13	0·223	0·40	2100	3·1
86·79	11·20	0·44	0·31	0·11	1·17	2350	3·2
85·70	12·15	0·51	0·12	0·385	0·84	3000	2·5
84·83	13·41	0·38	0·13	0·46	0·59	3100	2·1
84·30	14·60	0·40	0·10	0·215	0·56	3600	1·9
80·65	19·18	0·04	0·21	0·03	—	5000	1·4
83·35	6·60	8·44	0·16	—	0·10	1500	4·8
80·55	2·25	10·86	2·67	0·21	0·60	1500	4·8
84·70	10·05	4·0	0·14	0·11	0·46	2000	3·2
82·30	8·98	7·27	0·14	0·39	0·10	2700	2·4

These compression tests were carried out on test pieces 15 mm. in height and 10 square mm. sectional area.

Zinc is added with the object of producing sound castings, but it should not exceed 2 per cent. owing to the reduced tensile strength and ductility that results. Large amounts tend to produce brittleness and the breaking away of particles which score both the steel shaft and bearing.

Phosphorus in small amounts is beneficial since it produces a sound casting, but owing to the formation of a very hard compound Cu_3P which separates out and forms a eutectic with the other compound $SnCu_3$ only small amounts are permissible where the running parts are made of medium carbon or softer steels. In fact, high phosphoric bronzes are only suitable for hardened steel (case-hardened or otherwise), and if they contain no lead they should not be used for any other material.

---

* "Alloys," by E. F. Law, 1917, pp. 250–251.

The composition of some of the more usual bearing bronzes is given in the following table :—

SOME BEARING BRONZES

General use.	Approximate Analysis.								Remarks.
	Copper.	Tin.	Lead.	Zinc.	Aluminium.	Iron.	Nickel.	Phosphorus.	
General bearings ..	90	10	—	—	—	—	—	Trace	
Hard bearing metal	90	10	—	—	—	—	—	0·5	
Extra hard bearing metal	87	11	—	—	—	—	—	1·0	
Bridge bearings for soft steel * ..	85	15	—	—	—	—	—	1·0	For pressures below 1500 lbs. per sq. in.
Bridge bearings for hard steel * ..	80	20	—	—	—	—	—	1·0	For pressures above 1500 lbs. per sq. in.
For medium carbon steel and medium hard steel ..	88	8	4	—	—	—	—	0·2	
Slide valves ..	84	9·5	6·3	—	—	—	—	0·2	
High speeds, heavy pressures, shock, etc.	80	10	10	—	—	—	—	Trace	
High speeds, medium pressures	78	7	15	—	—	—	—	—	
Railway axles, (wagons) ..	64	5	30	—	—	—	1	—	For pressures less than 600 lbs. per sq. in.
Common bearing ..	83	14	1	2	—	—	—	Trace	

Brass.—The substitution of zinc for tin to form brass is resorted to when expense is all important, but bearings made of this material are not so good as those made from bronze. The tensile strength and ductility is not high, and therefore their use is limited to light work only.

White Anti-friction Alloys

This series of alloys, which are very complex, owe their popularity to the ease with which the bearings can be made up, fitted and scraped down to a smooth and polished surface, together with their low friction even under inefficient lubrication.

As a rule these alloys are exceptionally plastic and, in consequence, will mould themselves (under pressure) to the journal, thus increasing the area of contact and distributing the load more equally

They have also an advantage in that the metal removed by wear is easily and quickly replaced, and this operation is more economical than the replacing of other forms of bearing.

Further, as Archbutt and Deeley point out, there is not the same necessity

---

* Metal Industry.

for fatty oils having a high degree of "oiliness;" mineral oils may be used with good results. In fact, Dewrance states that very little lead or zinc should be contained in white metal alloys lubricated with oils containing fatty acids, owing to the formation of soaps with these metals and the consequent corrosion. As lead is a common constituent in most of the anti-friction alloys and as fatty oils (animal or vegetable) nearly always contain a proportion of fatty acids, it is clear that mineral oils are preferable on this account quite apart from their lower cost. Tin, which is another common constituent, is not attacked so readily.

The principal metals used in these alloys are copper, tin, antimony, lead, and zinc, and the melting points of the resulting alloys are usually low. Should the lubrication fail and the metal heat, the bearing will simply wear away rapidly or may "melt out," but the shaft will remain almost unaffected. With ordinary bronze bearings this is not the case: those portions rich in copper will adhere to the shaft and each revolution will aggravate the trouble. Phosphor bronze, however, does not behave in this manner, but, as already explained, it will tend to score the shaft should this be comparatively soft.

The compositions of the various alloys used may be summarised into the following types. In these, the functions of the different metals can be generalised as follows :—

Copper toughens and increases plasticity.

Antimony }
Tin } harden, and increase compressive strength, reduce plasticity,
Zinc } tending towards brittleness.

Lead softens and increases plasticity, but reduces compressive strength and increases the friction.

Types of Anti-friction Alloys.—Law [*] divides these alloys into two important groups, which are—

(1) Alloys consisting essentially of tin, containing compounds of tin and antimony, and tin and copper

(2) Alloys consisting essentially of lead, or lead and tin, containing a compound of tin and antimony.

Group I Alloys.—The alloys of this group are characterised by their structure, which is shown in micrograph Fig. 196. The tin and antimony form a compound (SnSb) which crystallises in well-defined cubes that are hard and malleable. A second compound is formed between the tin and copper ($SnCu_3$), and this crystallises in the form of needles which often radiate from a centre like stars. These needles are very hard and brittle. These two compounds are embedded in a matrix of tin containing a percentage of both copper and antimony, the amount of which depends on the rapidity of cooling.

The composition of the metal represented by the micrograph is as follows :—

Main Constituents.	
Tin	79·63 per cent.
Antimony ..	14·60 ,,
Copper ..	5·21 ,,

Impurities.	
Lead	0·23 per cent.
Bismuth ..	0·01 ,,
Iron	0·12 ,,

---

[*] E. F. Law, "Alloys," 1917, pp. 242–49.

According to Charpy, the alloy having the greatest compressive strength without being brittle is the following :—

Tin	83·33 per cent.
Antimony	11·11 „
Copper	5·55 „

Charpy also considers that the best alloys should have such a composition to within 3 or 4 per cent. The following analyses show how near some of the standard brands on the market approach Charpy's composition.

Analyses of some Standard Brands of Anti-friction Metals

	1	2	3	4	5
Tin	79·63	88·77	83·50	78·30	85·49
Antimony	14·60	6·26	12·05	11·30	8·40
Copper	5·21	3·76	4·19	9·30	4·62
Lead	0·23	0·23	Trace	0·66	1·02
Iron	0·12	Traces	0·10	—	0·09
Bismuth	0·01	0·005	0·005	—	0·011
Aluminium	Traces	Nil	—	—	Traces
Zinc	Traces	Traces	0·15	0·15	Traces

The rate of cooling affects the size of the tin-antimony cubes, which are smaller with rapid cooling. This is shown by the two micrographs, Figs. 196 and 197, which were taken on the same ingot but in different positions. The large-size cubes were found in the upper portion of the ingot, while the small cubes were found in the lower portion close to a thin fin. The cooling of this fin by the metal ingot mould was more rapid than that of the upper surface. The importance of the size of the cubes is demonstrated by the experiments carried

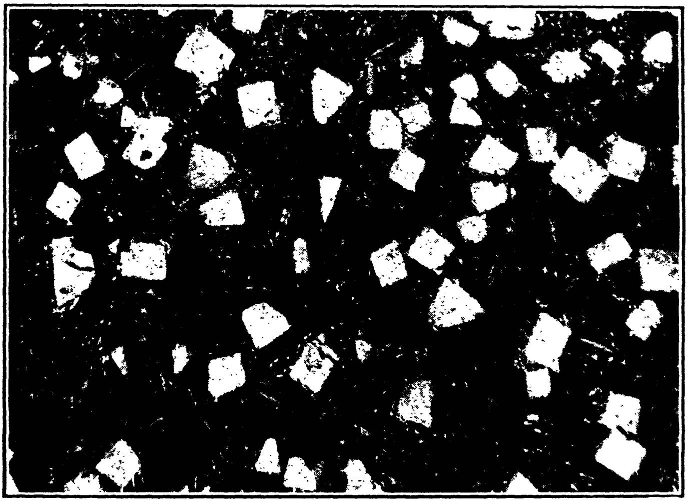


Fig. 196.—Micrograph of a Typical Bearing Metal. Magnification 75 diameters.

out by Behrens and Baucke. In these, three bearings were cast on cores maintained at different temperatures, one red hot, one cooled by running water, and the third with water at 100° C. These bearings were then machined to take a polished steel shaft 15 mm. diameter, which was rotated at 1,600 revolutions per minute. The amount of lead in the blocks constituting the load was varied, and the temperature rise was measured by means of thermometers placed in holes in the block filled with amalgam. One minute runs were made with different loads, and the following temperature rises were observed :—

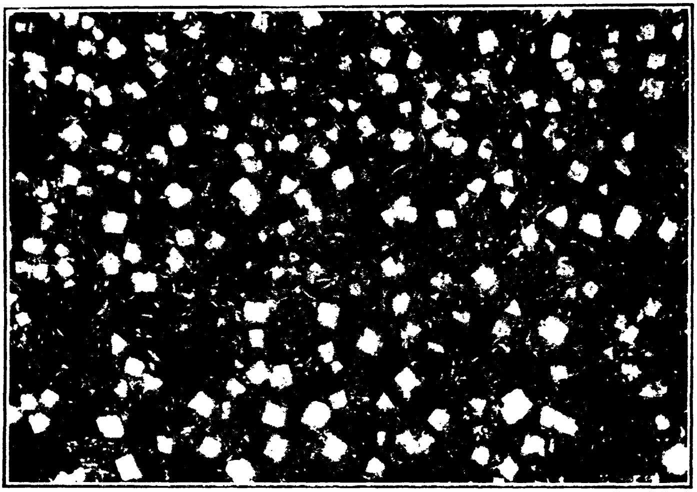


Fig. 197.—Micrograph of similar metal to that shown in Fig. 196, showing smaller cubes due to more rapid cooling. Magnification 75 diameters.

Temperature Rise °C.

State of Core . . . . Size of Cubes	Slowly cooled. Approx. 0·5 mm.	Water cooled. Confused structure.	100° C. Approx. 0·25 mm.
Load 0·3 kg.	0·65	0·50	0·64
„ 0·4 kg.	1·60	0·82	0·64
„ 0·6 kg.	1·72	1·12	0·74
„ 1·2 kgs.	2·62	1·50	0·75
„ 3·0 kgs.	4·64	3·80	1·64

After the final run the bearings were examined and both the slowly cooled (red-hot core) and the chilled ones showed irregular grooves and scratches, while that cooled on a core at 100° C. was found to have the tin-antimony cubes partly rounded and the matrix surrounding them worn away. The appearance of this last bearing gave the impression that the cubes might eventually be loosened and removed from their edges, and that this occurs was more or less proved by the fact that the oil on examination was found to contain small spheroidal bodies which might easily have been cubes. On the other hand, the oil from the other bearings was found to contain small angular fragments, and as a result Behrens and Baucke conclude that the brittle needles of the tin-copper compound are crushed and act as an abrasive on the tin-antimony cubes, tending to round and to loosen them. In a quickly cooled bearing the cubes are not formed, and consequently are not there to be rounded off, while in slowly cooled bearings the cubes are so large that they are broken instead of being rounded. It is only in a properly cast bearing that the cubes are of the right size to retain their hold during the rounding off, and yet are not too large to crack up. Such a bearing will present a large number of hard points which are rounded off during use and form what may be considered as the next best alternative to a ball bearing.

Apart from the effect of the cooling rate on the size of the cubes, the hardness of the matrix is also affected, being harder and therefore less plastic with rapid than with slow cooling.

Hague points out that these alloys have the greatest compressive strength of all the white metals not containing zinc, and they run the coolest.

Group II Alloys.—These alloys contain either lead and antimony or lead, tin, and antimony. The simpler alloy, lead-antimony, is not used to any extent now, but according to Charpy, who determined the compressive strength of these alloys, the best are those containing from 15 to 25 per cent. antimony. The two metals alloy in any proportion, but a eutectic is formed which contains 13 per cent. antimony and 87 per cent. lead, and excess of either metal exists as free metal embedded in the eutectic. Thus with the alloys recommended by Charpy the excess metal is antimony, and this crystallises out as cubes embedded in the eutectic. These cubes of antimony are brittle, and if the amount of this metal exceeds 25 per cent. the alloy is too brittle, while if it is lower than 15 per cent. the excess of lead renders the alloy too soft.

The addition of tin to this alloy improves it considerably, because of the formation of the tin-antimony compound (already referred to under the alloys of Group I). This compound, which crystallises out as cubes, is not so hard or so brittle as the plain antimony cubes, while as a constituent in the eutectic matrix it increases the compressive strength.

To avoid brittleness the antimony should not exceed 15 to 18 per cent., and to obtain in these conditions as high a compressive strength as possible, the alloy should contain between 10 and 20 per cent. of tin.

These lead-tin-antimony alloys are said to wear better than the tin-antimony-copper alloys of Group I. This is probably due to the large amount of lead they contain. On the other hand, the friction is greater and they run hotter, a fact which makes them less suitable for high speeds. Again, their lower compressive strength renders them unsuitable for high pressures. They also appear to be very susceptible to the pouring temperature, far more so than the tin alloys.

Casting White Metal Bearings.—The white metal used for a bearing generally takes the form of a thin layer or lining inside another metal forming the main support for the shaft. It is good practice to employ for this support a metal or some alloy which itself is a good bearing metal, so that in the event of overheating and the melting away of the white metal, the shaft will still be running against a material which has good bearing qualities. For example, the big end bearings of a petrol engine connecting rod should be made of gunmetal (or bronze) lined with white metal; so that, should the white metal melt out through overheating, the engine can still run on the gunmetal bushes without serious risk of damage to the crankshaft.

In many instances, however, where weight and expense are important considerations, the white metal lining is fitted direct to the steel member (such as a connecting rod) and no intermediate bush is used: a large number of aero engine rods are lined in this manner.

Whatever material is used for supporting the white metal lining, it is important to ensure that it is firmly attached, and this depends on the success of the preliminary tinning operation.* This often proves to be a difficult operation, especially with alloy steel. Pure tin should be used, and the article of steel should be thoroughly cleansed with a solution of potash or caustic soda (hot), rinsed in boiling water, and immediately tinned, using a flux such as the following:—

Ammonium chloride (sal ammoniac)	59 per cent.
Zinc chloride (anhydrous)	40 ,,
Sodium fluoride	1 ,,

This flux is very hygroscopic and should be kept in a well-stoppered bottle.

The articles can be tinned with the white metal alloy itself, but this is not so satisfactory as pure tin because of the oxidation of such alloying metals as copper.

While still hot, the superfluous tin should be wiped out with a clean cotton rag or a brush, and the flux deposit removed. A second dip into the tin bath will remove the flux and at the same time produce a virgin surface for the bearing metal to adhere to, and this next operation should be done immediately while the tinning is still fluid or before it commences to tarnish, which it does very rapidly, especially if it is too hot. The white metal can be poured into position after the necessary dummy shaft has been put in position. This latter should be warm but not too hot.

The temperature of the white metal should be watched carefully and should not exceed that required to make it run freely. A piece of dry white paper dipped into the bath should turn brown. The temperature, of course, depends on the alloy used, but ranges between 280° and 320° C. Overheating spoils the metal, and may make it useless. Any bluish ash (oxide of tin) found on the surface indicates this, and the metal should not be used.

Dross or scum increases the friction and produces overheating, while pouring too hot causes the metal to be soft. Too low a temperature produces a coarse structure which may lead to overheating, as also will slow cooling. The metal before pouring should be well stirred from the bottom to prevent separation of the constituents and to secure uniformity, and as a rule it should not be heated more than three or four times.

Die castings of white metal are employed to a considerable extent, and in many cases these have some form of reinforcement such as steel or gunmetal rings or sleeves. The advantage of die casting lies in being able to make provision for oil grooves and other recesses, etc.

Solid bearings of white metal are to be recommended; these are made up just like ordinary brasses. When worn they can be recast, but the success of this depends very much on the alloy; for example, Richards' Plastic white metal will, with care, stand remelting many times without the structure being affected appreciably.

---

* The following notes are an abstract of the instructions issued by the Hoyt Metal Company.

Aluminium Alloys.—The employment of aluminium alloys for bearings is comparatively new, and with the increasing use of these alloys for engine work it is desirable that their values for bearing surfaces should be determined.

Comparative tests with phosphor bronze and manganese bronze show that an alloy of aluminium 87 per cent. and copper 13 per cent. does not wear more or heat more than these two standard materials. The shaft employed was case-hardened nickel steel, and did not suffer to any greater extent with the aluminium alloy than with phosphor bronze or manganese bronze.

Tests for Bearing Metals.—There are no practical standard tests for bearing metals, and it is not possible for the buyer to select an alloy in the same way as with steel and many other materials. An analysis is not a reliable guide, while tensile tests do not give the information required. The microscope is more helpful in so far that it shows the distribution of the constituents, their relative sizes and proportions, all of which have a direct influence on the bearing quality of the material.

The correct form of test, of course, is a friction test, but commercially this is difficult to carry out, and is dependent on many conditions not easy to repeat. There are certain physical tests, however, which are useful if not completely satisfactory, and these are :

(1) Compression tests.
(2) Hardness tests.
(3) Bending tests.

Compression tests are useful inasmuch as they indicate the load that a bearing made of the particular alloy would stand, but, seeing that this factor is determined long in advance by the frictional quality of the material, such figures are not often of much service. There are instances, however, where, the load is semi-stationary as with bridge bearings, and it is in such cases that the compression strength is more important than the frictional quality.

A test of this description should be applied to specimens of one size only, and the load, as far as practicable, should be the same throughout; the strength of the material being determined by the strain.

An interesting series of tests has been carried out by Smith and Humphries * on white metals, and these results show some of the difficulties in testing such materials. Five alloys were tested, the first approximating to the Charpy alloy, which has a high resistance to compression, and others having some of the 83 per cent. of tin replaced by lead, although all the series are of high tin content. The specimens were 1 inch cubes, the load being 6 tons approximately, and the results obtained were :—

Specimen.	Mean Stress, tons per sq. in. at 6 tons load.	Average Strain.
	Per cent.	Per cent.
F.D.S.	5·98	1·45
A.M.A.	5·95	0·66
T.X.S. Al	5·88	3·12
T.X.S.	5·98	4·07
M.B.	5·84	30·63

---

* "Some Tests on White Anti-friction Bearing Metals," by C. A. M. Smith and H. J. Humphries, *Institute Metals*, vol. v, pp. 194–211; 1911.

From the above it is evident that lead reduces the compressive strength of the alloy.

The time element is important, for in the above tests it was found that some specimens had not settled even after 20 or 30 minutes, contraction continuing to take place although in diminishing amounts.

Hardness tests can be carried out with the Brinell machine, having a load of 500 kilos. and a 10 mm. ball. It is doubtful, however, if such tests can be regarded as true hardness tests, but for rapid commercial practice they form a useful comparison between one alloy and another, and also, what is more important, a test for consistency in the batches of bearings made up. The testing of castings, however, with the Brinell machine requires considerable experience and discrimination, because of the localised nature of the test and because of the inherent structure of all castings; the variation between one portion and the adjacent piece often being very great. The time element also must be taken into account, and a period of, say, one minute allowed.

Bending tests give useful information as to the amount of distortion the material can bear. The specimen should be in the form of a bar of rectangular cross-section. Such bars might be supported at points 10 inches apart and loaded at the centre. Smith and Humphries give some tests on bars $\frac{3}{4}$ inch deep by $1\frac{5}{16}$ inch wide, supported on points 10 inches apart. The skin stress at fracture is given and also the permanent dip at fracture. The results are as follows :—

Specimen.	Load, lbs.	Maximum Stress, tons per sq. in.	Maximum Deflection inches.
F.D.S.	950	8·60	0·33
A.M.A.	935	8·48	0·29
T.X.S. Al	875	7·93	0·50
T.X.S.	825	7·13	0·57
M.B.	700	6·34	0·68

These figures are for the same white metal alloys as those referred to under compression tests.

Another series of tests on anti-friction alloys are described in an important paper * by Mundey, Bissett, and Cartland. The results of these tests are given in the following table :—

Test No.	Approximate Composition.				Tensile Strength.		Brinell Hardness No.	Compression.	
	Tin.	Antimony.	Copper.	Lead.	Tons per sq. inch.	Elongation per cent.		Yield point 0·001 inch.	Compressed to half length.
1	93	3·5	3·5	—	5·12	11·6	24·9	3·569	14·732
2	86	10·5	3·5	—	6·65	7·1	33·3	4·372	17·232
3	83	10·5	2·5	4·0	5·60	None	34·5	4·284	17·640
4	80	11·0	3·0	6·0	5·70	None	32·1	4·640	17·500
5	60	10·0	1·5	28·5	5·04	None	27·1	3·696	12·856
6	40	10·0	1·5	48·5	4·58	None	21·8	3·660	11·284
7	20	15·0	1·5	63·5	5·48	None	31·3	4·016	12·212
8	78	11·0	11·0	—	6·36	None	37·0	4·550	17·856
9	5	15·0	—	80·0	4·69	2·8	24·9	3·590	13·356

---

* "White Metals," by A. H. Mundey, C. C. Bissett, B.A., B.Sc., B.Met., and J. Cartland, M.C., M.Sc., *Inst. Metals*, September, 1922.

The tensile test pieces were cast at 350° C., the mould being heated to approximately 100° C. The diameter was 0·564 inch and the distance between gauge points was 2 inches. The Brinell results were all obtained with a 10 mm. ball and a load of 500 kg. The compression tests were made by taking cylinders 0·564 inch diameter and 0·5 inch high. The first observation (yield point) was made when a permanent deformation of 0·001 inch was produced, the ultimate figure when the test piece was compressed to one-half its original height.

The No. 1 alloy has been used to a considerable extent for aero engines. It is probably ideal for big-end bearings. The No. 2 alloy is useful for general work for main bearings. The No. 3 alloy is also useful, the small proportion of lead having no serious detrimental effect. Although the elongation percentage is nil, the alloy is excellent in its resistance to shock. The No. 4 alloy is useful for heavy loads and high speeds: rolling mills, locomotives, turbines, and Diesel engines. The No. 5 alloy is suitable for internal combustion engines of all types, dynamos, locomotives, and steam engines. The No. 6 alloy is suitable for heavy pressures and medium speeds, or for medium pressures and high speeds: railway and tramway bearings. The No. 7 alloy forms an alternative for No. 6 alloy.

The No. 8 alloy is commonly known as "plastic metal." It is used extensively by millwrights and marine engineers for repair jobs. It is hard and durable, and is self-tinning. This alloy behaves in the same manner as plumbers' soft solder, and can be spread or formed in much the same way as a wipe-joint is made.

The No. 9 alloy is similar to those used on some of the continental railways. Bearings made of this alloy are capable of carrying their load and continuing their duty under increased temperatures to a greater extent than some of the tin-base alloys in similar circumstances. If the bearings can be made somewhat longer than usual, thus ensuring the distribution of the load over an extended area, excellent results in running and endurance can be obtained.

It is obvious that the different groups of bearing metals will require different treatments on test; cast-iron would not be compared with a white metal alloy, nor in practice would the question arise as to which material is the more suitable for the particular bearing. On the other hand, a white metal might be substituted for a bronze or gunmetal, and these materials would have to be compared. In these circumstances the requirements of the designer would probably indicate the form of tests that would give the best comparative results. Such demands as loading, speed, bad working conditions (like corrosive fumes), high temperatures, uncertain oiling, or intermittent but excessive loading, would each call for special qualities, some of which would be possessed by bronze or gun-metal but not by white metal, and *vice versâ*.

The following table gives particulars of a few of the many alloys used for bearing purposes. Data as to the physical properties of many alloys are not available, but an indication of the usefulness of each alloy is given for guidance in selection.

No.	Description or Name of Alloy.	Chemical Composition (approximate).							Compressive Strength.
		Copper. Per cent.	Tin. Per cent.	Lead. Per cent.	Zinc. Per cent.	Phosphorus. Per cent.	Antimony. Per cent.	Other elements. Per cent.	Reduction per cent. 10,000 lbs. loading per sq. in.
1	Gun-metal	88	10	—	2	—	—	—	—
2	Plain bronze	90	10	—	—	Trace	—	—	—
3	Phosphor bronze	90	9·5–10·0	—	—	0·5	—	—	—
4	Hard phosphor bronze ..	87	11	—	—	1·0	—	—	—
5	” ” ” ..	85	15	—	—	1·0	—	—	—
6	” ” ” ..	80	20	—	—	1·0	—	—	—
7	Lead bronze	88	8	4	—	0·2	—	—	—
8	” ”	84	9·5	6·3	—	0·2	—	—	—
9	” ”	80	10	10	—	Trace	—	—	—
10	” ”	78	7	15	—	—	—	—	—
11	” ”	64	5	30	—	—	—	nickel, 1·0	—
12	” ”	81	7	9	3	—	—	—	—
13	Common bronze	90	6·5	1·5	2	—	—	—	—
14	Common bearing alloy ..	83	14	1	2	Trace	—	—	—
15	Red brass	83	2	10	5	—	—	—	—
16	Yellow brass	55	—	—	45	—	—	—	—
17	Manganese bronze	58	—	0·4	39	—	—	Manganese, 0·75 Iron, 0·8 Aluminium, 0·6	—
18	Zinc alloy	—	10	—	80	—	10	—	—
19	Babbitt metal* (Charpy's alloy)	5·6	83·3	—	—	—	11·1	—	1·1
20	Babbitt metal (general alloy)	1·5	89	—	—	—	9·5	—	—
21	” ” ” ”	7·0	79	—	—	—	14	—	—
22	Admiralty white metal ..	5·5	86	—	—	—	8·5	—	—
23	Lead-antimony	—	—	90	—	—	10	—	—
24	” ”	—	—	85	—	—	15	—	—
25	“ Magnolia ”	0·5	0·5	79	—	—	20	—	—
26	”	—	6	80	—	—	14	—	—
27	Lead-tin-antimony (Hughes' alloy)	—	17	70	—	—	13	—	—
28	Eastern Railroad of France	—	10	70	—	—	20	—	—
29	” ” ” ..	—	12	80	—	—	8	—	—
30	Common white metal ..	1·0	54	34	—	—	11	—	—
31	Marine engine alloy	3·0	77	17	—	—	3	—	—
32	Marine alloy	2·0	40	48	—	—	10	—	—
33	High speed alloy	6·5	17·5	—	—	—	76	—	—

---

* Genuine Babbit metal contains approximately 3·7 per cent. copper, 7·4 per cent. antimony, and 89 per cent. tin.

Bearing Alloys

Compressive Strength.	Hardness and Tensile Properties.						Possible Applications.	No.
Reduction per cent. 100,000 lbs. loading per sq. in.	Elastic Limit. Tons per sq. in.	Brinell Number.	Ultimate tensile. Tons per sq. in.	Yield. Tons per sq. in.	Elongation. Per cent.	Reduction of Area. Per cent.		
28–29	6·5	70-75	15–17	8–10	15–18	11–15	High speed bearings and high pressures, thrust bearings.	1
28–29	7·0	65–70	15–18	9–10	16–18	16–20	High pressure bearings for medium carbon shafts.	2
—	—	—	15	—	10	—	High speeds and high pressures for hardened steel.	3
12–16	8–10	—	10	—	3	—	Extra hard for high speeds and pressures for dead hard steel shafts (case-hardened).	
12–25	8·5–10	—	—	—	—	—	For pressures below 1,500 lbs. per sq. in. with soft steel for bridge bearings.	5
6-10	11–18	—	—	—	—	—	For pressures above 1,500 lbs. per sq. in with hard steel for bridge bearings.	6
—	—	—	14	9	15	15	High speeds for medium carbon or medium hard steel.	7
—	—	59–61	13·0–14·5	—	8–10	—	Typical slide valve metal.†	8
33–35	5–5·5	55–60	12·5–14·5	8·5–9·5	5–7	6–10	High speeds, heavy shocks, and vibration medium hard steel.	9
38–39	4–5	48	12·5–13·5	7·5–8·0	12–18	17–23	High speeds, medium pressures and vibration medium or low carbon steel.	10
—	—	—	—	—	—	—	Railway waggon axles, U.S.A., for pressures less than 600 lbs. per sq. in.	11
34–35	5·5–6·0	50–55	13·5–15·5	8·5–9·0	15–18	22–24	Cheap bearing metal for machine bearings.	12
33–34	5·5–6·0	50–60	15–18	8–10	25–33	26–34	High speeds, heavy pressures, used in automobiles.	13
—	—	20–24	11·0	7·5	2	—	Machine bearings and other ordinary work.	14
46–47	3·0–3·5	34	8·5–10·0	4·0–4·5	7–13	11–17	Cheap bearing metal for low pressures and no shocks.	15
—	—	80–93	17–20	—	9–13	—	Low grade bearing metal.	16
11–12	10–11	100–105	28–32	19–23	20–25	25–35	Low speeds, heavy pressures for hard steel shafts; withstands corrosion.	17
—	—	—	—	—	—	—	Recommended for rock-breaking machinery.	18
—	8·0	30	5·0	—	—	—	Maximum compressive strength with minimum brittleness.	19
—	—	—	—	—	—	—	Light loads, as a lining in C.I. boxes—dynamo bearings.	20
—	—	—	—	—	—	—	Heavy loads, as a lining in C.I. boxes.	21
—	—	—	—	—	—	—	Standard Admiralty white metal.	22
—	—	16	—	—	—	—	Heavy loads, slow moving for large shafts.	23
—	—	17	—	—	—	—	Light loads, slow moving.	24
—	—	—	—	—	—	—	Light loads, high speeds.	25
—	—	—	—	—	—	—	Light loads, high speeds, vibration.	26
—	—	23	—	—	—	—	Metallic packings.	27
—	—	—	—	—	—	—	Eccentric straps and bronze slide valves.	28
—	—	—	—	—	—	—	Metallic packings.	29
—	—	—	—	—	—	—	Light loads, cheap bearings.	30
—	—	—	—	—	—	—	Recommended for marine engine bearings.	31
—	—	—	—	—	—	—	Recommended for submerged bearings.	32
—	—	—	—	—	—	—	High speeds, light loads.	33

---

† This alloy is passing out of use. Slide valves are now almost invariably made of cast-iron.

CHAPTER XVII

THE INSPECTION OF MATERIALS *

Organisation.—In connection with the Inspection of Materials, two kinds of organisation are prevalent:

(1) Inspection on a cheap production basis.

(2) Inspection on a safety or "luxury" basis.

These two conditions overlap to a certain extent, and there are some considerations that apply equally to both of them, but the details of working and general arrangements are different.

In aeroplane or aero engine work, where the number of parts to be produced is comparatively small, the life of the pilot depends very largely on the quality of the materials contained in his machine, and it is therefore necessary to safeguard this by the most rigid inspection. Also in works where it is desired to produce, say, a motor car that shall be absolutely reliable, and safe to work under any conditions, this surety can only be obtained by most careful inspection, and scrapping of all parts that do not conform to a very high standard.

In both of these cases, the production must necessarily be comparatively small, but of very high and guaranteed quality, and consequently the product must be sold at a high price.

For production in large quantities, the risks taken are considerably greater. When large quantities of material are being dealt with, some batches are bound to be slightly below standard, but otherwise of reasonable quality.

Thus, much material that is not absolutely of first-class quality gets into the engines or machines. Also the proportion of test pieces taken in the case of quantity production cannot be as high as in the case of high standard production, as the cost of test pieces, both in material and workmanship, becomes excessive. It is therefore necessary both to widen the limits of usability, and to diminish the scrutiny, so that greater risks of using poor material have to be taken, although the working standard may be the same in both cases.

Other things being equal, the strictness or thoroughness of inspection will be determined by commercial considerations, *i.e.* by the price that can be obtained for the finished product in competition with other manufacturers.

In the following pages, the procedure for production on a safety basis is laid down, and the remarks contained therein must be modified to suit the peculiar circumstances of each case and the margin of safety desired in the articles to be manufactured.

Receipt of Materials.—When the specifications governing the orders for materials have been decided, and the orders placed, it is necessary to formulate a procedure for receiving the materials at the works, and for following them

---

* For a fuller discussion see "Engineering Inspection," by Allcut and King (Routledge & Co.).

through the various stages of manufacture in such a way that they can be readily identified at any stage.

This is necessary for three reasons.

(1) Because flaws, and other defects, invisible in rough stampings, forgings, or castings are often revealed in the course of machining.

In these cases it will be impossible to debit the maker with the value of the scrap material unless some system of identification is employed.

(2) Because materials from different sources are often used for making similar details. When the materials in question have to be heat treated, the different kinds of material must be separated out before heat treatment, and this cannot be done without some system whereby the different consignments can be followed through.

(3) Because troubles are sometimes experienced in finished machines or engines, and are traced to a particular part or to a certain consignment of material. If this trouble recurs, it is a great advantage to be able to trace all parts made from that particular consignment, and to scrap or rectify them before assembly. The selection of a suitable marking system is therefore an important factor in works organisation, and, once selected, it must be rigidly enforced.

Any system of stamping or marking raw material is open to the objection that the marks disappear during machining processes. The identification marks must therefore be impressed on a surface that is not removed during the early machining operations. They must then be transferred to a machined surface before effacement, so that the identification marks remain on the job during its whole life. It is inevitable that some mistakes will occur, such as incorrect transference of marks, or omitting to transfer marks, but this can be minimised by marking the ticket accompanying each batch of work with the identification symbol that should be stamped on each article.

A critical point in the procedure is the handling of raw material on the receiving deck. At this stage, there will be no identification symbols on the material, other than those put on by the makers. It may be argued that the identification marks of the purchasing firm can be put on by the makers before delivery, but this is a very risky procedure, and it is very difficult to get the makers to undertake the responsibility of doing this. When the raw material is received, it must be kept together until it is bonded. The bonded store will be provided with bins, racks or marked spaces, for accommodating the various classes of work involved, and each new batch received will be labelled with a bond number as soon as it is deposited in the store. The material must never leave the bonded store until it has been inspected and passed as fit for use, when it will be marked with an identification stamp, and sent to the machine shop store to be drawn upon as required.

In dealing with inspection of material from bond, three classes of work will be involved :—

(1) Raw material, such as steel bars or billets.

(2) Partly manufactured material, such as forgings, castings, or stampings.

(3) Finished and assembled parts, such as oil pumps, magnetos, etc.

The procedure will vary somewhat in these three cases, so that they will be taken seriatim.

Raw Material.—This has been purchased to a material specification. It is therefore necessary to take physical and chemical tests to ensure that the provisions of the specification have been fully met. On receiving the material, the storekeeper of the bond sends a note in duplicate to the Materials Inspector, asking for the consignment to be released.

This inspection note also acts as a release note when the signed duplicate is returned to the storekeeper.

The inspector then selects test pieces from the consignment, and when satisfied that the material is correct for use, signs the release note, issues an identification mark to be stamped on each bar and billet, and, where necessary, indicates the colours with which each bar or billet is to be painted. When this has been done, the material may be issued to the general stores.

It is advisable (wherever possible) for the identification mark to be stamped at frequent intervals along the bars, and on each piece cut from the billet, so that it may appear on all rough machined parts.

Partly Manufactured Material.—The raw material from which this is made may be checked by the purchaser's inspector at the supplier's works, but it is seldom practicable to do this. A good plan is to arrange for test pieces to be cast or forged on the parts themselves so that these test pieces may be cut off and tested at the purchaser's works. If this is done, several other considerations arise. Chief among these is the question of cost. If the test piece is cast or forged on every article (or batch of articles for plate moulded work), the cost of cutting these off, and that of the material wasted, is excessive.

In some instances, parts can be designed in such a way that the test piece may be left on the finished job. In this way the cost of cutting off superfluous test pieces may be avoided.

If, on the other hand, a test piece is made on a percentage of the total number of forgings or castings, this waste is avoided, but there is nothing to prevent the test parts from being made of better material than the bulk consignment.

In the latter case, systematic examination of parts scrapped in machining is necessary to ascertain whether the materials used in the actual jobs are as good as those in the test pieces.

Manufactured Material.—In this case it is impossible to check the material used without scrapping one of the finished articles, but in important details it often pays to do this rather than to run the risk of putting faulty parts into an assembled machine, as, by its failure, a faulty detail may wreck other important and costly parts. The best procedure is to dissemble a definite percentage (say 1 per cent.) of the total number of articles received, and to check these for material and dimensions.

The castings, forgings, etc., can be cut up into test pieces, analysed, or otherwise checked, and the remainder of the consignment passed into use, or rejected, on the results of these tests. In this way an independent check can be taken, as the supplier does not know which article will be chosen for testing.

It should be remarked that no system of testing will give absolute security: the material can only be judged by the evidence available, which is invariably incomplete.

It provides, however, a reasonable safeguard, and its moral effect on suppliers and workmen is great. Any manufacturer or operative who knows that the results of his work will be subjected to tests before acceptance, will usually be careful not to submit work that he knows to be faulty.

Heat Treatment.—The identification symbol stamped on each article is an invaluable guide in the case of steel or other material that has to be heat treated. Each test piece, representing a consignment of material, must be put through the heat treatment proposed for the finished article.

If, after this treatment, the required results are obtained, the bars or articles are marked accordingly, but if the chemical composition is slightly different to that of previous consignments of the same brand, it may be necessary to vary the temperatures slightly to obtain the required results.

This means that the system of marking adopted must be capable of indicating the heat treatment to be given to each class of material used, by means of a card index or other arrangement.

With case-hardened or other heat-treated work, it is possible that owing to incorrect transferences of identification marks, or on account of carelessness or accident in the heat-treating processes, some of the articles may be spoiled. As this fact is sometimes not discovered until the parts are in actual work, it is advisable that each batch of work treated in the same furnace at the same time shall bear a distinguishing number, and this number should be impressed on each article in that batch. In this way, if trouble is experienced with a particular part, and the failure is due to faulty heat treatment, the whole of the articles treated in that way can be isolated and examined before being assembled, or can be withdrawn for further examination if already assembled.

With this safeguard much of the trouble experienced with case-hardened and heat-treated parts can be avoided.

Shop Tests on Case-hardened and Heat-treated Steel.—The object of the inspector, however, is to avoid these troubles as far as possible, and this is done by a few simple tests, which are applied to each batch of heat-treated work.

The easiest test to apply, and the most rapid in operation, is visual examination of the broken section of the heat-treated part.

To avoid scrapping good work, it is advisable to arrange for an article of the same form as those being treated (but scrapped in machining at a previous operation) to be included with each batch of good work, as a test piece.

This is carburised and heat treated with the batch of work, and is then broken to indicate the condition of the core and case in the other articles comprising the batch, and on the results of this examination, the batch is accepted, rejected, or returned for another heat treatment. If the inspector is doubtful whether the test piece actually represents the character of the work, he may order one of the actual articles to be fractured, when, in case of re-heat treatment, the broken part can be used as the test piece.

In case-hardened work the fracture test is of great value, and in very important details, such as aero-engine camshafts, a fracture piece is incorporated with every shaft (each shaft being previously numbered), and the shaft is passed or rejected on the evidence of the fractured piece.

Considerable discretion must be exercised in providing test and fracture pieces, as, if the test piece is not similar in size and shape to the actual article carburised, the results obtained may be very misleading.

The disadvantage of visual examination, is that its success depends entirely upon the experience of the examiner, and to a certain extent on the light by which the fracture is examined. Artificial light is very bad for such examinations—it is always preferable to inspect in good daylight wherever possible.

Fractures and their Characteristics.—Fracture tests on steels may be divided roughly into three classes :—

(1) Normalised plain carbon steels.
(2) Heat-treated steels.
(3) Case-hardened steels.
    (*a*) Plain carbon case-hardening steels.
    (*b*) Alloy case-hardening steels.

Normalised carbon steels should be fairly fibrous in structure, but the actual appearance of the fracture will depend to a large extent on the carbon content. In some cases the steel is still coarsely crystalline after the normalising operation, and in such instances a second normalising often effects a great improvement.

Heat-treated steels, if properly treated, are usually finely fibrous in structure. Sometimes bright crystalline patches are observable in the centre of the section. These are due to insufficient soaking in the furnace. Large, coarse crystals on the outside surface generally denote overheating, particularly in the case of stampings.

FIG. 198.—Fracture of Case-hardened Part.

A good carbon case-hardening steel will give a dark grey fibrous core with a characteristic " pulling " fracture and a very light grey, compact case, both being free from a crystalline appearance. The fracture should show short, silky fibres, not long, coarse, stringy ones. The latter are generally due to the presence of slag in the steel and are often incorrectly taken as evidence of good quality.

It is more difficult to get a good core and case with alloy steels, but it is quite possible to obtain a light grey fibrous core with an almost white case.

It often occurs, however, that either core or case, or both, are slightly crystalline.

The longitudinal fracture (*i.e.* along the direction of rolling) is very little guide in such instances, the cross section being much more reliable.

There is nothing exact about the method, as the results cannot be expressed in figures, and differences of opinion are frequent. Its advantages are speed and cheapness.

The time taken in making mechanical tests on the cores of case-hardened parts, where this is possible, and the expense of machining test pieces, gives the fracture test an important advantage over all other tests.

In the case of heat-treated parts which are not carburised, the fracture test is still useful, as it gives a very good indication of the success or otherwise of the treatment, but it is usual in such cases to check the actual articles by a Brinell test. There is probably no better method than this of checking oil-hardened gears, and it has the additional merits of being speedy and easy to apply. In such instances, the test must be taken on some part of the surface from which the scale has been ground or otherwise removed, leaving a clean, flat surface. Otherwise incorrect results are likely to be obtained.

Case-hardened parts are generally tested for hardness by means of the file, or scleroscope, after grinding, and in some cases before that operation.

In thin sections, where it is important that the core should be flexible and free from carbon, a bend test is often very useful. This can easily be applied by clamping the article in a vice and striking with an ordinary hand hammer. If the work breaks off short, instead of bending over, it may denote that the wrong steel has been used, or else that the carbon has penetrated into the core, making the article useless.

When case-hardening steels have become mixed in the stores, or have been wrongly marked, the case may be ground away from some part of the finished articles, and a Brinell test taken on the core. This will often indicate which articles have received the wrong treatment, and will enable them to be sorted out.

In judging the cross section, it is often found that the " crushed " part of the section has a very crystalline appearance. This should be viewed with caution, as it is often due to the method of breaking. This can be proved by breaking the specimen again in the opposite direction, when the crystalline patch will be found on the opposite side of the section.

Case-hardening Troubles.—Difficulties are experienced both in the operation of case-hardening and in the inspection of case-hardened work, and a few of these will now be considered. (See also "Case-Hardening Steels," Chapter XIII.)

It is frequently found that the depth of case shown by the test piece does not agree with that found in the actual work. This can only be checked by the systematic examination and fracture of the finished work.

To avoid scrapping useful work, articles scrapped by machining or other processes after case-hardening should be used for this purpose. There are several reasons which may account for such differences, viz.—

Variation in the carburising compound, or the use of old compound. Bad packing in carburising box. Variation in temperature of furnace. Too many articles in carburising box. The depth of case indicated by the fracture is occasionally doubtful or misleading, and further evidence must then be obtained. A convenient method is to grind off a portion of the surface, and etch the ground part with picric acid solution. Dilute nitric acid is much quicker in action, but is usually not so reliable as the slower reagent.

When case-hardened gears are in question, it is advisable to grind the end off one of the teeth, so that the etched part shows the section of the tooth. This will give a correct idea of the relative proportions of core and case.

Articles that are rejected because the case is too thin, may be recarburised and submitted again for examination. Such parts must be very carefully watched, as the carbon must not be allowed to penetrate into surfaces required to be soft. This is avoided in the first treatment by machining the carbon away from such surfaces, but obviously this cannot be done again, as the part would then be below the required dimensions.

Surfaces required to be soft after re-carburising are therefore protected in some way, either by painting, claying up, or copper plating.

In spite of these precautions, carbon often penetrates such surfaces. Paint is seldom efficacious when long periods of carburisation are required. Clay is apt to crack on heating and allows the carburising gases to penetrate the metal. Copper plating is sometimes spongy, and often fails to adhere properly to the metal. In the latter case, the superior expansion of copper causes a space to be left between the copper and the steel, and allows the carburising gases to enter.

Recarburising and retreating, particularly in the case of long hollow work, such as aero-engine camshafts, is apt to produce considerable distortion, often scrapping the work in this way. It also adds considerably to the cost of the job, and should therefore be avoided as far as possible.

Hardening shops that have been "pulled up" several times for faults due to thin case are apt to proceed to the opposite extreme, and carburise too deeply. This is very objectionable for several reasons. The excessive thickness of case reduces the amount of soft core, and in thin articles such as hollow shafts or wheel teeth, this may be fatal, as the strength of the part is mainly derived from the core. A thick case also makes it much more difficult to straighten or remove distortion from the case-hardened object, and cracks are very liable to develop in the straightening operation. A further objection is the development of a coarsely crystalline layer on the outer edges of the case. The cause of this is discussed in Chapter XIII.

Case-hardened gears subjected to heavy loads and high speeds are liable to "pit" and crack when running at full load. The cause of this is often thin case on the teeth, but this is sometimes assisted by bad bedding. If the teeth of the opposing gears are only in contact over one-half or one-third of their length, the case is crushed and overcome piecemeal, and is unable to stand up to the required load.

Cracks are also liable to occur on case-hardened surfaces after grinding. This trouble is very often caused by machining and grinding operations, and is fully discussed in Chapter XIII.

When quantities of small articles have to be heat treated, an occasional cause of trouble is the presence of cool areas in the furnaces. This is either due to the design of the furnace, or to bad working. For instance, in one case of this kind it was found that a gas-fired furnace was regulated by shutting off some of the burners altogether, instead of by reducing all burners equally. The presence of such areas can generally be detected by looking into the furnace when heated. They will appear dark in comparison with the other parts.

A frequent difficulty with case-hardened details is the presence, before grinding, of comparatively soft patches on an otherwise hard surface. This is caused either by bad quenching or by uncarburised or decarburised areas. In the former case, the trouble can be remedied by another quenching. A fracture test will assist materially in ascertaining the cause of the softness.

Care should be taken in testing the hardness of case-hardened surfaces that the actual hardness of the job is observed. In some instances, the surface is covered with a hard scale, which must be removed by filing, or preferably by sandblasting, before testing. Also it sometimes happens that a slight amount of surface decarburisation takes place, causing a soft surface, which can be filed or ground away. Below this, the surface is found to be quite hard and suitable for use, but if mere surface indications were accepted, the work would be sent back as "too soft."

When work has to be case-hardened and ground, there is a great temptation for workmen on first operations to leave the surface very roughly machined. This is often detrimental to the hardness of the surface, as grinding has to be continued until the machining marks are removed, and if these are very deep, a good deal of the case is ground away. The cost of grinding also becomes excessive, so that a fairly smooth surface should be encouraged on all work sent for carburising.

The presence of surface flaws or seams in the steel is detrimental in case-hardened work, as the continuity of the case is thereby destroyed and a potential cause of trouble set up.

The machining of objects after carburisation, and before quenching, is sometimes made very difficult, and occasionally impossible, by opening the carburising box too early. This cools the surface at too rapid a rate and causes it to harden. When this happens, it is impossible to machine off the surface material before quenching, and as this is frequently in such a position that it is difficult to grind off, the parts in question sometimes have to be scrapped. The carburised parts, in such instances, should always be allowed to remain in the box until cold.

It is advisable to make this a regular procedure.

Defects in Stampings or Drop Forgings.—The usual defects observed in stampings are due to working too hot, too cold, with imperfect dies, or with poor clipping tools.

The most troublesome item in this list is overheating. The effects of this, if not too pronounced, may be removed in a mild steel stamping by putting more work on the article, but in an alloy steel, such as a nickel chrome steel, this cannot often be done. The greatest precautions must therefore be taken to detect all cases of overheating, and to reject such stampings before any machining work is done upon them. In some works, the extreme step is taken of putting a special inspector in the stamp shop, to watch for cases of overheating and to stamp with a special mark all doubtful forgings, so that these may be specially viewed when cold.

It should be remembered that when a stamper is paid piece-work prices, it is to his advantage to use high temperatures, so that the stampings will be made quickly and easily. Stampings rejected for overheating, or other defects due to the stamper, are not paid for.

Cold stamping is deleterious in putting undue stresses on the stamping, and wearing out the dies. Frequently, also, the material fails to fill the dies, and then the stamping is faulty in shape and dimensions. Splitting of stampings is sometimes due to cold clipping. If the flash which is formed round the stamping is clipped off when the stamping is cold, there is sometimes a tendency for the metal to tear into two parts, and the division is marked by a longitudinal crack or cracks (Fig. 199).

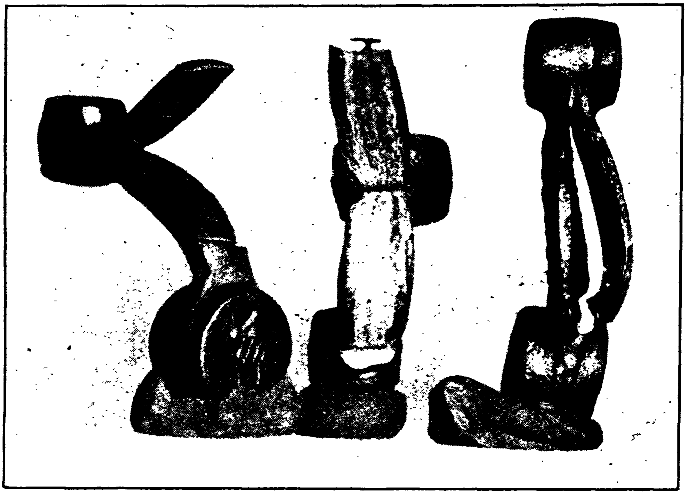


FIG. 199.—Stampings split by Cold Clipping.

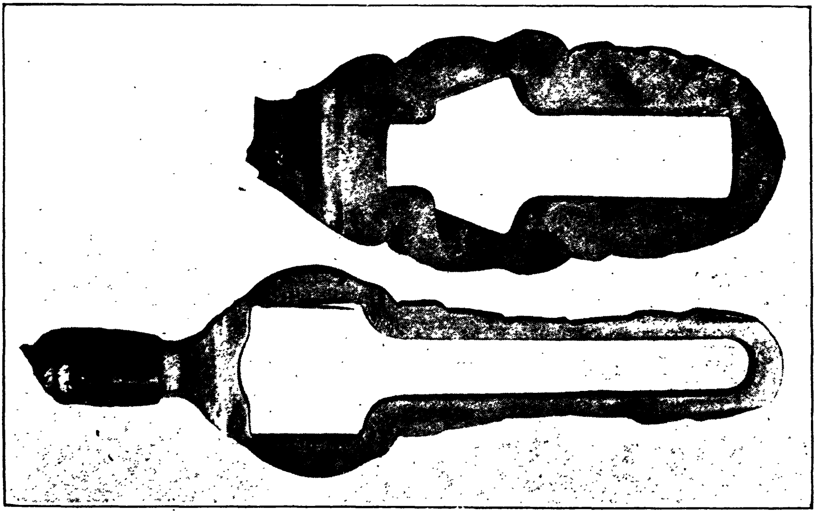


FIG. 200.—Flash clipped from Stamping, showing Normal and Excessive Amounts of Material.

This has happened on many occasions in the clipping of valve stampings.

Cold clipping is done because it saves time to make all the stampings in rapid succession, and then clip the flash off each one afterwards.

Gaps are sometimes caused in the sides of hollow stampings, by the excessive use of oil on the dies, particularly during the last few blows, which should be made without oil.

The form and appearance of the "flash" often give useful indications of imperfections likely to be found in the stampings. The flash should be thin and of fairly uniform width round the stamping (see Fig. 200). Overheating during manufacture is shown by the appearance of the flash (Fig. 201), but this does not invariably mean that the stamping is useless. The overheating may be confined to the extreme end of the bar or billet, particularly when this has been forged down for making a previous stamping from the same bar. In this case the flash will show signs of overheating, but this may not extend as far as the stamping itself. If this is observed, the inspector may mark the stamping as "suspect" while it is still hot, for a further examination to be made when cold.

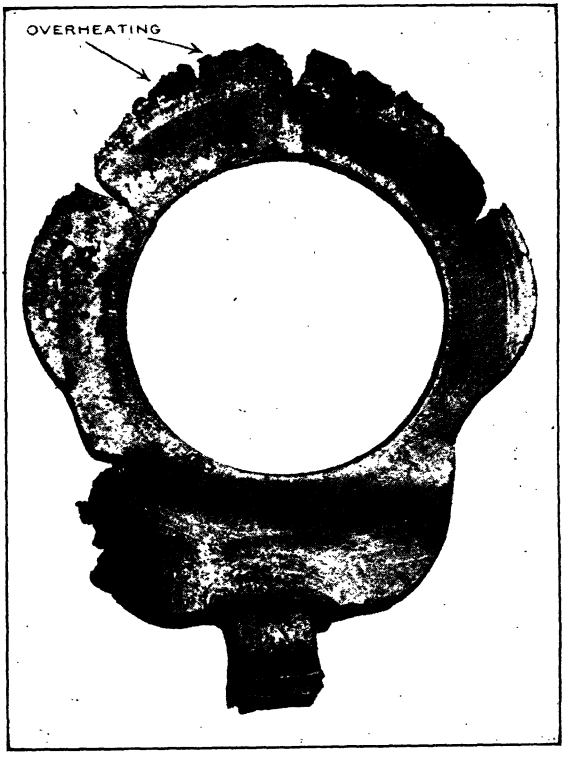


FIG. 201.—Flash of Stamping showing Signs of Overheating.

With some forms of stamping, the "fin" formed in roughing down may become flattened down on the surface of the stamping, and in the finished article this "overlap" will show up as a longitudinal seam.

" Offset " forgings are caused by the upper and lower dies working out of line with each other, often after a number of correct stampings have been made. This can only be remedied by continual supervision in the stamp shop.

The steel used for making stampings must be carefully inspected for mechanical faults or flaws. It is not unusual for flaws to be found extending down the centre of the billets. This is caused by " piping " in the ingot, and can only be remedied by cutting more off the top of the ingot before rolling. Any steel showing this defect must be rejected for stamping purposes.

A more insidious trouble, and one not easily discovered in the billet, is the presence of minute hair cracks on the surface. These cracks are frequently only about $\frac{1}{8}$ to $\frac{1}{16}$ inch deep, and extend along the billet in the direction of rolling.

When billets of this kind are stamped, the cracks often open out, producing large flaws that are fatal to the appearance and usefulness of the stamping.

These cracks are particularly prevalent and dangerous in alloy steels, and the best way of preventing their occurrence is to rough turn the ingots before rolling.

Ragged ends on a stamping billet are occasionally responsible for the appearance of flaws in a stamping, as they cause overlaps. Large billets should therefore have the rough ends cut off before being issued to the stamp shop.

The operation of cutting up billets of large section into smaller pieces for making stampings should be carefully performed, as, if the pieces are cut off too long, the excess material is liable to split the dies when stamping. If the pieces are shorter than they should be, the metal will fail to fill the dies, and the stamping will be defective.

Failures of stampings after heat treatment are often due to insufficient care during the cooling stage. The stampings, especially when made in alloy steels should be placed on ashes and shielded from draught. This helps to maintain uniformity in the condition of the stampings sent for heat treatment, and solves many troubles that have been ascribed erroneously to the heat treatment itself. Cases of cracking after heat treatment are also recorded as stamping defects, but in hard alloy steels this is often due to rough machining before heat treatment. In such cases, the stamping should be fairly smoothly finished before heat treatment, and internal radii made as large as possible. Sharp corners must be avoided at all costs

Superficial defects in stampings and forgings are very difficult to detect unless the scale is properly cleaned off the surface before examination. It is advisable, therefore, that all stampings should be sandblasted or pickled before inspection, so that any surface defect will then be observed quickly and easily.

Defects in Castings.—The material troubles experienced in dealing with castings are of a well-known nature, but a brief reference to some of them may be useful at this stage.

The most prevalent defects are due to blowholes. These, if small in size and not too numerous, may be accepted for most classes of work, but where they are large or close together, and particularly when accompanied by spongy places, the castings must be rejected. In many instances, the external appearance of the casting is quite good, and the blowholes are only revealed during the process of machining.

Blowholes existing below the machined surface of a casting cannot be detected by superficial examination, but this defect, together with porosity and spongy places, can be discovered by subjecting the casting, whenever possible, to a water or air test.

This consists of plugging up all the openings in the casting, and pumping in water until a certain test pressure is reached, when defective spots will be indicated by the water oozing through the metal. The test pressure adopted will depend upon the material of which the casting is made, and the purpose for which it is to be used. With aluminium and iron castings, hot water is often found to reveal defects more readily than cold water. A more severe test is to pump air into the casting, and either submerge it in water, or brush the surface over with a solution of soap and water. The presence of bad spots is immediately shown by the bubbles formed on the surface of the casting. In complicated castings a good deal of trouble is often caused by distortion due to the design of the casting or to uneven cooling in the mould. Distortion is very common in malleable iron and steel castings, and is due to the prolonged annealing process in such cases.

It may be so pronounced as to prevent some of the surfaces from cleaning up when machined, and to make the casting useless.

It is advantageous, in such instances, to mark out all important surfaces before allowing the castings to proceed to the machine shop, as, otherwise, the defect may not be discovered until some expensive machining processes have been performed.

Judicious marking out frequently enables distorted castings to be saved by suitably manipulating the earlier machining processes to permit the faulty surfaces to be machined.

The cooling of complicated castings also introduces the question of cooling stresses. Parts of large section cool very much slower than thin walls or ribs, so that if two thick parts of a casting are connected by a thin wall, or section, the latter will be rigidly set before the bulkier parts have solidified. The subsequent contraction of these will set up stresses in the thinner parts, and may cause them to crack.

If no crack occurs, the existing cooling stress, combined with the externally applied stresses when the casting is actually in use, may exceed the elastic limit of the material and cause it to give way. This can only be remedied by simpler designs, and by making the metal in each casting as uniform in section as possible.

The temperature of pouring also has a great effect on the structure of materials, particularly in the case of alloys. This point is discussed in greater detail in the foregoing pages.

Motor cylinders made of aluminium alloys are generally lined with steel. To do this, it is necessary to heat the cylinder and expand the bore sufficiently to slip the liner into position so that, as the cylinder cools, the liner will be gripped due to the shrinkage. When this is done, care must be taken to allow for shrinkage to be as little as possible, consistent with the proper support of the liner.

If the shrinkage allowance is excessive, the walls of the cylinder may be so highly stressed that cracking will result, particularly as these alloys have low tensile strengths.

Displaced cores, resulting in local thinness of castings, are responsible for some difficulties. Occasionally this displacement is so great that the wall of a casting is reduced to a mere shell, and drilled holes surrounding a cored hole may run into the edge of the flange.

Spongy places in castings, if not too bad, can be remedied by rusting or "doping." The former process is used in iron castings which leak slightly on water test.

These, after rusting up with sal-ammoniac, or after exposure for some time to weather, will frequently sustain the hydraulic test without leakage, owing to the pores being filled up with rust. Castings so treated, however, frequently leak after machining. Porous aluminium castings can be stopped from leaking by "doping" with "water glass," which consists of a solution of commercial sodium silicate in hot water. This is applied under pressure at a temperature of 40—60° C.

The pressure must be maintained until leakage ceases; the casting is then washed in hot water, and dried.

If the casting has been completely machined before this treatment is applied, it may be sufficient merely to immerse the casting in the hot solution. If the machining allowance on the casting is large, it should be treated after machining.

The repairing of costly and complicated castings by welding and burning has now almost assumed the proportions of a separate industry, but some firms deal with their own castings in this way. Cast-iron can readily be repaired by welding, but aluminium and its alloys are difficult to weld and are generally unreliable in this respect.

It is found that, even though a good weld may be made, the heating up of the surrounding portions of the casting very often causes stresses and cracks to be set up, and these show up when the machine or engine is put to work, and cause much expense, delay and inconvenience. The welding of expensive aluminium castings is not a matter to be lightly undertaken, as it is a difficult matter to detect bad work or imperfect welds, and the risk of setting up cracks in the castings at a later date is very great. (See also Chapter XIX.)

Where surface blowholes cause leakage on joint faces, it is often possible to save the casting by filling these up with a soft solder, as these blowholes do not greatly affect the strength of the casting. It should be ascertained, before doing so, that the blowhole does not extend to a long distance below the surface, and does not communicate with other holes, or porous metal. This can be ascertained by probing, and tapping with a small centre punch.

Machining troubles are sometimes experienced in iron castings, on account of hard spots due to segregation or local chilling. In malleable iron such hard spots are frequently due to insufficient annealing. These can often be machined by the use of a different tool or by allowing more time for the job. When the operator is working on piece-work prices, and meets with difficulties of this nature, he is apt to reject castings unnecessarily.

Pickling and sandblasting is also advisable, in the case of castings, to reveal defects before proceeding with machining.

Forgings.—Many of the points dealt with under "Stampings" also apply to forgings, but there are troubles peculiar to forgings that will now be described.

Long cylindrical forgings, such as shells or cylinders, are usually made by heating the billets to a "bright red heat," and pressing to the required shape and size in a hydraulic press. If the billet is not sufficiently heated, the punch is sometimes deflected to one side, or bent, in which case an eccentric and unusable forging will result.

When the punch is not pressed sufficiently far down the billet, the forging is generally pierced again.

Re-pierced forgings are apt to have false bottoms in the bore due to dirt being forced in front of the punch on its downward stroke. This is difficult to detect until the machining operation, when it is found in boring.

Cylindrical forgings formed by hammering down larger sections with many light blows ("rolling") are apt to work hollow. If the centre of the forging is subsequently removed by machining, this is not a fatal defect, but in the case of solid forgings, it is an important tendency and must be looked for.

General.—The inspection of materials is an operation which calls for great care and discrimination, together with unceasing vigilance.

Dimensional defects can generally be located and dealt with effectively, as they appear on the surface, but in material inspection the troubles mostly lie beneath the surface. Most of the work must therefore be passed on the evidence of fractured samples or upon superficial examination.

This is necessarily incomplete, but as the work cannot be scrapped for the purpose of providing evidence, considerable risk has to be taken in passing material for engineering work.

The general tendency among operatives is to ascribe to defective materials all troubles that they cannot understand.

This the materials inspector must be prepared to meet, and as the onus of proof is generally placed upon him the task is no light one.

In addition to this, he will find that, if not continually kept up to a proper standard, both suppliers and workmen will constantly slip back into poor quality and slipshod methods, and the only way by which this can be prevented, is ceaseless watching combined with the systematic examination of all materials entering and leaving the works, and also at all stages during its progress through the works.

Test Pieces for Forgings, Stampings and Castings.—The provision of test pieces with forgings or stampings presents some difficulty, as the condition of the material in the test piece must accurately represent that in the forging, otherwise the results will be useless. When small stampings are heat treated in batches, the best arrangement is to cut up for test one of the stampings in each batch. If the stampings have only to be normalised, a fracture test is all that is necessary, the fractured stamping being brinelled to ascertain its uniformity in hardness with the rest of the batch.

Large and important stampings or forgings have a test piece forged with each article. The position of such a test piece must be very carefully chosen, so that the work done upon it in forging is similar to that put upon the other parts of the article. It is also important that the direction of the grain is *along* and not *across* the test piece,* as otherwise incorrect test figures will be obtained. The direction of flow in various parts of a forging or stamping may be seen by cutting sections of the forging and taking sulphur prints on the cut surface.

If the stampings are too small to be cut up into test pieces, the test piece

---

* In some instances, however, it may be important to take special tests *across* the grain.

must be taken from a part of the bar which has been subjected to the maximum forging temperature, and it must then be heat treated with the stampings. The Brinell hardness of the test piece must then be similar to that of the stampings treated in the same batch.

In most cases, with reasonably careful heat treatment, the diameters of the Brinell impressions will not vary more than 0·2 to 0·3 mm. in the same batch. When a test piece has to be heat treated, it should be of nearly the same dimensions as the stampings or forgings, as, if smaller, it cools more rapidly, and if larger, more slowly, than the forgings and so gives incorrect results. For this reason, also, it is advisable to use actual forgings (scrap, if possible) for test purposes.

The position and size of test pieces in castings are also a matter of importance. The position must be carefully chosen, so that the metal may be representative of that in the casting, and the thickness should be as nearly as possible equal to that of the casting itself, so that differences due to cooling in the mould will not arise. The test piece should be run with, and attached to, the casting, as, if this is not done, there is a possibility of the test piece being of different material to that in the castings.

It is better to have no test piece at all than to have one that gives false or misleading results.

CHAPTER XVIII

NON-METALLIC MATERIALS

Timber

Inspection.—The testing and inspection of the different varieties of timber is a considerably more difficult matter than is the testing and inspection of metallic parts, as in the former case the material is not homogeneous, and therefore the results obtained on any sample tested to destruction are not necessarily representative of the mass. Strictly speaking, timber is not a material, but is a structure or series of structures.

In timber, also, the effects of time, atmospheric temperature, and moisture are very considerable, whereas metallic bodies are not influenced by these conditions to any marked degree, except in the case of corrosion.

The extended use of timber in the construction of aeroplanes has had an enormous influence on the economical use and scientific study of timber. Where weight has to be cut down to the finest possible limit in a material of notorious unreliability (as compared with metals), it naturally follows that extraordinary precautions must be taken to eliminate as many doubtful factors as possible.

The first stage in the inspection of timber is the identification of the consignment with the class of wood ordered, and a superficial examination to ascertain its freedom from defects. For the former purpose, an examination by low-power microscope is necessary, but as facility in the identification of different kinds of timber is entirely a matter of practice and experience, it is impossible to deal satisfactorily with that phase of the subject in this book. The reader is therefore referred to the various standard works on the subject of timber, and to a paper read by Mr. W. H. Barling before the Royal Aeronautical Society in 1918, from which many useful hints may be gleaned.*

The defects to be looked for are compression shakes, dote, deleterious knots, dead wood, grub holes, and resin pockets. Beech, birch, maple, etc., are also subject to troubles known as "pith flecks," which are little black defects caused by insects. In addition to freedom from these defects the timber must be clean, straight grained, and cut parallel to the grain.

The latter property is investigated by making a splitting test.

Short samples about 6 inches long are split in two directions, approximately at right angles to each other. In this way the true direction of the grain will be obtained, and the maximum inclination of grain to length should not exceed the following values :—

Walnut	1 in 12
Ash	1 „ 10
Spruce	1 „ 20

---

* Further information on the structure and properties of American timbers may also be obtained from "Materials of Construction," by A. P. Mills (Wiley & Co.).

If the grain is not straight, there is a possibility of a beam breaking under a load considerably less than the estimated strength, due to shearing on the tension side of the beam.

Moisture.—The effect of seasoning on the strength, reliability, and freedom from warping of timber, has long been known. Wertheim discovered, about 80 years ago, that the density and maximum elongation of timber diminished with its dryness, and that the modulus and tensile strength of the timber increased. If the moisture is reduced to 10 per cent., however, the timber tends to become brittle, and a further desiccation causes a diminution of strength.

The following figures give a rough idea of the increase in tensile strength of various timbers after proper seasoning :—

Ash	45 per cent.	Oak	26 per cent.
Beech ..	62 ,,	White Pine ..	9 ,,
Elm	12 ,,		

The seasoning and drying of aeroplane timbers are therefore a very important matter. The standard amount of moisture at which weights of timber are recorded is 15 per cent., but the percentage allowable varies with the season.

In walnut and ash, for the months April to October, the allowable percentage of moisture is 2 per cent. higher than for the months October to April, but in each case the average is 15 to 16 per cent. The percentage of moisture is calculated on the weight of the dried sample.*

For silver spruce and similar timbers the specified compression strengths are reduced by about 230 lbs. per square inch for every 1 per cent. of moisture above 15 per cent., and are increased by the same amount for moisture contents of less than 15 per cent.

Rate of Growth.—The rate of growth and density of the timber will obviously have an influence on its strength and reliability, and therefore it is desirable that the number of annual rings per inch of cross section should not be less than a standard fixed for each kind of wood.

In silver spruce and similar timbers the number of annual rings should be not less than 8 to 10 per inch, but in ash the number of rings should not exceed 16 per inch. The reason for this is that if ash is grown very slowly, there is a predominance of weak spring wood in the section, increasing from 30 per cent. for 6 rings per inch, to 60 per cent. in the case of 20 rings per inch.

The density of the timber is expressed in pounds per cubic foot at 15 per cent. moisture, and the following are the minima for aeroplane timbers :—

Walnut	35 lbs. per cubic foot
Ash	38 ,, ,, ,,
Silver Spruce	25 ,, ,, ,,

In the case of fir, pine, elm, ash, maple, sycamore, aspen, and alder, the mechanical properties of the timber increase steadily from the centre to the circumference of the tree. Therefore, in these timbers, wood showing annual rings with only a slight curvature is stronger, other things being equal.

Compression Tests.—Before the war it was a common practice to test timber in compression in the form of large cubes, but with the use of timber

---

* *It is practically impossible to determine experimentally the true moisture content* of a sample of timber, but wood is generally considered to be thoroughly dry when a thin cross-sectional disc ceases to lose weight when heated to a temperature of 100° C.

in aeroplane construction, the available dimensions would not permit of large sections being tested. Also, the use of square sections is objectionable, as if the faces of the compressing platens, or the two ends of the specimen, are not exactly parallel, the specimen is liable to fail by local crushing at one of the corners, and to give incorrect results.

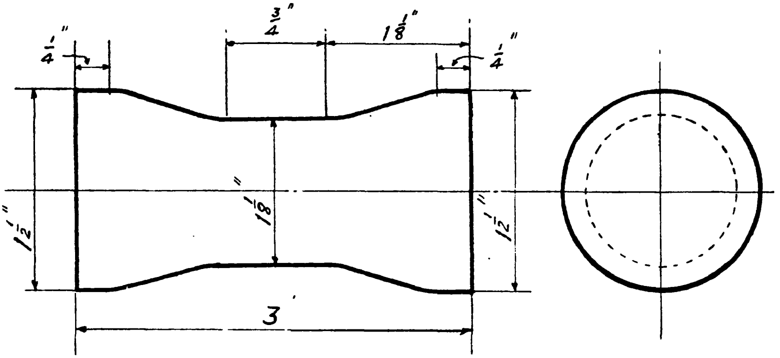


FIG. 202.—Compression Test Piece for Aeroplane Timber.

To avoid this, the form of specimen shown in Fig. 202 was adopted, the ends being covered by steel caps and the load applied through steel balls, which ensure an axial application and eliminate bending stresses as far as possible (Fig. 203). Single tests are not conclusive ; a series of tests should

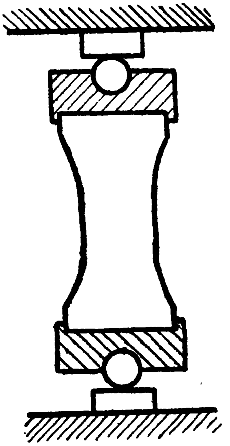


FIG. 203.—Method of Mounting Timber Compression Specimen.

therefore be made and the average result taken. The load should be applied at a regular rate between 3,000 and 6,000 lbs. per minute. Slow loading tends to give low results, and rapid loading high results.

The compressive strength of ash is 5,600 lbs. per square inch at 13 per cent. moisture, and 4,400 lbs. per square inch at 17 per cent. moisture.

Silver spruce gives 4,000 to 5,000 lbs. per square inch.

The test piece should always be cut with its axis parallel to the grain of the wood, and the ends should be squared up carefully before testing.

Bending Tests.—Tensile tests on timber are very difficult to perform on account of the tendency of the ends of the specimen to crush or shear in the grips when pulled. A better method is to test a specimen of timber in bending as shown in Fig. 204.

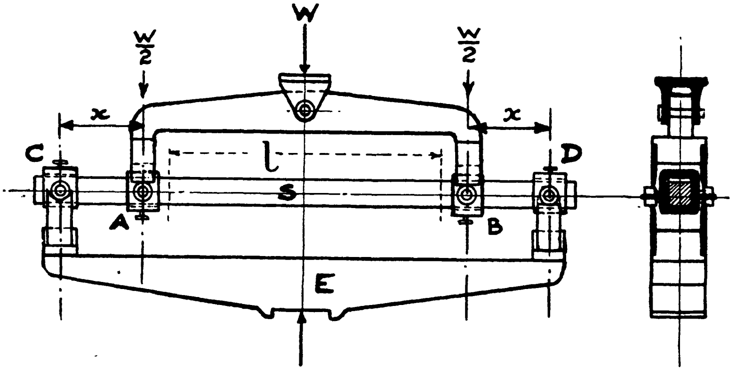


Fig. 204.—Tools for Testing Timber in Bending.

E is the bending beam of an ordinary tensile testing machine, the specimen S being supported in a V block at C and on a plane surface at D. This enables the free end at D to move when the specimen is deflected.

The load W is applied in two halves at A and B respectively, the distances AC and BD being x in each case.

The object of applying the load in this manner is to eliminate all shearing stress in the middle of the beam AB.

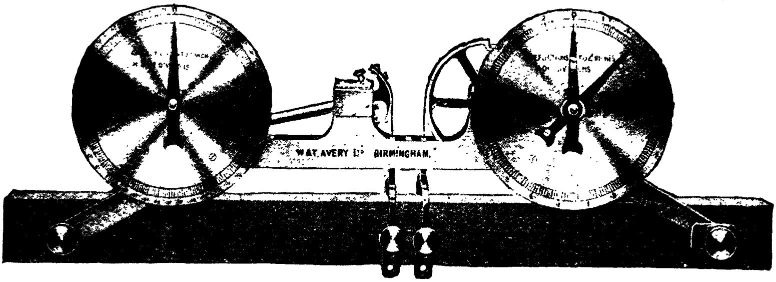


Fig. 205.—Apparatus for Indicating Deflections of Timber-bending Test Pieces. Left-hand dial reads by increments of 0·001 inch to a maximum of 0·5 inch. Right-hand dial reads by increments of 0·01 inch to a maximum of 2 inches.

A length l is then marked off on AB, and the deflection d measured at the centre of this length.

The load is applied by rollers at the neutral axis of the beam, and all crushing is eliminated by the provision of steel saddles in the manner shown in Fig. 204.

The deflections are measured by a lever and dial indicator shown in Fig. 205.

If the loads and corresponding deflections are plotted, the resulting curve will be a straight line up to a certain point. From this curve, the modulus of elasticity of the timber may be calculated, thus :—

W and d are the load and deflection for any point on the straight part of the curve,
b = breadth of beam,
h = depth of beam,
E = modulus of elasticity of timber.

Then $$E=\frac{Wxl^2}{16dI}$$

and $$I=\tfrac{1}{12}bh^3$$

When the test is taken to destruction, the brittleness of the timber is indicated by the nature of the fracture. A tough wood will give a long splintering fracture.

The usual size of specimens is

$$40'' \times 1'' \text{ (wide)} \times 2'' \text{ (deep)}$$

For thin timber, a test taken by bending a lath $\frac{1}{4}$ inch thick round a semicircle 18 inches diameter is employed. The lath should show no signs of fracture under this treatment.

This test is useful for ash.

The deflections produced by loads on timber beams are generally composed of an elastic part which is practically proportional to the load, and a plastic part, which is measurable even in the case of small loads, and which depends to a certain extent upon the time during which the load acts.

Mr. W. H. Barling is of opinion that " slow creep " will cause a wooden beam to give way, in time, under a constant load exceeding 50 per cent. of the breaking load.

Impact Test.—An impact test for aeroplane timbers has also been adopted, and gives a useful indication of the brittleness of the timber tested. The form of the machine and nature of test are similar to the Izod test described in Chapter V, but the dimensions of the machine and test pieces are different, being as follows :—

Weight of pendulum	20 lbs.
Radius of swing	24 inches
Striking distance above centre of notch	$2\frac{1}{2}$,,
Size of specimen	$\frac{7}{8}$ inch square

Both the " V " and the " Copenhagen " notches are used, the dimensions of the test pieces being shown in Fig. 206.

The point where the knife-edge of the pendulum strikes the specimen is protected by a steel clip which prevents local crushing of the timber when the blow is delivered.

The various aeroplane timbers should have the following minimum impact strengths when tested under the above conditions :—

Walnut	9 ft.-lbs.
Ash	10 ft.-lbs.
Spruce	4 to 8 ft.-lbs.

Glued Joints.—In aeroplane and other light constructional work glued joints are now used to a considerable extent, and, notwithstanding the apparently unsatisfactory nature of this class of joint, failures are by no means common.

Probably the most satisfactory way of testing a glued joint is by means of the shear test. Two blocks of wood are each planed along one side, and the planed surfaces of a smaller block (about 2 inches cube) are glued to them as shown in Fig. 207. The load is then applied, gradually increasing in intensity, until the joint fails. Frequently it is found that the wood gives way before the glue.

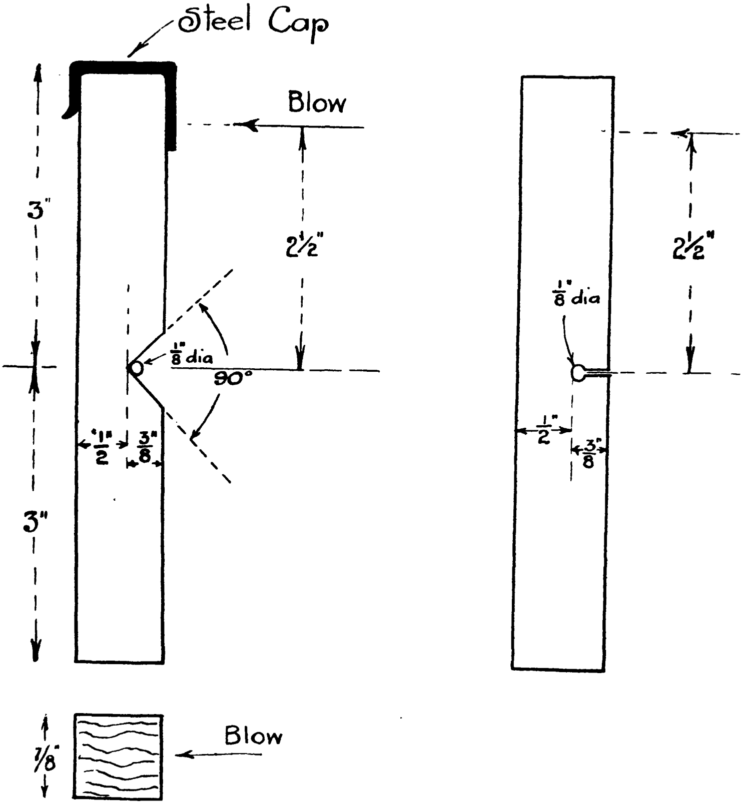


FIG. 206.—Dimensions of Impact Test-piece for Timber.

A good joint made in this manner supports from 3,000 to 7,000 lbs. before fracture.

In preparing the specimens, the planed surfaces should be heated to about 100° F. before the glue is applied, and then the test pieces should remain in the clamp for two days. The surplus glue round the joint should then be washed off before testing.

Other tests, such as tensile and impact tests on glued joints, will readily suggest themselves, but these have not been used to a sufficiently large extent to give any correct idea of their relative values.

Ply-wood.—One of the great disadvantages incurred in using timber, especially in thin sections, is the fact that it is very weak in one direction, but the introduction of ply-wood enables thin sections of timber to be used with safety.

Three-ply wood consists of two very thin layers of timber, between which a third layer is glued, the intermediate section having its grain at right angles to the other two. Five-ply and other ply-woods are made by using more layers, using the grain at right angles (also other angles) in alternate sections. Thus a light but very strong structure is obtained, which can be bent to shape and used without danger of cracking.

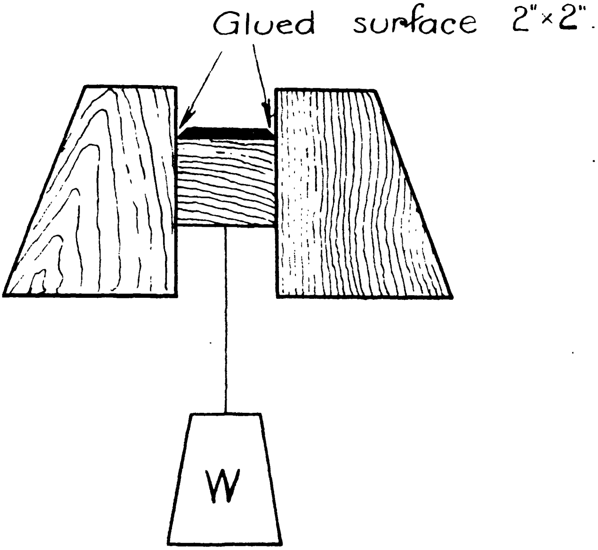


FIG. 207.—Shear Test on Glued Joint.

A moisture test at 105° C. for 10 hours should not show more than 15 per cent. loss of weight. A shear test on the glued joints is made by cutting the section as shown in Fig. 208, and loading uniformly in a testing machine. The strength of the joints should not be less than 150 lbs. per sq. inch.

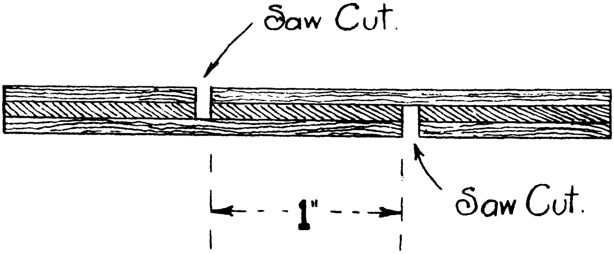


FIG. 208.—Tensile Test on Three-ply Wood.

The plies may also be tested for separation by immersing a piece 6 ins. × 6 ins. in water at 45° C. for 3 to 6 hours, after which the plies should not show signs of separation at the edges.

For ply-woods not exceeding ⅛ inch in thickness a bending test is made on a specimen 12 ins. × 2 ins., the length running along the grain of the outer plies. This is bent round a circle 18 inches diameter and the wood must not show any signs of fracture, crack, or parting when so tested.

Timber and Design.—An important point to note is that timber does not follow the law of Galileo, as its resistance to transverse strain does not vary inversely as the length; it diminishes with much greater rapidity.

Tests were made by Mr. B. E. Fernow (U.S. Forestry Division) on large beams 12 ft. × 6 ins. to 10 ins. and on smaller pieces 24 ins. × 2 ins. × 2 ins.

He found that the large beams gave results less than half of those expected from the tests made on the smaller pieces.

It is therefore unsafe to base a design on any formula that does not take this fact into account, and wherever possible, it is advisable to test the timber in the size and length actually used in the design.

Physical Properties of Timber.—The following table gives the average values of the various properties of timber, when dried at atmospheric temperature. If dried at a high temperature, the timber will gain weight owing to absorption of moisture.

Individual results will vary from these figures to a considerable extent.

Timber.	Weight, lbs. per cu. ft.	Breaking Stress, lbs. per sq. in.	Young's Modulus, lbs.	Torsion modulus, lbs.	Shearing Stress, lbs.
Ash	45·0	13,000	1,600,000	20,300	600
Alder	34·6	9,500	—	—	—
Bay	51·0	14,000	—	—	—
Beech	48·5	11,500	1,350,000	21,240	—
Birch	39·2	11,500	1,300,000	17,250	700
Box	63·5	20,000	1,856,000	30,000	—
Cedar (American)	30·8	9,000	486,000	—	400
Chestnut (Sweet)	39·2	10,500	1,140,000	18,360	—
Cypress	40·2	6,000	—	—	—
Deal (Christiania)	—	12,400	—	11,220	—
Elm	43·5	13,400	700,000	13,500	800
Hornbeam	50·7	—	—	26,400	—
Lance	57·5	23,000	—	25,245	—
Lignum Vitæ	69–89	11,800	—	—	—
Lime	31·0	11,000	—	18,300	—
Locust	45·0	20,500	—	—	—
Mahogany	43–69	21,000	—	—	—
,, (Honduras)	35·0	12,000	1,255,000	—	—
Maple	36·0	10,500	—	—	450
Oak (American)	53·0	11,500	2,150,000	12,000	900
Oak (English)	44·0	10,000	1,451,000	to	850
Oak (African)	60·0	14,500	2,283,000	20,000	—
Pear	48·0	9,800	—	18,110	—
Pine (Pitch)	43·0	12,000	1,255,000	10,500	—
,, (Yellow)	28·8	8,000	1,600,000	to	350
,, (American White)	30·0	11,800	1,300,000	14,700	400
Poplar	31·9	10,200	—	9,500	—
Spruce (Norge)	32·0	12,400	—	—	—
,, (Silver)	27·0	8,000	1,300,000	—	300
Sycamore	39·0	13,000	—	22,900	—
Teak	45·5	14,000	2,350,000	16,800	—
Walnut	41·0	7,800	—	—	—
Willow	35·0	13,000	1,400,000	—	—

Factors of Safety.—The factors of safety recommended by different authorities for use when designing timber structures vary considerably; and this variation is due to the prevailing uncertainty as to the true values to be adopted for the strength of different kinds of timber. A further contributory cause is the variety of results that may be obtained on the same class of timber. For dead loads, the factors recommended range from 4 to 10, for live loads 5 to 10, and for shocks about 15.

Fabric

The use of fabrics for the wings of aeroplanes and for the envelopes of airships, has made a close study of this class of material necessary to engineers. The first quality required in all fabrics used for this purpose is strength, combined with lightness, and therefore, after examining the fabric for manufacturing faults, it is necessary to determine its weight. In the case of linen fabric, the weight must not exceed 4 ozs. per square yard. The strength of this fabric must be not less than 92 lbs. per inch width of warp, and 95 lbs. per inch width of weft.

Cotton fabric is made in various weights and strengths, according to the table given below :—

Weight of Scoured Cloth.		Minimum Strength of Unwashed Cloth.	
Grms. per sq. metre.	Ozs. per sq. yd.	Kg. per metre width.	Lbs. per inch width.
130	3·85	1,250	70·0
110	3·25	1,100	61·6
90	2·66	900	50·4
80	2·37	800	44·8
80	2·37	900	50·4
65	1·92	650	36·4
45	1·33	510	28·6

The fabric is usually tested in the type of machine shown in Fig. 209. The specimens used in aero work are usually 7 inches long between the grips and 2 inches wide after trimming, or 20 cm. between grips (18 cm. measured length) and 5 cm. wide. The test pieces are trimmed to ensure the same number of threads being in each piece.

The test piece is then gripped between the corrugated surfaces of the holders, and the load is applied at a constant rate by means of a stream of lead shot pouring from the top can into another can suspended from the free end of the steelyard. The latter is connected to the test piece by a series of levers and links and is kept in equilibrium by means of the handwheel (shown at the side of the machine) which moves the straining screw in an upward or downward direction as may be desired. If the fabric stretches rapidly, or slips, the steelyard falls, automatically deflecting the flow of shot into another can, which is mounted on the frame of the machine. When the stretch, or slip, has been taken up, the steelyard rises, and the shot flows again into the loading can. When the specimen breaks, the steelyard operates an automatic cut-off which stops the flow of shot. The can is then suspended from the other side of the steelyard and the equivalent weight of shot is obtained by weighing the shot by means of the proportional weights supplied. By rotating the top of the machine, the weighing apparatus may be converted from the compound to the single-lever type, giving greater sensitiveness and accuracy in the latter form.

The compound-lever system indicates up to 1,200 lbs., the total leverage being 50 to 1, so that 24 lbs. of shot are required for this capacity. The single-lever system indicates up to 240 lbs. and has a leverage of 10 to 1.

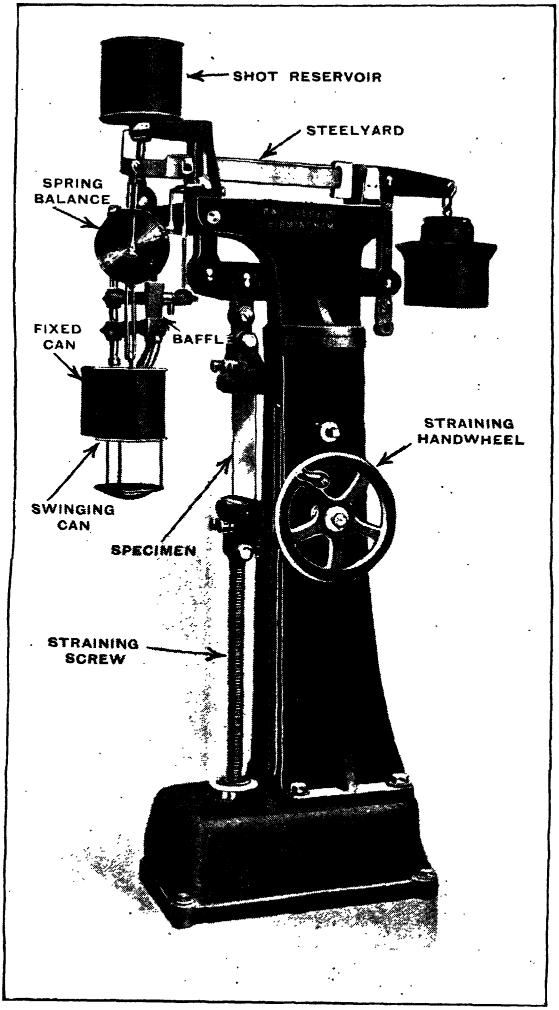


FIG. 209.—Fabric Testing Machine. Capacity: Compound Lever, 1,200 lbs.; Single Lever, 240 lbs.

The maximum size of specimen that can be taken is 6½ inches wide by 28 inches stretched length, but this size is seldom needed for aero work, so that such machines are too large and unwieldy for this purpose. It is very convenient, however, for use with canvas and other heavy fabrics.

A smaller machine, designed to take aero specimens, is shown in Fig. 210. This has specially designed corrugated grips operated by single handles for facility in inserting specimens (Fig. 211). The lever system is single and reads up to 500 lbs. The cut off is electrically operated (Fig. 212) and only one swinging can is employed. The "gate" valve shown in Fig. 212 is for the purpose of regulating the supply of shot to the required rate of loading, and when the test is completed, the shot is weighed by the movable poise and hanging weights shown on the right-hand side of the steelyard.

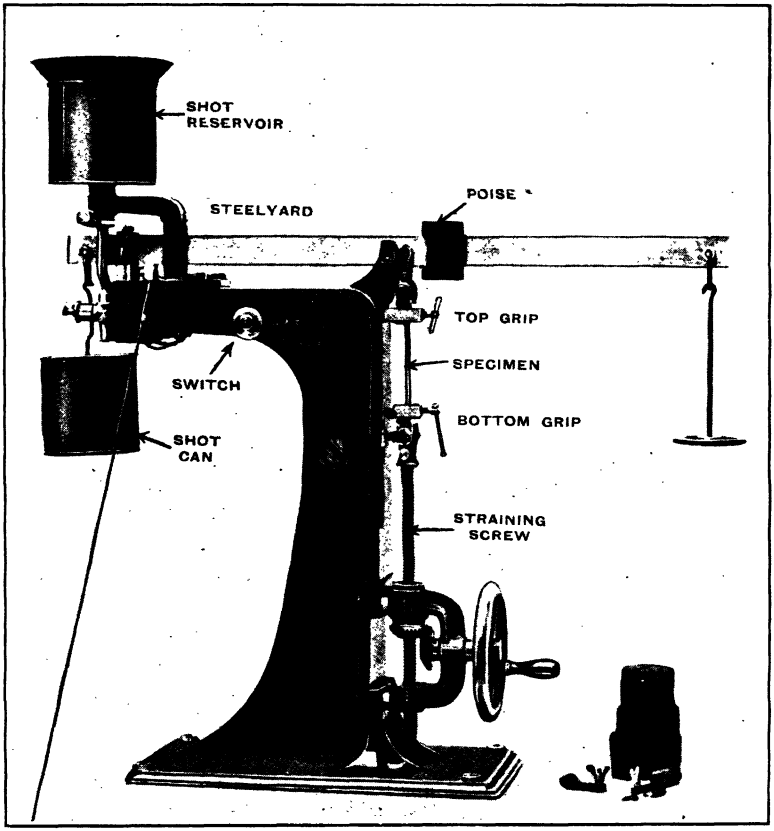


Fig. 210.—Fabric Testing Machine. Capacity 500 lbs.

The loading is usually specified in lbs. per inch width per minute, and the standard loading for linen fabric is 150 lbs. per inch per minute, so that a 2-inch specimen would be tested at 300 lbs. per minute. Cotton fabric is tested on the single-lever machine at 18 kg. (40 lbs.) per minute.

Some specifications state that the specimen is to be soaked for two hours, and excess water removed before placing in the jaws of the machine. This is to avoid the effect of changes which occur from day to day in the condition of the test pieces and of the atmosphere. Generally, however, soaking for

15 minutes gives the same results as soaking for 2 hours, viz. an increase of strength varying from 20 to 40 per cent. according to the kind of fabric.

Narrow specimens show greater proportional strength than wider ones.

Increasing the width of specimens to 2 and 3 inches gives results 4 per cent., and up to 13 per cent. less, respectively, than are obtained on a 1-inch specimen.

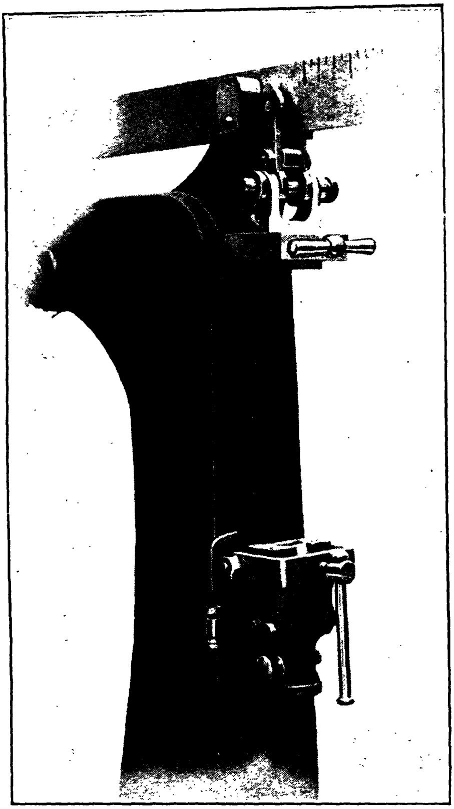


FIG. 211.—Special Handle-operated Grips for Fabric Testing Machine.

The effect of length is comparatively small, a slight increase of strength for the shorter lengths being due to the fact that there is less liability of finding a weak place in a short length than there is in a longer one.

The rate of loading, when increased from 150 to 450 lbs. per minute, gives an increase in strength of about 6 per cent.

Experiments made upon different samples of the same material, showed a variation of 7 to 10 per cent. for good quality fabric, and up to 20 per cent. for poor quality material.

The most prevalent cause of inaccuracy is a slight slip of the fabric in one side of the grips, causing it to give way on the tight side by tearing. It is advisable, when fixing the specimen in the grips, to leave the latter slightly slack, and then to pull taut with the straining screw until the fabric begins to slip, after which the grips may be tightened up. In this way an even pull on the fabric will be ensured as far as possible.

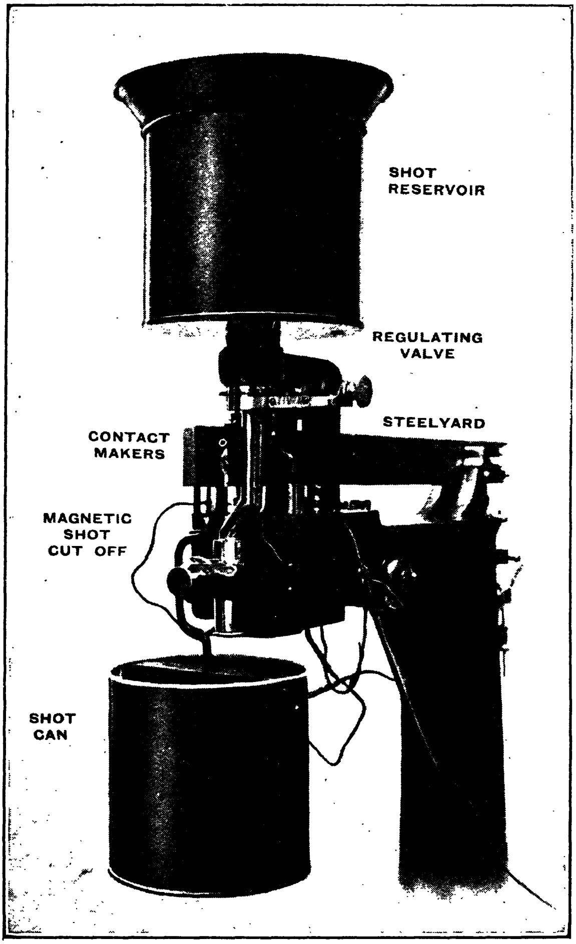


Fig. 212.—Electric Control Gear for Fabric Testing Machine, showing valve for regulating supply of shot.

The "Avery" machines shown above all depend for their operation upon the rate of loading given by a flow of shot, but those of the "Goodbrand" type are operated by a constant speed of the straining screw, the load being measured by a pendulum, and indicated on a dial. The standard speed

(18 inches per minute) of this machine, as compared with a rate of loading of 150 lbs. per inch per minute on the " Avery " machines, gives results 5 to 9 per cent. higher than the latter. This is due to the fact that the load is applied at a greater rate in the " Goodbrand " machine when run at the speed given above than in the " Avery " machines.

Users of fabric-testing machines should always be careful to see that the two grips are properly in alignment, as any twist in the test piece will adversely affect the result.

Balloon fabrics are also tested for resistance to bursting pressure. One method employed is to clamp the specimens between two iron rings, and to employ air pressure direct from a bottle or from an air pump, the pressure being gradually increased in intensity until the fabric gives way. The limiting pressure is naturally dependent on the size of ring used. Gas tightness may be measured by a similar apparatus, measuring the quantity of gas which passes through the fabric disc under a given difference of pressure. Thermal transparency may be measured by stretching samples of the material across an opaque cylindrical vessel, with the source of heat on one side and a thermo couple on the other. The amount of radiant heat passing through the fabric may be measured by means of the thermo couple. The source of heat, and the couple must be placed at the same distance on opposite sides of the fabric in each experiment.*

Tyre fabrics are tested in tension in a similar manner to that already described for aeroplane fabrics, but these are much tougher and stronger, requiring the larger size of machine to break the samples. As these fabrics are coarser than those already described, samples of greater width than those used in aero work are advisable.

A further important application of fabric is in connection with clutch and brake surfaces for motor vehicles. Bonded asbestos, as used in " Ferodo " and other fabrics, has a very high frictional resistance, and is capable of resisting the temperatures generated by friction.

A series of tests on " Ferodo " gave the following results :—

	Tensile strength.	Elongation per cent. at 200, 400, 600 and 800 lbs. per in. width.			
	Lbs. per sq. in.	200 lbs.	400 lbs.	600 lbs.	800 lbs.
Ferodo bonded asbestos	4,058	0·45	0·84	1·29	1·81
Ferodo fibre	4,039	0·44	1·05	1·68	2·39

At a pressure of 60 lbs. per square inch, and a speed of 1,000 feet per minute, Ferodo fibre absorbed 39,000 ft.-lbs. per square inch, and bonded asbestos absorbed 18,000 ft.-lbs. per square inch.

Over a range of 20 to 176 lbs. per square inch, and speeds of 600 to 5,600 feet per minute, it was found that the coefficient of friction was 0·30 to 0·32 for Ferodo bonded asbestos.

---

* Considerations of space make it impossible to enter fully into the description of airship and balloon fabrics, but interested readers are referred to a paper by Mr. J. W. W. Dyer, " Airship Fabrics " (*Aeronautical Journal*, July, 1921). In this paper the properties and testing of airship fabrics are fully dealt with.

The following table gives the energy absorbed by dry and lubricated bonded asbestos under different conditions :—

Pressure.	Speed.		
lbs. per sq. in.	600 ft. per min.	2,900 ft. per min.	
142	—	133,000 ft.-lbs.	Dry
173	34,000 ft.-lbs.	—	
291	14,000 ft.-lbs.	92,000 ft.-lbs.	Lubricated

The coefficient of friction of Ferodo fibre for pressures from 16 to 39 lbs. per square inch, and speeds from 600 to 5,500 feet per minute was 0·73 to 0·56.

The following table gives the energy absorbed by Ferodo fibre in the dry and lubricated states :—

Pressure.	Speed.			
lbs. per sq. in.	600 ft. per min.	2,900 ft. per min.	5,500 ft. per min.	
27	—	—	80,000 ft.-lbs.	Dry
29	12,000 ft.-lbs.	—	—	
39	—	72,000 ft.-lbs.	—	
160	10,000 ft.-lbs.	70,000 ft.-lbs.	—	Lubricated

The coefficient of static friction for bonded asbestos was 0·33 and for fibre 0·43.

It was found that the best results were obtained when the fabric had worn to a black polished surface. The general effect of increase in temperature is to raise the coefficient of friction, and this also follows upon an increase of pressure and speed.

Cement

The testing of Portland cement does not strictly come within the scope of this work, but as mechanical engineers have frequently to deal with this material, a few notes on cement are included for the sake of completeness.

Full instructions for examining and testing Portland cement will be found in the Engineering Standards Specification.*

The qualities to be observed are fineness, specific gravity, tensile strength, setting time, and soundness.

The cement is first passed through a sieve containing 76 meshes to the inch, and the residue should be not more than 3 per cent. of the total weight. It is then passed through a 180-mesh sieve, and should not leave more than 18 per cent. residue. The gauze generally used is made of copper, to avoid corrosion of the wire.

The specific gravity of cement, when freshly burnt and ground, should be not less than 3·15, and when more than one month old, should be at least 3·10. This property is tested by means of a specific gravity bottle.

---

* Engineering Standards Committee, 28, Victoria Street, London, S.W.1. For American practice *see* Specification issued by the American Society for Testing Materials, adopted August 16, 1909.

The tensile strength of the cement, both neat and mixed with sand, is determined by means of the machine shown in Fig. 213.

The cement is mixed with fresh water and placed in a briquette mould of standard form, so that the breaking section is one inch square. The briquette is so designed that it can easily be held in the jaws of the testing machine, without undue local crushing, and will align itself to some extent to prevent bending stresses while the test is in progress. The cement must be put into the mould, without ramming, and must be kept in a damp state for 24 hours. It must then be kept in a bath of fresh water at about 60° F. until ready for testing.

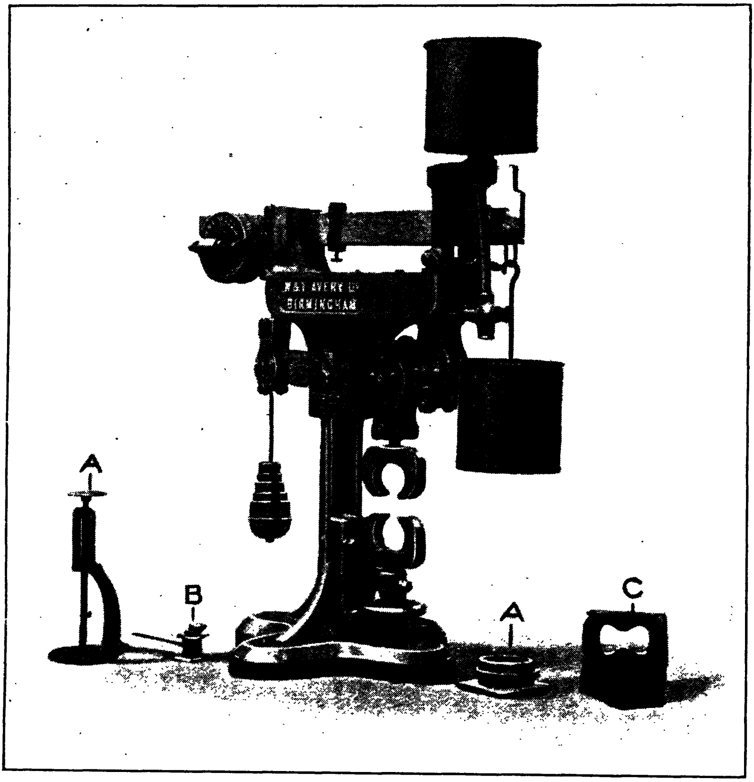


Fig. 213.—Cement Testing Machine. A, Vicat needle and mould; B, Le Chatelier gauge; C, briquette mould. Capacity: 1,200–1,500 lbs.

The cement testing machine shown in Fig. 213 has specially shaped grips to take the standard specimens, but the shoulders of the latter should be slightly greased to allow the briquette to pull easily into line, when the preliminary tightening up is done. Care must also be taken, to see that the specimen is in the vertical position so that the load will be evenly distributed over the section.

The load is applied by means of lead shot flowing from the can mounted on top of the machine to another can suspended from the end of the steelyard. It is transmitted through levers to the specimen, the total capacity of the machine being 1,200 lbs. The standard rate of loading is 500 lbs. per minute, and the flow of shot is adjusted to this by means of a screw check in the automatic cut-off valve. The latter stops the flow of shot instantly when the specimen breaks.

The breaking load is then measured by transferring the shot can to the other side of the steelyard, and using the latter as an ordinary weighing machine.

The steelyard and special proportional weights are calibrated to indicate the breaking strength of the cement in lbs. per square inch. Seven days after gauging, neat cement should give a tensile strength of not less than 400 lbs. per square inch, but strengths considerably higher than this have been obtained.

A mixture of 3 parts cement to 1 part Leighton Buzzard sand should give a strength of not less than 150 lbs. per square inch, 7 days after gauging.

The following tests, made at various periods after gauging, show the increase of strength with age in the case of neat cement, and cement and sand mixtures.

Neat Cement

1 day.	7 days.	14 days.	28 days.	6 months.
Av. 204 lbs.	462 lbs.	485 lbs.	553 lbs.	754 lbs.

Mixture of One Part Cement, Three Parts Sand

7 days.	14 days	28 days	6 months	—
Av. 116 lbs.	125 lbs.	163 lbs.	268 lbs.	—

Setting time is tested by means of the Vicat needle. This is a steel rod 1 mm. square with a flat end, weighted to 300 grammes, and sliding freely vertically. The cement is deemed to be set when the needle makes no perceptible impression on its surface, and the standard times of setting are as follows :—

Quick setting	10 to 30 minutes
Medium	30 ,, 120 ,,
Slow	120 ,, 300 ,,

Soundness is tested by putting the cement into a Le Chatelier gauge. This is a circular mould, 30 mm. diameter, split at one side, and carrying two long gauge points.

The two ends of these gauge points are 165 mm. from the centre of the mould, and the distance between them is measured after immersion in a bath of water at 60° for 24 hours, and again after boiling for 6 hours.

The distance between the points must not have increased more than 10 mm. after 24 hours' aeration, or 5 mm. after 7 days' aeration.

Compression tests are generally made on cubes of about 3 inches square.* In this case care must be taken to bed the specimen truly on the compression platens, as otherwise the corners are apt to crush locally. The bedding is done by means of plaster of paris or other quick-setting material, and the load

---

* Sometimes also on cylindrical specimens.

must then be applied slowly and evenly until crushing occurs. Cement and concrete usually fail by shearing at an angle of 45°, producing two pyramids in the case of a cubical test piece, or two cones when a cylindrical test piece is used.

It should be observed that both tensile and compression test results on cement are very variable, as they are affected by numerous details in the preparation and testing of the specimens, and also by variations in the raw materials.* Too much reliance should not, therefore, be placed upon the results of single and isolated tests, but wherever possible a series of tests should be made.

---

* A full discussion, with test results, on the influence of various factors on the tensile strength of cement and cement mixtures, will be found in "Materials of Construction," by A. P. Mills (Wiley & Co.), and other standard works.

CHAPTER XIX

EXAMPLES OF PRACTICAL APPLICATION

Sheet Steel.—Sheet steel is now used to a large extent for making light pressings, which are subsequently welded or brazed together to form important sockets and junction pieces on aeroplanes.

The sheets arrive at the works in bundles, and must be carefully inspected for visible defects such as scale, corrosion, blisters, or lamination before the physical tests are made. Variation in thickness must also be eliminated by gauging each sheet, as if sheets are above or below standard thickness they are likely to give trouble in the dies when being pressed into form. Limits are usually given in the specification. Tensile tests should be taken both in the direction of rolling and also crossways, and if these are satisfactory, a bend test should be made to reveal any brittleness or tendency to fracture. The close bend test is made by turning over a corner of the sheet, the radius of the inside of the bend being $\frac{1}{2}t$ for mild steel sheets, and $1\frac{1}{2}t$ for alloy steel sheets (hardened and tempered). Here t = thickness of sheet.

On mild steels, a reverse bend test is often made by taking a narrow strip (say $1\frac{1}{2}$ inches wide) with smooth edges, and bending over a radius of $3t$ through 90 deg., and then backwards and forwards through 180 deg. until the specimen shows signs of fracture. Mild steel sheets should stand 3 such reversals, but frequently 7, 10, and 15 are recorded before signs of cracking appear. It is necessary that the sides should be filed smooth before this test is taken, as cracks are liable to start from rough edges at a very early stage. A good deal of trouble has been experienced with brazed brackets owing to cracks which appear after liquid brazing. This was at first attributed to defects in the material, but it was subsequently found that they were due to insufficient care being taken in the brazing operation. The trouble was particularly marked on brackets where two flat surfaces were brazed together. In this work, care must be taken to keep the brazing bath at a reasonably low temperature, as otherwise the sheet is liable to be overheated. On the other hand, if the temperature is only just over the melting point of the brass, the bath will not be sufficiently fluid for the metal to fill the narrow space between the two surfaces. Cracks may also be caused by the edges of pressings not being properly dressed after shearing.

Care must also be taken when spot welding brackets of this kind. If this is not done carefully, cracks are liable to appear owing to the expansion of the different plates comprising the bracket, when placed in the brazing bath.

All welding is risky on sheet steel pressings for aero work, as there is a great liability of burning the plate, and also of oxide being left in the track of the weld. Welds are frequently unsound, and there is no means of determining their soundness in practice. All welds should be normalised before use.

Special sheet steels are made to resist the passage of a bullet. This is necessary for steel helmets, armoured car turrets, etc. Obviously, the only satisfactory test for these is a firing test from distances depending on the gauge of the steel. This may be supplemented in the case of thick steels by a Brinell test. This does not always indicate the resistance of the steel to the passage of a bullet, but shows whether or not the heat treatment has been properly performed. The Brinell impression on armoured car steel is usually about 2·8 mm. diameter with a load of 3,000 kg. A scratch hardness test was tried on steel helmets, but gave no indication of the bullet resisting power of the helmets.

When steels are used for press work, it is advisable to add a dishing test with a hemispherical or other tool to prove the drawing powers of the material.

This property is indicated to some extent by the Erichsen test, which is applied by bulging out the centre of the flat sheet with a hemispherical tool, and measuring the height of bulge produced before fracture. The first appearance of a fracture is observed by means of a mirror placed at a convenient angle, and the height of bulge is measured by a micrometer attachment as the load is applied.

When this test is applied, the appearance of the "bulge" often gives a valuable indication of defects in the material.

If the domed surface does not retain an appearance similar to the original sheet, a rough surface indicates an open and coarse structure liable to give trouble in drawing or pressing operations. This structure may be caused by excessive or incorrect annealing.

In copper or brass sheets the bulge may have a coarse-grained appearance. This, in copper, is often due to the influence of reducing gases in the furnace, and in brass to the effect of too sharp pickling.

The formation and position of the fracture is also a useful guide in many cases. Fibrous sheets are indicated by the fact that the fractures in the different impressions all run in the same direction. In good homogeneous material (particularly in copper and aluminium) the fracture generally runs round the bulge.

A consignment of tinned sheet (20 gauge) gave trouble in the presses and was tested by the Erichsen test. This showed an average height of bulge of 6·3 millimetres in six tests.

A sample was then taken from a consignment of sheet that had given satisfactory results in the presses, and this gave an average test of 8·99 millimetres, showing that the drawing quality of this material was much better than that of the previous sample.

Average values obtained on different samples of materials used in commercial practice were as follows :—

Material.	Maker.	Gauge.	Thickness. ins.	Bulge (mm.).	Average.
Steel Sheet, Cold Rolled, Close Annealed (C.R.C.A.), for press work	A	22	0·029	9·08– 9·48	9·28
	B	22	0·029	7·0 – 8·38	7·84
	B	22	0·027	7 2 – 8·42	7·90
	C	22	0·027	7·90– 8·70	8·29
	B	20	0·039	8·35– 9·50	9·0
—	B	20	0·037	7·85– 9·70	8·56
—	A	20	0·034	8·85– 9·25	9·0
—	D	16	0·065	8·45– 8·98	8·66
—	D	16	0·067	9·06–10·10	9·48
—	E	14	0·089	9·40–10·56	10·16
—	E	14	0·090	10·55–11·10	10·83
—	F	16	0·057	10·06–10·48	10·27
—	G	16	0·069	10·17–11·25	10 74
—	H	12	0·100	11·60–11·72	11·68
—	K	—	0·123	6·92– 8·44	7·67
Brass	—	17	0·050	6·65– 6·85	6·78
Copper ..	—	20	0·037	10·98–11·70	11·33
Aluminium ..	—	17	0·050	8·76– 8·90	8 80
Duralumin ..	—	16	0·064	6·86– 7·90	7·42
” ..	—	22	0·028	7·20– 8·20	7·67
Aluminium ..	—	16	0·067	9·1 –10·25	9 83
Copper ..	—	—	0·011	5·5 – 6·91	6·30

The following figures are given by the makers of the Erichsen testing machine as standards for trade qualities of sheet metal (soft), and are given as a general indication of the results that may be expected from these materials.

Gauge .. .. Thickness (in.)	16 0·064	17 0·056	18 0·048	19 0·040	20 0·036	22 0·028	24 0·022	26 0·018	28 0·014	30 0·012
Brass stamping sheets ..	14·6	14·5	14·4	14·25	14·2	14·0	13·8	13·6	13·4	13 2
Yellow metal	13·65	13·4	13·2	12·9	12·75	12·45	12·15	11·9	11·5	11·3
Copper	12·6	12·35	12·1	11·8	11·65	11·3	10·95	10·65	10·35	10·1
Polished hoop iron	12·1	11·8	11·4	11·05	10·85	10·4	10·0	9·7	9·3	9·1
S.M. iron draw sheets ..	11·4	11·0	10·55	10·1	9·8	9·25	8·8	8·4	8·0	7·8
Pickled stamping and folding sheets	11·3	10·85	10·4	9·9	9·65	9·1	8·6	8·2	7·8	7·5
Aluminium	11·1	10·75	10·35	10·0	9·75	9·4	9·1	8·85	8·5	8·2
Ordinary folding sheets and tinned sheets (1st class) ..	10·9	10·5	10·0	9·5	9·25	8·7	8·2	7·8	7·3	7·0
Tinned sheets (2nd class) ..	—	—	—	8·6	8·3	7·75	7·3	6·95	6·5	6·3
Zinc	8·5	8·45	8·3	8·1	8·0	7·6	7·1	6·75	6·3	6·0

The manufacture of brackets and clips for aero work is apt to cause considerable cold work to be put on the steel, when the parts are made by hand. If the angle of bend is carried a little too far, the material has to be bent back again, and this reverse bending causes local weakness in the material. To prevent this, high tensile steels should always be bent in a machine or jig, so that the required angle of bend cannot be exceeded.

Tubes.—The great stiffness and rigidity of steel tubing in proportion to its weight makes it of great utility in aeronautical work and all other classes of engineering design where lightness is important. Special stream line sections are now being drawn for the purpose of reducing wind resistance to a minimum, and very thin sections are produced solely for aeroplane construction. As these tubular members are subjected to suddenly applied stresses of unknown magnitude (particularly in the case of the landing gear), it is essential that all tubing received for aeronautical work shall be carefully inspected and tested before being allowed to proceed to the shops.

The best plan is to put each consignment of steel tubing into a bonded store, and to keep it there as a separate batch until every tube has been carefully looked over by viewers skilled in this class of work, and until tests have been taken to ensure the material being up to the specified standard.

The visible defects to be looked for are roughness, variable section, scale, dirt, specks, seams, lamination, grooves and blistering. The tubes should also be straight when received.

The tubes may be examined easily and quickly for straightness by providing the tube viewer with a cast-iron table or plate, the upper surface of which has been planed flat. In rolling each tube across the surface for examination, any kink or curvature is immediately revealed.

Round tubes can be made to an accuracy of 0·004 inch, and if such limits are called for, the viewer must be provided with a limit gauge set to the limits imposed. This is particularly necessary in some classes of work, where the tube has to fit inside a socket, or slide over a sleeve without undue clearance.

It will frequently be found that the tubes are slightly oval, and in such cases, acceptance or rejection is a matter for individual consideration. In some instances the bore is not concentric with the outside ; the wall varying in thickness.

Another prevalent trouble is longitudinal seams in the tubes. These are detected by polishing up the end of each tube, when the seams will appear black. This should be done with discrimination, however, as draw marks from the dies often appear very much like seams. In cases of doubt, a small piece should be cut off the end of the tube and examined under a low-power microscope. The authors have in mind several instances where steel tubes have been refused by the shops as being welded, but microscopic examination showed no trace of a weld.

When dispatched from the makers, the tubes should be coated with an oil free from acid, to prevent rusting or corrosion. With very thin sections the presence of rust seriously affects the strength of the tube.

Carbon steel tubes are tested in tension (Fig. 214), but the more important tests are crushing and flattening.

For the crushing test, a piece of the tube 1½ diameters long is taken and compressed in a testing machine or press until the diameter has been increased by 25 per cent., or until one complete fold has been formed. Pieces of tube tested in this way are shown in Fig. 215. Any seams or flaws usually open out during this test.

The ends of the tubes and other parts suspected of being defective, are flattened out with a few blows until the sides are not more than three thicknesses apart. Seams or defects show up best when in the middle of the *flat* sides. This is contrary to what might be expected. Dead soft tubes must flatten completely without cracking.

Nickel chrome steel axles are tested by a bending proof load applied by a lever. The load is applied in two parts, the first being about $\frac{1}{3}$ of the total load. After the proof load is removed the permanent set should be not more than $\frac{1}{8}$ inch.

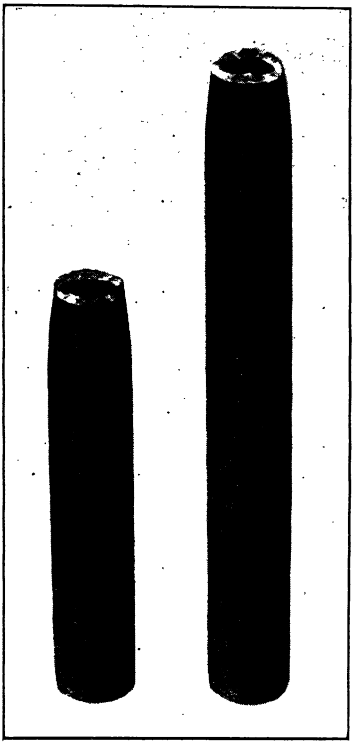


FIG. 214.—Tensile Test on 3-inch Diameter Steel Tube. Breaking load 98·4 tons.

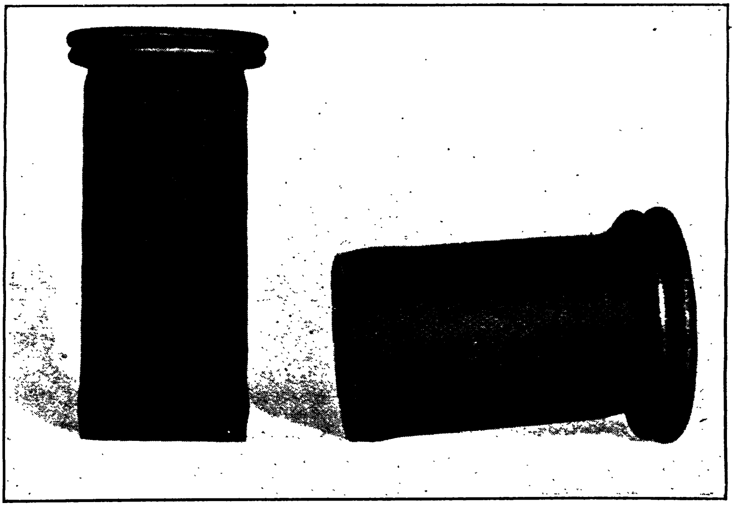


FIG. 215.—Steel Tubes tested in Compression.

Aluminium, nickel brass, and phosphor bronze tubes must crush to half the original length of the test pieces. No compression or flattening tests are usually made on duralumin.

Brass, nickel brass, copper, and phosphor bronze tubes are tested by drifting out the ends until the diameter is increased by 25 per cent.

Copper and phosphor bronze tubes must flatten and double over without cracking, but nickel brass is only flattened until its diameter is reduced by 33 per cent.

Seamless copper tubes for oil, petrol, etc., are tested hydraulically to 100 lbs. per square inch. If used for compressed air, oxygen, or interrupter gear, the test pressure is about 5,000 lbs. per square inch. When used for high pressures, it is important that copper tubing is not made from tubes used previously, that no copper is used without remelting, and that the ingot from which the tubes are drawn is clean and sound.

Tubes made by the electro deposition process are unsuitable for this class of work.

Very small tubes must be specially tested to prove that the bores are open along the entire length of the tubes, and are not blocked up in any way. This can be conveniently done by means of an air or steam jet.

For water-tube boilers best quality steel tubing is used, as copper, although superior in heat conductivity and resistance to corrosion, is not so reliable and strong. Galvanising is useful for boilers liable to be out of use for long periods, but is of doubtful utility under any other conditions.

It has the advantage, however, that the preliminary pickling reveals faults that otherwise might be overlooked.

In the case of tubes or rods liable to season cracking, the following test gives a quick method of determining the likelihood of such cracking taking place. A short length of the tube or rod is immersed in a 1 per cent. solution of mercurous nitrate (in water), the specimen being previously pickled in nitric acid. If the specimen is susceptible to season cracking, cracks will then develop within about 30 minutes.

Toothed Gears.—In fast-running mechanisms such as motor cars or aeroplane engines, where weight must be cut down to a minimum, considerable trouble is likely to be experienced with gear wheels, unless these are very carefully designed and manufactured.

The teeth of such wheels are generally designed for strength in bending, but they are also subjected to abrasion, shock, and bearing pressure. If the teeth on case-hardened gears are not properly bedded, the latter alone is sometimes sufficient to break down the case piecemeal, causing considerable pitting on the teeth and ultimate failure of the gear.

In addition to this, the wheel centre is subjected to continual torsion (shear), and occasionally also to shock. The centre of the wheel, therefore, should be comparatively soft, to store energy, while the outside surface of the teeth must be as hard as possible to resist wear.

This immediately raises the question whether case-hardening or alloy oil-hardening steels are best for gears of this description. The answer must obviously depend very largely upon the design of the gear and the work to be done, but case-hardening steels best meet the above conditions, as they give a hard surface and a soft core.

Case-hardening, however, is usually a somewhat costly process, as, when machining has to be done on the gear after hardening (and this is usually the case) extra machining operations must be put on to machine off the carbon from all parts required to be soft. Even then, many difficulties are frequently experienced with hard cores when high-tensile alloy case-hardening steels are used, or when meagre amounts of material are left on for removal between the operations of carburising and "dipping off." Although the case may have been machined off, there is a layer of material immediately below it that is considerably harder than the core proper, and unless this is also removed trouble will be experienced in the final machining. In work where the case is about 1 mm. thick, it is advisable to machine off about $\frac{1}{8}$ inch or more to obtain a soft surface.

Distortion can often be prevented to a large extent in case-hardened gears, by leaving the solid web or inside of the rim very thick, and turning off the extra material at a subsequent operation.

There are also other troubles such as soft patches on the surface, case low in carbon (and therefore soft), surface decarburisation, and scale, to which oil-hardened gears are not liable.

Both kinds of steel are subject to distortion in hardening, and in this respect oil-hardened gears are better than case-hardened ones, as they are not so liable to crack in straightening. Also, if the case is "sharp," it sometimes chips off the teeth when the gear is running, and if these hard chips get in the gears or bearings, they cause considerable trouble and loss.

Silent running depends on the nature of the steel used, and in this respect oil-hardened gears are superior to case-hardened ones, as the former have the greater resilience.

Noise is largely due to inequalities in the rolling surfaces, as in the case of a cart wheel rolling over a rough road. As the surface of a case-hardened gear is of a comparatively unyielding nature, the inequalities are not so elastic as they are in an oil-hardened gear.

In the design of motor car gear boxes, case-hardened gears are preferable for wheels that are constantly in mesh, on account of their good wearing properties. For "clashing" gears, however, that have to be moved into and out of mesh, oil-hardened gears should be employed, as the case is liable to be damaged when the teeth are being engaged.

Generally, oil-hardened gears are preferred because of the cost of the case-hardening process. For small pinions in mesh with large gears, case-hardening steel is essential, on account of the large amount of wear that takes place on the small gear.

Experience has shown that air-hardened gears (on aero engines) are liable to pitting and disintegration, and that case-hardened gears are more suitable under these special conditions.*

Piston Rods.—The piston rods of steam hammers and other similar mechanisms are apt to break unexpectedly after a working life much shorter than that anticipated by the makers. This cannot always be attributed to the steel of which the rod is made, as the working conditions in the case of steam hammers are very variable and the amount of shock which such rods have to stand is unknown. If the steel under the hammer is being worked at

---

* "The Use and Abuse of Steel," by Bagnall-Wild and Birch, read before Institution of Automobile Engineers, March, 1917.

a high temperature, it is very plastic and deadens the shock considerably, whereas if it is nearly cold the effect on the rod is almost as bad as when striking a rigid object. When this is taken into consideration, it is obvious that the effective life of a piston rod cannot be stated as a certain number of blows, unless the conditions of such blows are accurately known. The plasticity of the hot steel and the truth of the blow are never constant, and therefore such a statement has no meaning in practice. Dr. Hatfield * recommends an alloy steel of 50 to 55 tons per square inch for this purpose, and such a steel, suitably heat treated, should give an Izod impact test of at least 45 to 50 ft.-lbs. Some users state that the life of piston rods in cold weather is prolonged by allowing a period of heating up before using when the hammer has been standing for a day or two.

Pistons.—Engine pistons are usually made in one of three materials—cast-iron, steel, or aluminium alloy. Of these, the best for running and wear is cast-iron, as the friction between the cylinder and piston is smaller, and seizure is less likely when the piston is made in this material. All pistons of small size were originally made in cast-iron, but with the advent of large cylinders a lighter and stronger material became necessary, and consequently steel pistons were adopted. The latter are still used to a very large extent in marine work and in large stationary engines.

The increasing use of small, fast-running engines made the reduction of reciprocating weights necessary in the case of small pistons, and therefore aluminium alloys were largely adopted for aero-engine and automobile work. These are usually made in the form of die castings, and their superior heat-conductivity and lightness make them very suitable for this purpose.

The tops of the pistons used in internal combustion engines are frequently exposed to very high temperatures (Dr. Hatfield † refers to the case of a piston whose head had been above the carbon change point—730° C.), but such temperatures are of very short duration. High conductivity reduces the temperature fluctuations and liability of distortion, and in this respect the aluminium alloy piston has a great advantage. Its lightness also diminishes the inertia stresses, which are very serious in high-speed engines.

The materials used in pistons are also referred to in Chapters XIV and XV.

Valves for Internal Combustion Engines.—One of the principal causes of trouble in internal combustion engines is the failure of the valves. These failures are fully described in a paper read by Dr. Aitchison,‡ which may be summarised briefly as follows :—

The valves in petrol engines work at temperatures considerably above the normal. The temperature of inlet valves varies from about 100° C. to 600° C. and that of exhaust valves from about 250° C. to 860° C. These temperatures vary very considerably with different designs, as the cooling conditions are varied in each case. Rotary engines are usually the coolest and air-cooled stationary engines the hottest of the different types.

---

* "Mechanical Properties of Steel," by W. H. Hatfield, D.Sc., *Proc. Institute Mechanical Engineers*, May, 1919.

† "Steels used in Aero Work," *Royal Aeronautical Journal*, September, 1917.

‡ "Valve Failures and Valve Steels in Internal Combustion Engines," by Leslie Aitchison, D.Met., etc., Institution of Automobile Engineers, November 5, 1919.

By far the greatest proportion of the heat is conducted away from the head through the face of the valve, and any inaccuracy in the seating or distortion of the valve at high temperatures will greatly affect the temperature attained by the head of the valve and will be a contributary cause of failure.

Types of failure may be classified as follows :—

1. Elongation of stem of the valve.
2. Distortion of valve head.
3. Cracks in the valve face.
4. Excessive wear of valve stem.
5. Excessive wear of valve foot.
6. Burning out of head.
7. Scaling of valve.
8. Breaking of head or neck due to self-hardening.

Many of these may be avoided by suitable mechanical design, but the material used for making the valve has a very decided influence on its life under the strenuous conditions imposed upon internal combustion engine valves.

As the weight must be reduced as much as possible, strength is an important item, and therefore such valves are usually made of alloy steel.

The following is a list of the properties that should be possessed by a good valve steel :—

1 The greatest possible strength at high temperatures.
2. The greatest possible impact strength.
3. The capacity of being forged easily.
4. The capacity of being manufactured free from cracks, whether in the original bar or the finished forging.
5. The capacity of being heat treated easily and uniformly.
6. The least possible tendency to scale, or if scale does occur, it should be as adherent as possible.
7. The ability of retaining its original physical properties after frequent heatings and coolings, also after being heated to an elevated temperature for a considerable length of time.
8. No liability to harden after cooling in air from working temperature of valve.
9. Capacity of being heat treated after forging so that it will be free from strains liable to produce subsequent distortion.
10. Sufficient hardness to withstand excessive wear in the stem.
11. Capacity of being hardened at the foot of the stem with considerable ease (if necessary).
12. Capacity of being machined easily after heat treatment.

The steels that have been employed and are probably still used for these valves are divisible into the following classes :—

1. Tungsten steels from 10 to 18 per cent. tungsten and 0·2 to 0·7 per cent. carbon.
2. Chromium steels from 7 to 14 per cent. chromium, and 0·25 to 1·0 per cent. carbon, with varying proportions of silicon, nickel, and cobalt.
3. 25-per cent. nickel steel.

4. Steels with 3 to 5 per cent. nickel, 0 to 1·5 per cent. chromium, and 0·15 to 0·65 per cent. carbon.
5. Ordinary plain carbon steels.

Steels of the same type have very similar properties, but the different types vary considerably from one another in the above properties. Variations in composition in any type, however, have a distinct effect on the mechanical properties at high temperatures. This is particularly true of the high tungsten and high chromium steels, which are very susceptible to variations in carbon content.

Tungsten steels with high percentages of carbon (0·6 per cent.) have the greatest tensile strength at high temperatures, and are followed in this respect by the high chromium steels with high carbon content. Stainless steels (high chromium and low carbon) are distinctly weaker, and plain nickel and nickel chrome steels are quite weak at high temperatures. The influence of vanadium on tungsten steels appears to be negligible, and the inclusion of cobalt does not appear to influence the properties of valve steels.

High chromium steels are best for non-scaling properties, and are followed in this respect by the " stainless " steels. Nickel chrome steels scale more than any others, and tungsten steels scale very little up to 850° C., but are considerably worse beyond this temperature.

The impact value roughly follows the tensile strength (inversely), high carbon steels being very much worse than low carbon steels in this respect. The impact value rises very considerably at high temperatures, as might be expected. Curves and tables giving the actual results obtained are included in the original paper.

Laminated Springs.—With the increased use of heavy road vehicles, and the deterioration of the roads due to increased wear and lack of repair, the question of springing is becoming more and more important, and greater care is being taken in the manufacture and inspection of springs.

Laminated springs, such as are used for vehicle and rolling stock suspensions, are generally made out of acid open-hearth steel containing 0·5 to 0·8 per cent. carbon, but if the springs are so designed that the eyes have to be welded, the carbon should range from 0·45 to 0·7 per cent.

As the greatest bending moment on a plate spring is at the centre, the method of fastening the leaves together is important.

This is usually done by enveloping the leaves with a buckle and riveting through the centre. The holes through which the rivets have to pass are usually made by cold punching. It is probable that the internal stresses set up by this procedure are removed by the subsequent heat treatment, but in any case, these holes should be kept as small as possible, say $\frac{1}{16}$ inch less than the thickness of plate.

Where the eye at the end of the top plate is welded, the arrangement shown at A (Fig. 216) is better than that at B, as, in the former case, the back plate is supported up to the end by the second plate, and if it breaks the broken end would probably remain in place, being supported by the other plates. In the arrangement shown at B the load is carried by the weld, and the back plate cannot be supported up to the centre of the eye ; consequently there is a liability of the back plate taking a reflex curvature, and giving way in course of time.

When hardened, the springs have a liability to warp, and this tendency must be corrected by hand fitting.

Laminated springs are usually tested under a steam scrag, which compresses the springs to a fixed deflection, removes the load, and repeats the operation in quick succession for a given number of times.

After this repeated loading the camber must not be less than the amount specified for each spring. The scragging test is also made on the steel plate itself before being passed as suitable for making springs. The scragging test is best performed without the buckle, as otherwise there is sometimes a difficulty in detecting a fractured plate.

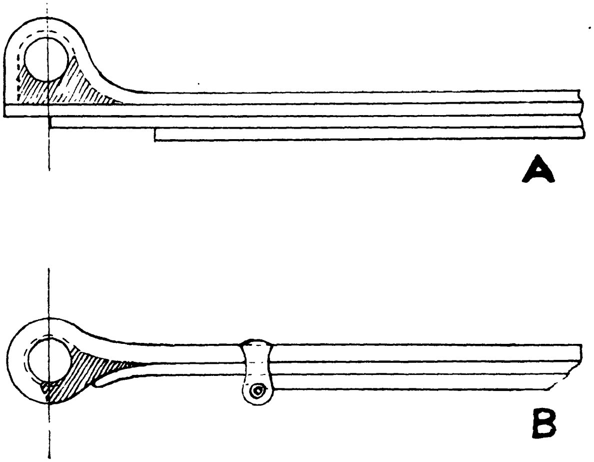


FIG. 216.—Eyes of Laminated Springs.

In addition to the scragging test, a proportion of the springs is also tested in compression with a measured load. A machine for making this test is shown in Fig. 217. The spring is placed with its two ends on the trolleys shown. These are mounted on wheels to allow the ends to move freely outwards when the load is applied by means of the screw gear shown. The latter is driven by belt or motor through a bevel or worm gearing and has adjustable stops, which switch off the drive when a given compression is reached. The load applied to the spring is then measured by the weighing machine, upon the platform of which the ends of the spring rest.

In view of the different conditions that have been adopted from time to time for making these tests, and the confusion that has arisen between manufacturers and users as a consequence of this, the American Society of Automotive Engineers has recommended the following standard procedure for making compression tests on laminated springs.

The pressure block at the end of the straining screw, or ram, should have a width equal to that of the spring seat. It should be cut away in the centre, at the under side, to receive the bolt, and should have the upper side rounded to rock against the lower face of the straining screw. This will allow the spring to adjust itself.

Full elliptic springs should be tested in the upright position, and quarter, half, and three-quarter elliptic, and cantilever springs in an inverted position.

The arrangements suggested for half and quarter elliptic and cantilever springs are shown in Fig 218.

The springs should be supported in such a way as to give full lateral movement on compression. The load should be applied gradually, and the height of the spring measured without rapping or otherwise disturbing the spring.

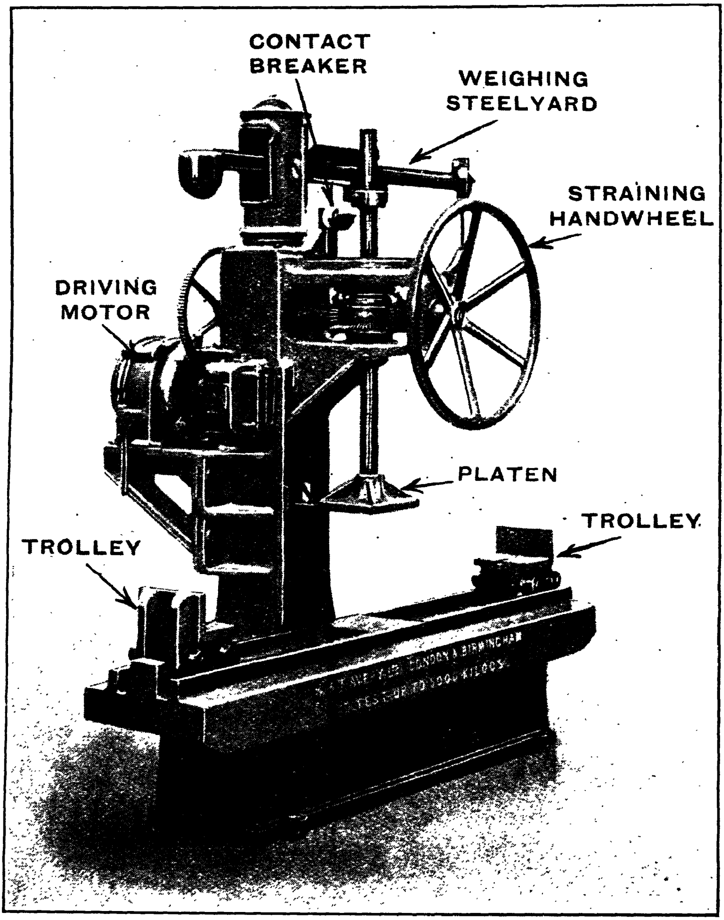
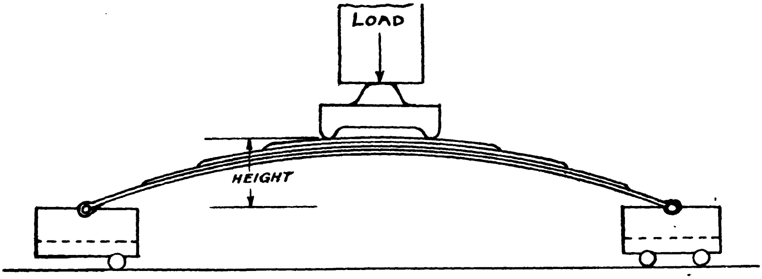


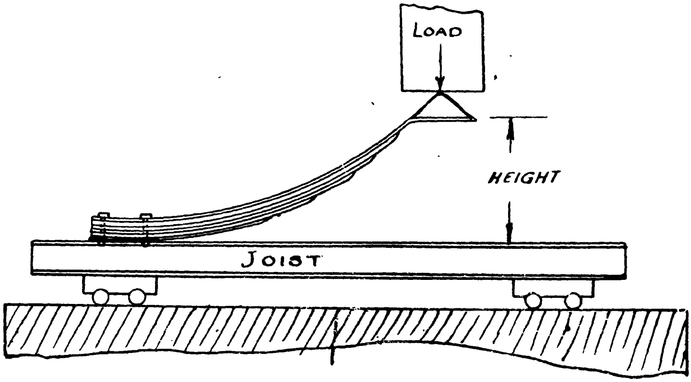
Fig. 217.—Testing Machine for Laminated and Coil Springs—motor driven. Capacity, 5 tons.

A suggested method of estimating the flexibility is to take the height at 75 and 125 per cent. of the full rated load and divide the difference between these two loadings by the difference in height. The result ("flexibility") is the average rate of the spring in pounds per inch of compression, and should not vary more than 5 per cent. up or down. It is not always possible to get the exact specified rate, owing to differences in the thickness and uniformity of the raw material.

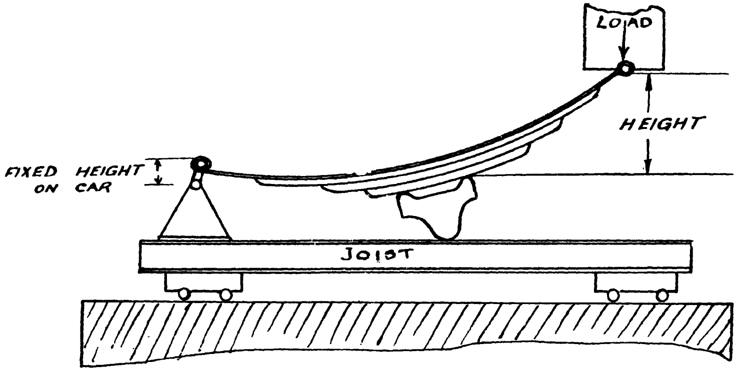
Any stamping, such as name, date, grade number, etc., should always be stamped on the compression side of the leaf, as any stamping on the tension side is equivalent to a nick or notch in the steel, and will produce early fracture. The less stamping there is on the spring, the more reliable the latter will be.



(1) Arrangement for Semi-Elliptic Springs.



(2) Arrangement for Quarter-Elliptic Springs.



(3) Arrangement for Cantilever Springs.

Fig. 218.—Bending Tests on Laminated Springs.

The identification symbol should never be stamped on the buckle or clip, as these are often broken or lost.

The amount of deflection under the steam scrag varies with different makers. Some manufacturers allow a deflection equal to twice the working deflection. Others work to the following formula, recommended by the British Standards Committee :—

$$D=\frac{L^2}{900t}$$

D = Deflection in inches.
L = Length of top plate when flat (inches).
t = Thickness of thickest plate (inches).

This specification is used for railway rolling stock. The buckles are made of steel of 24 to 30 tons per square inch tensile strength, with an elongation of 20 per cent. When made of iron, they should have a tensile strength of 20 to 24 tons, and an elongation of 20 per cent. The steel should also stand without fracture a cold bend test round a bar 1½ inches diameter, to an angle of 180°.

Coil Springs.—The steels generally used for making coil springs, have a carbon content of 0·8 to 1·0 per cent., not more than 0·3 per cent. silicon, and 0·6 to 0·8 per cent. manganese. Where alloy steels are used, the carbon does not usually exceed 0·5 per cent. The above steels have the following approximate physical properties :—

	Elastic Limit.	Ultimate Strength.	Elongation.	Reduction of Area.
As rolled ..	30 tons per sq. in.	46 tons per sq. in.	17 per cent.	42 per cent.
Hardened and tempered ..	75 ,, ,,	81 ,, ,,	4 ,,	12 ,,

The modulus of such steels is about 13,500 tons per square inch, whether in the hardened state or as rolled.

In the case of laminated springs, the range and load are limited by the tensile strength of the steel, but the range and load of coil springs are dependent on the maximum shear stress.

A steel having an elastic limit (as rolled) of 59 tons per square inch in tension, has a torsional elastic limit of 43 tons per square inch, and a maximum shear stress of 70 tons per square inch, with a torsion modulus of 5,000 tons per square inch.

After coiling, the springs are hardened in whale oil, and tempered in molten lead. The temperature of the oil should not exceed 40° C. at any time. If a large percentage of the springs subsequently break on "closing," it is an indication that the oil in the hardening bath needs renewing.

After hardening the springs are scragged, in some cases being given 100 blows over the whole range. This is probably unnecessary, as a few smart blows will reveal any latent defect in the material as effectively as such severe handling, and the spring is made no safer by the latter means. Its life is also shortened to a certain extent by long and continued scragging. The British Standard Specification stipulate five blows under a stream scrag for coil springs, and this is ample for most purposes.

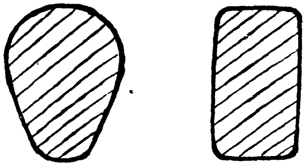
The "proof" stress, or maximum fibre stress produced during the scragging test, usually works out at about 60 tons per square inch, but different authorities vary considerably as to the safe stress applicable for springs. The figure here given (60 tons) is on the low side when compared with existing designs, but is a fairly safe limit for general adoption.

A higher proof stress can be used on small than on large springs, as a heavy section cools much more slowly in the quenching bath, and therefore the material is not so strong or homogeneous as that in the smaller sections.

In the case of volute springs, the inner coils are protected from the action of the quenching bath by the large outer coils, and consequently it is necessary to adopt a lower safe stress in these springs than in helical springs.

The working stress is usually about one-half to two-thirds of the proof stress, the actual ratio depending on the material and the functions of the design.

The sections of material used for making coil springs are usually rectangular or circular. The latter should be used wherever possible. It is evident that if the section is to be rectangular after coiling, it will not be rectangular before that operation. Fig. 219 gives a rough indication of the form of section used for making rectangular springs, and as the actual section to be used varies with the size of spring and diameter of mandrel, it is obvious that rectangular bars cannot be stocked except for a few regular lines. The cost and extra time of delivery required for making special sections make it advisable to use circular sections wherever possible.



Before coiling. After coiling.

FIG. 219.—Section of Wire for Square Springs.

A spring is an instrument for storing energy, but in few cases is it possible to use a spring of sufficient size to take the whole energy of a moving vehicle.

The balance is therefore expended in shocks. A laminated, or volute spring, has a good deal of internal friction, which helps to dissipate more energy.

The form of section used also has considerable influence in determining the energy-storing power of a spring. The circular helical spring is easily the most efficient in this respect, being about 50 per cent. better than any others.*

In some cases coil springs are made of hard drawn wire. This is not recommended, but where necessary it is advisable to stiffen the springs after closing to correct length by dipping into a lead bath to remove internal stresses. This only applies to compression springs and may be omitted in the case of tension springs.

The "rate" of coiled springs is tested by loading up gradually to the full load and measuring the change in length. This rate is expressed in lbs. per inch and is obtained by dividing the total load applied by the total compression

---

* See paper on "Springs," read by Mr. C. E. Squire before the Junior Institute of Engineers, December, 1916.

or extension produced. This is done in a machine similar to those shown on Figs. 217 and 220. In Fig. 217 the load is applied by means of a screw driven through gearing by hand, belt, or motor. Small coil springs are tested in the machine shown in Fig. 220, the load being applied by the small handwheel, and measured by the lever system on top of the machine. Hydraulic machines are sometimes used for heavy springs, but for machines up to 3 or 5 tons capacity belt or motor drives are preferable, as the load may be kept steady with greater facility while the weighing operation is being performed. The compression of the spring (or extension) under any load is indicated by the scale fixed to the frame of each machine.

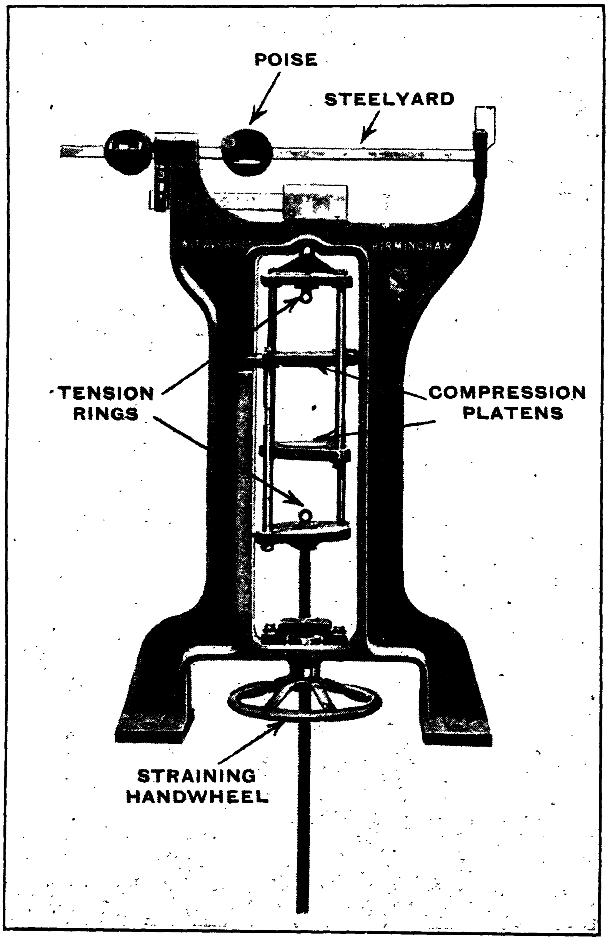


FIG. 220.—Hand-driven Machine for Testing Coil Springs in Tension and Compression. Capacity : 400 lbs.

Tests on Spring Steel.—The only tests usually made on spring steel are tensile tests and analyses. Impact tests are not generally made, as the steel is comparatively brittle (usually about 8 ft.-lbs. Izod), and high elastic range is of greater importance. Tests have been made, however, by Mr. C. G. Carlisle * on silico manganese and chrome vanadium spring steels, and the various results are classified by him as follows. In each case the results obtained from silico manganese steel are taken as 100 :—

	Silico Manganese Spring Steel.	Chrome Vanadium Spring Steel.
Ultimate tensile stress	100	124
Arnold alternating test	100	118
Charpy impact test	100	160
Izod impact test	100	221
Stanton repeated impact test	100	261
Scragging test	100	260

Materials for Railway Rolling Stock.—In view of the serious consequences attending the failure of materials used in railway work, it is important to apply exhaustive tests to all material used for rolling stock parts, and many special tests have been developed for the purpose of revealing latent defects in any detail.

All important forgings such as crank axles, straight axles, tyres, etc., are analysed for sulphur and phosphorus content, and tensile test pieces are taken to ensure that the mechanical quality of the steel is reasonably good in all cases. Axles have a tensile strength of 30 to 40 tons, and an elongation of 20 to 25 per cent. It is usual to specify the yield as not less than 50 per cent. of the ultimate tensile strength. Forgings that have to withstand a considerable amount of wear are made out of a special steel of 40 to 45 tons tensile strength, and an elongation of about 16 to 18 per cent.

Cold bend tests are made on test pieces $1\frac{1}{4}$ inch square section, by bending round a bar $2\frac{1}{2}$ inches diameter, to an angle of 90°. The two ends of the test piece are then brought together, and this test must be withstood without the bar showing signs of fracture. The test pieces are rounded at the edges to a radius of $\frac{1}{16}$ inch. A machine for making bend tests is shown in Fig. 221.

The impact tests to which axles are subjected have already been described (Chapter V).

Tyres are placed vertically on a heavy block of metal and subjected to repeated blows from a falling weight of 2,240 lbs. This is first dropped from a height of 10 feet, and the fall is increased by 5 feet for successive blows until a standard deflection laid down by the Engineering Standards Committee is obtained.†

This destruction test is only carried out on a small percentage of the tyres made, but every tyre may be tested by dropping it on to an iron block from a height of 5 feet for a 3 feet 6 inch tyre, and a height of 2 feet 6 inches for a

---

* Discussion on "Mechanical Properties of Steel," *Proc. Inst. Mech. Eng.*, May, 1919.

† Report No. 24, "Material used in the Construction of Railway Rolling Stock."

6 feet 6 inch tyre. The tyre is then turned through 90° and dropped again. If these tests do not reveal any defects, the tyres are deemed to be satisfactory.*

The drop test described in connection with tyres is also made on wheel centres, which are dropped from a height of 3 feet on to the end of a spoke. They must show no crack or flaw under this test. Destruction tests of a similar nature, but with greater heights of fall, are also made on wheel centres.

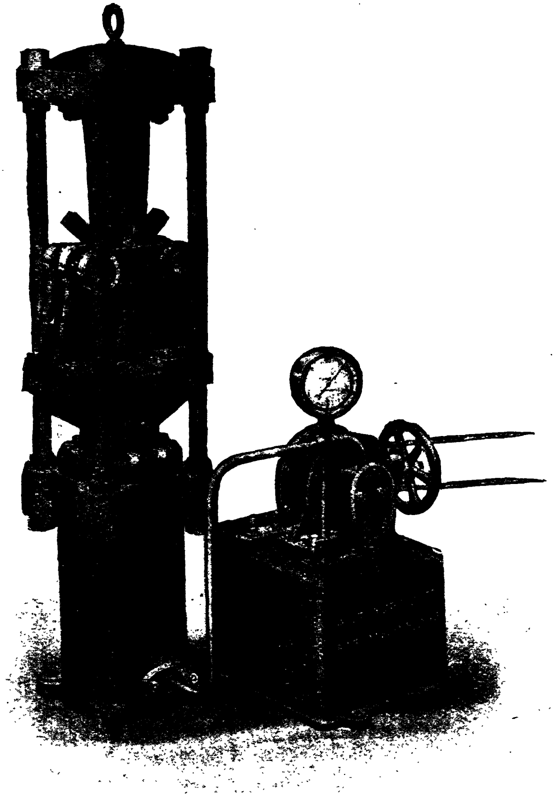


FIG. 221.—20-ton Hydraulic Bending Machine showing 1¼-inch square specimen in position. Hele-Shaw pump with screw control.

The cold bend test made on steel castings is taken on a 1-inch diameter test piece, which is bent round a bar 2½-inches diameter through an angle of 90°. If this is sustained without fracture the material is passed. This bend test is not made on castings having wearing surfaces.

Copper plates for locomotive work should bend 180° flat both cold and at a red heat. Copper bars should crush from 1 inch to ⅜ inch long without wing signs of fracture or cracking.

pper tubes are tested by bulging or drifting the ends until they are

capa
with gr
compressi
scale fixed

---

ther particulars see article on "Falling Weight Test on Railway Tyres," by enny, *Engineering*, November 15, 1918.

increased in diameter by 25 per cent. They are also flanged at the ends to a diameter of 1·4d, when d is the original diameter of the tubes, and should flatten and double over both cold and at a red heat. A hydraulic test of about 700 lbs. per square inch is also frequently applied.

On rivet bars, cold bend tests are made, and also tests after heating to a red heat and quenching in water. Rivets are bent cold and hammered until two parts of the shank touch, and the heads are flattened hot until their diameter is 2½ times that of the shank.

It is well known that rivet holes in boilers should be drilled and not punched, as the latter operation seriously injures the metal immediately surrounding the hole. It is stated by Dr. J. E. Stead * that drilling with a blunt drill has a similar effect and that under such treatment cracks are liable to form round the rivet holes.

Welding Repairs.—In recent years there has been a decided movement in favour of the repair of broken or defective castings and forgings by oxy-acetylene and electric welding, and many difficult jobs have undoubtedly been satisfactorily performed by these means.

The increased popularity of motoring, whereby comparatively delicate fast-running mechanisms are handled by unskilled or semi-skilled owners and drivers, has made such repairs frequently necessary, and in consequence a number of firms have sprung up who make a speciality of welding repairs.

In boiler work the welding up of cracked plates and the building up of wasted parts by welding, for a considerable time was looked upon with great suspicion, particularly as in this class of work the consequences of any failure are liable to be serious. Mr. E. G. Hiller † states that welding is useful for repairs and for replacing riveted joints, and gives many instances where defective and fractured boiler parts have been repaired in this way and have worked satisfactorily afterwards. Among such repairs are those relating to the grooving of endplates over the furnace connections, to defects in the flue tube, and to parts under compression. He does not approve of welding parts subjected to tension, such as the external shells of steel boilers.

In this case it may only be used for filling up local pittings and similar defects.

Welding is also occasionally used in the case of large forgings for building new metal on to worn parts. In America, if the cone of a piston rod wears, it is stated to be quite customary to build up the worn part and turn to size again. This would possibly have been done in the case of expensive aero engine parts but for the fact that electro deposition of steel has been a solution of the difficulty.

Welded repairs on steel forgings or plates are liable to give low tensile results and low elongation when tested.

When failure takes place, however, it often occurs *near* the weld. This is due to the fact that the metal surrounding the weld is heated to a high temperature and no work is subsequently put upon it to restore the normal structure. Consequently the steel near the weld is in a coarse crystalline condition and is liable to fracture at a much lower stress than the other parts of the plate or

---

* Discussion on "Mechanical Properties of Steel," *Proc. Inst. Mech. Eng.*, May, 1919.

† Discussion on "Welding," *Proc. Inst. Mech. Eng.*, April, 1919.

forging. The structure may be improved considerably by suitable heat treatment after welding.

Faults that are likely to be met with in electric welding are slag pockets, weakening by overheating, globules, and voids caused by insufficient heat. A rough, untidy weld indicates a careless operator or, in the case of electric welding, excessive supply voltage. In welds made by metallic electrodes, and sometimes in the case of acetylene welding, nitrogen is apt to be present. The inclusion of this element is very detrimental to the life and strength of the weld as it causes brittleness. A further possibility in the case of oxy-acetylene welds is the presence of phosphoretted or sulphuretted hydrogen in the gases, causing abnormal percentages of phosphorus and sulphur with their well-known physical accompaniments in the weld.

The great difficulty met with in passing welds for service is that of determining whether the weld is sound over the whole surface. In most cases it is impossible to ascertain this by examination, as the indications are not visible on the surface, and fracture of samples is of very little value save to the extent that it gives confidence or otherwise in the general reliability of the work. Where individual welds are made, or where it is necessary to apply some test, a proof load may be applied.

This is done in the case of chains, where the whole length is tested to a proof load in excess of the working load, and three links are cut out of the centre of each chain and tested to destruction. This is the best kind of test that can be applied to a weld, but it is not always possible to test repair welds in this way. A chain-testing machine is shown in Fig. 6.

Iron and steel castings for engines, hydraulic work, etc., are now frequently repaired by welding, and there appears to be little difficulty generally in obtaining local adhesion. In many instances, however, failure occurs through distortion of machined surfaces, making the casting unusable. The welding of cracks in steel castings may be satisfactorily performed, but when the castings are fairly large or complicated, further cracks are liable to develop after the welding, on account of the local heating of the welded portion.

These can be reduced to a minimum by heating up the whole of the casting to a red heat before welding and annealing afterwards. Even when the cracks do not show up immediately after welding, parts of the casting are liable to be highly stressed and to give way after a period under load. In view of these facts welding of complicated steel castings of thin section should be avoided as far as possible. If practicable, it is advisable to subject all important castings that have been repaired by welding, to a pressure test before putting to work.

The presence of oil on cast-iron or steel is very objectionable as the oil is liable to carbonise and produce a porous weld.

The welding of copper fireboxes has been attempted, but without success. The trouble in this case is chiefly that of building up the copper plate. In the experimental work it was found that owing to the high conductivity, heat got away too rapidly.

The suitability of the metal for welding is a point that is too frequently overlooked in making welded repairs, and many failures of such repairs can be traced to this cause. For this reason a pressure or proof test should be made in all possible cases to ensure, as far as possible, that a sound result has been obtained.

For further information *re* details of welding methods and results obtained, readers are referred to a series of papers by Messrs. Heaton, Cave, Davies, and Hazeldine, read before the Institution of Mechanical Engineers in January, 1919,* and a report on "Welding Mild Steel," by Mr. H. M. Hobart.†

Steel Wire Ropes and Cables.—The wire used for the manufacture of strands and cables ‡ is usually made of medium carbon steel, uniformly heat treated § to give a tensile strength of 70 to 120 tons per square inch, the actual strength specified varying with the quality of the steel employed.

For aeronautical work, the ultimate strength of the wire when drawn to size should not be less than 120 tons per square inch, and heat treatment should be as uniform as possible.

Uniformity of size is important, and for ordinary industrial work the maximum diameter should not exceed the nominal by more than 0·003 to 0·005 inch for wires below and above 0·064 inch diameter respectively. For aeronautical work the maximum size should not exceed the minimum by an amount exceeding 0·001 to 0·002 inch. In both cases, the minimum diameter should be not less than the nominal size. Uniformity may be tested by gauging each coil in three or more places with a micrometer

Tensile tests on wires are made with machines up to 5 tons capacity, a suitable size being that illustrated in Fig. 14. The length of specimen is usually 12 to 15 inches, and the specimens should be straight and free from bends or kinks. Short specimens are liable to give incorrect results.

In rope making, if samples of the wire used are not available for test, a piece may be cut out of the rope itself and used for this purpose.

Wires are frequently protected from corrosion by galvanising. In this case the effective cross-section of the wire is taken to be 90 per cent. of the gross area. The coating must be smooth and uniform in thickness and should preferably be of pure zinc.

In addition to the tensile test, a torsion test is generally applied by means of a machine similar to that shown in Fig. 24. In British practice the length of the specimen is usually 8 inches, but some specifications call for a minimum length of 10 inches. The rate of twisting is generally specified to be not greater than one revolution per second, and the results are recorded as the number of twists sustained per length of 100 diameters without showing signs of splitting or other visible defects.

Suitable minimum results are as follows :—

Wire.	Turns per 100 diameters.
Galvanised	15·0
Ungalvanised	25·0
Aeroplane (0·018 inch diameter and under) ..	27·5
„ (over 0·018 inch diameter)	20·0

---

* "Electric Welding," by T. T. Heaton; "The Development of the Oxy-Acetylene Welding and Cutting Industry in the United States," by Henry Cave; "Oxy-Acetylene Welding," by J. W. Davies; "Oxy-Acetylene Welding," by F. Hazeldine.

† "Welding Mild Steel," by H. M. Hobart, *Engineering*, June 13, 1919; also "Electric Welds," by E. E. Thum, *Chemical and Metallurgical Engineering*, September 15, 1918.

‡ *See* "Standard General Specification for Wire Rope" and "Standard Specification for Flexible Steel Wire Rope and Flexible Strand for Aircraft Purposes," both issued by the Canadian Engineering Standards Association.

§ This treatment is usually that known as "patenting"; the wire being passed through heated tubes and then into the open atmosphere, where it cools at a rate which ensures the formation of a sorbitic structure, *i.e.* the maximum of toughness with the minimum of brittleness.

The wires used for rope manufacture should be free from scales, flaws, inequalities, splints, and other injurious defects, and the ropes themselves should be examined for such defects as kinks, uneven lay, loose wires, open strands, and other similar irregularities, and should remain in this condition when unwound from a reel or coil, or when bent round a standard thimble, provided that the ends are properly secured and that due precautions are taken. The diameters at the bottom of the groove of thimbles used in aeronautical work are usually about four times the diameter of the rope or strand.

The joints in such ropes should be widely distributed, being not more than one wire joint for every 50 feet of strand in ordinary power work, or one in every 100 feet for aeronautical practice. There should be a proper and uniform tension on the wires during the manufacture of the rope and the individual wires and strands should be lubricated with a suitable compound which should have no injurious effect on the wires or on the cores. The wires must be properly protected, without excess of preservative or lubricant, particularly when purchased by weight.

In making tensile tests on the completed rope, the first difficulty is that of cutting out the specimen or test piece. The length of the piece set aside for test should be about 80 inches, and in order to avoid disturbing the original and uniform relation of tensions set up during manufacture, it is necessary to place two seizings or servings of soft iron wire, each about 1 inch to 1½ inches long on each side of the points at which the rope is to be cut. In some cases, two or three seizings are placed on each side of the cut. For this purpose, annealed iron wire 0·054 to 0·105 inch diameter for ropes ½ inch to 2 inches diameter is suitable.

Rope cannot be tested in the ordinary tensile grips, as the compression would damage the wires and the rope would slip through the grips. In the case of small ropes, the ends of the specimen are sometimes bent round a standard thimble, and the latter is attached to the straining and weighing grips by means of a pin. Larger sizes are fixed at the two ends in special conical sockets (taper about 1 in 4 on diameters) by opening out the wires at each end, and running solid with spelter. The sockets can then be attached by pins to the ordinary grips. Before opening out the ends of the specimen, the core must be removed as far as the servings, and the individual wires cleaned with waste, petrol, caustic soda, or hydrochloric acid, to ensure a good bond with the zinc.

The rope must be supported so that it is concentric with the socket, and a ring of fireclay placed round the bottom to prevent the liquid spelter from running down the rope. The metal must not be too hot when poured, as otherwise it may have an annealing action on the wire; and must not be too cold, so that a solid filling may be obtained.

When testing the rope, the rate of loading must be slow at first, so that the wires and strands may bed properly before the breaking load comes on.

In aeronautical work the length of the specimen between the grips should not be less than 4 times the lay of the rope.

Influence of Temperature.—The increasing tendency to employ steam at higher temperatures and pressures necessitates careful selection of the materials required for the working portions of the machine. Present-day designers are often called upon to deal with a difficult set of conditions involving extreme temperatures or large variations in temperature. As a practical example of temperature difficulties in design, that of the shaft used for the turbo-compressor actuated by the exhaust gases of an aero-engine (the compressor is used for super-charging the cylinders at high altitudes) is perhaps an extreme case. The turbo-compressor runs at a high speed, and the centrifugal forces therefore are considerable. The turbine rotor runs in exhaust gases at about 650° C., whilst the compressor rotor (on the same shaft) runs at temperatures down to $-55°$ C. Thus one end of the shaft is red hot while the other is so cold that the metal becomes very brittle.

The increasing use of superheated steam and higher working pressures is accounted for by the increased thermodynamic efficiency when the temperature is large. The ideal cycle for all heat engines, and the one that gives the maximum of efficiency, is represented as follows :—

$$\text{Efficiency} = \frac{T_1 - T_0}{T_1}$$

where $T_1 - T_0$ is temperature range in cylinder.

T_1 is temperature at which heat is supplied.

Thus (other factors being equal), the higher the temperature T_1 at which the heat is admitted to the engine, the greater is the possible efficiency.

Other mechanical devices are now made to withstand high temperatures, as for example charging machines for furnaces, conveyer chains for continuous annealing furnaces, roller mechanisms in molten metal baths, as with tinning, galvanising, etc.

Now tests at ordinary temperatures are no guide as to the behaviour of the materials at the higher temperatures. Moreover, it would appear that a metal which may prove satisfactory at high temperatures when not subjected to friction, may be quite unsuitable when it has a moving part working over it.

The influence of temperature on the strength of various metals and alloys is stated (wherever possible) in the chapters dealing with these materials.

Sir Henry Fowler gives some data * on non-ferrous metals used for certain locomotive parts subjected to the action of superheated steam.

The piston tail-rod bushes originally were made of gunmetal having the following composition :—

Copper	87 per cent.
Tin	9 „
Zinc	2 „
Lead	2 „

This metal was found to break in service, and was replaced by cast-iron, but this scored the rods. Phosphor bronze was then used having the following composition :—

Copper	88 per cent.
Tin	11 „
Phosphorus	1 „

This alloy has been running for over six years in a number of locomotives with satisfactory results. It should be noted that the flange and a portion of the bush only are exposed to the superheated steam (340° C.), and then only during one stroke (exhaust steam on the return stroke).

The piston-rod packing is interesting. A gland of the U.K. type of metallic packing, containing McNamee rings, is fitted. The McNamee rings are two thin rings lying side by side in a case which does not touch the rod. The rings are in halves held together and close to the rod by means of spiral springs mounted on their outer surface. The object of these rings is

---

* "The Effect of Superheated Steam on Non-Ferrous Metals used in Locomotives," by Sir Henry Fowler, K.B.E., *Inst. Metals*, September, 1922.

to prevent the steam coming directly in contact with the white metal in the gland proper. All other parts of the gland are made of gunmetal. The compositions of the rings and of the white metal packing rings are as follows :—

McNamee Rings.	
Copper	75·5 per cent.
Tin	8·5 ,,
Zinc	0·33 ,,
Phosphorus	trace ,,
Nickel	0·5 ,,
Lead	15·0 ,,

White Metal Packing Rings.	
Lead	70 per cent.
Antimony	30 ,,

Sir Henry Fowler states that the above white metal has been found more satisfactory under the conditions used than the usual 80/20 lead-antimony alloy. The working temperatures—340° to 370° C.—are approaching its critical point, as an increase above this figure has been found to cause trouble. At a temperature of 425° C. the trouble experienced was due to the packing rings fusing. These rings, of course, are subjected to the full temperature only intermittently.

The valve spindle packings are similar in design to those for the piston rods but of a smaller size, and the same metals are used throughout satisfactorily. In this case they are subjected to superheated steam during the whole of the time the engine is working.

Conveyer chains and other mechanisms of this kind, when required to withstand temperatures up to 600° or 700° C., should be made of malleable cast-iron. Steel castings will serve equally well. Cast-iron at these temperatures is liable to crack, especially if the parts are subjected to wide fluctuations in temperature.

Specifications.—The figures given in the preceding pages are designed to form a guide as to what can be obtained in practice.

The advantages of standardisation have long been apparent on the machining side of engineering work, but standardisation is possible on a much wider scale, and with considerably greater possibilities on the material side. Some firms lay down their own specifications for material, but only very large buyers can do this, as suppliers will not produce material to the special requirements of comparatively small customers at other than fancy prices. It is therefore advisable, as far as possible, to use standard specifications, so that both suppliers and consumers may become familiar with the materials involved with consequent facility of production, ease of handling and transformation, and avoidance of disputes. A nucleus for such a system of standard specifications exists in the series drawn up for use during the war by the Air Board and now adopted by the Engineering Standards Committee. Makers and users of the materials thus specified have had considerable experience in their manufacture and use, and the series might be enlarged with advantage, and adopted as a general standard for engineering work.

At the same time, there are considerable difficulties in the way of drawing up standard specifications to suit all trades, so that such a policy must be designed chiefly to avoid differences in practice within the borders of each particular trade.

This could best be done by arranging a separate series of standard specifications for each of the important branches of engineering industry, using as few varieties of material as possible, by extending the specification of any single material to cover several different branches of work.

CHAPTER XX

TABLES

TABLE I.—Reduction of Areas of Tensile Test Pieces

Reduced diameter, ins.	Area, sq. in.	Reduction of area per cent.		Reduced diameter, ins.	Area, sq. in.	Reduction of area per cent.	
		Orig. dia. = 0·564 in. Area = 0·25 sq. in.	Orig. dia. = 0·399 in. Area = 0·125 sq. in.			Orig. dia. = 0·564 in. Area = 0·25 sq. in.	Orig. dia. = 0·399 in. Area = 0·125 sq. in.
0·564	0·250	0·0		0·355	0·099	60·4	20·8
0·560	0·247	1·2		0·350	0·096	61·6	23·2
0·555	0·242	3·2		0·345	0·093	62·8	25·6
0·550	0·237	5·2		0·340	0·091	63·6	27·2
0·545	0·234	6·4		0·335	0·089	64·0	29·6
0·540	0·229	8·4		0·330	0·0855	65·8	32·0
0·535	0·225	10·0		0·325	0·083	66·8	33·6
0·530	0·221	11·6		0·320	0·080	68·0	36·0
0·525	0·216	13·6		0·315	0·078	68·9	37·6
0·520	0·213	14·8		0·310	0·0755	69·8	40·0
0·515	0·208	16·8		0·305	0·073	70·7	41·6
0·510	0·204	18·4		0·300	0·0707	71·8	43·1
0·505	0·200	20·0		0·295	0·0685	72·6	45·2
0·500	0·196	21·6		0·290	0·066	73·6	47·2
0·495	0·192	23·1		0·285	0·064	74·4	48·8
0·490	0·188	24·8		0·280	0·0615	75·5	50·4
0·485	0·185	26·0		0·275	0·0593	76·3	52·8
0·480	0·181	27·6		0·270	0·0572	77·1	54·5
0·475	0·177	29·2		0·265	0·055	78·0	56·0
0·470	0·173	30·8		0·260	0·053	78·8	57·6
0·465	0·170	32·0		0·255	0·051	79·7	59·2
0·460	0·166	33·6		0·250	0·0492	80·5	60·8
0·455	0·163	34·8		0·245	0·04715	81·3	62·4
0·450	0·159	36·4		0·240	0·0452	82·0	64·0
0·445	0·155	38·4		0·235	0·0434	82·8	65·5
0·440	0·152	39·6		0·230	0·0415	83·7	66·8
0·435	0·149	40·4		0·225	0·0397	84·4	68·0
0·430	0·145	42·0		0·220	0·038	84·7	69·6
0·425	0·142	43·2		0·215	0·0363	85·6	71·2
0·420	0·138	44·8		0·210	0·0346	86·4	72·2
0·415	0·136	45·6		0·205	0·0331	87·2	73·5
0·410	0·132	47·2		0·200	0·0314	87·6	74·8
0·405	0·129	48·4		0·195	0·0298	88·1	76·0
0·400	0·126	49·6		0·190	0·0284	83·8	77·3
0·395	0·123	50·8	1·6	0·185	0·0268	89·3	78·5
0·390	0·120	52·0	4·0	0·180	0·0254	90·0	79·7
0·385	0·117	53·2	6·4	0·175	0·0241	90·5	80·7
0·380	0·114	54·5	8·8	0·170	0·0226	90·9	82·0
0·375	0·111	55·6	11·2	0·165	0·0214	91·5	82·8
0·370	0·108	56·8	13·6	0·160	0·0201	92·1	84·0
0·365	0·104	58·5	16·8	0·155	0·0189	92·5	84·7
0·360	0·102	59·3	18·4				

TABLE II.—BRINELL HARDNESS NUMBERS AND APPROXIMATE TENSILE STRENGTHS FOR STEEL.

Diameter of impression, mm.	Hardness No., 3,000 kg.	Tensile Strength, tons per sq. in.		Hardness Numbers.		
		Carbon steels.	Alloy steels.	2,000 kg.	1,000 kg.	500 kg.
2·0	946	—	206	631	315	158
2·05	898	—	196	599	299	150
2·1	857	—	187	572	286	143
2·15	817	—	178	545	277	136
2·2	782	—	171	522	261	130
2·25	744	—	162	496	248	124
2·3	713	—	155	476	238	119
2·35	683	—	149	456	228	114
2·4	652	—	142	435	218	109
2·45	627	—	137	418	209	104
2·5	600	—	131	400	200	100
2·55	578	—	126	385	192	96
2·6	555	—	121	370	185	92
2·65	532	—	116	355	177	88
2·7	512	—	112	342	171	85
2·75	495	—	108	330	165	82
2·8	477	—	104	318	159	79
2·85	460	—	100	307	153	77
2·9	444	—	97	296	148	74
2·95	430	—	94	287	143	71
3·0	418	—	92	279	139	69
3·05	402	—	88	268	134	67
3·1	387	—	85	258	129	64
3·15	375	—	83	250	125	62
3·2	364	—	81	243	122	61
3·25	351	—	78	234	117	59
3·3	340	—	76	227	113	56
3·35	332	—	74	221	110	55
3·4	321	—	71·5	214	107	53
3·45	311	—	70	207	103	51
3·5	302	—	68	201	100	50
3·55	293	—	66	195	97	49
3·6	286	—	65	190	95	47·5
3·65	277	61	63	185	92	46
3·7	269	59·5	61·5	179	89	45
3·75	262	58	60	175	87	44
3·8	255	56·8	58·5	170	85	42·5
3·85	248	55·8	57·5	165	82	41
3·9	241	54·5	56	161	80	40
3·95	235	53·4	55	157	78	39
4·0	228	52	53·5	152	76	38
4·05	223	51	52·7	149	74·5	37·2
4·1	217	50	51·5	145	72·5	36·2
4·15	212	49	50·7	141	70·5	35·2
4·2	207	48	49·8	138	69	34·5
4·25	202	47	48·7	135	67·5	33·7
4·3	196	46	47·6	131	65 5	32·7
4·35	192	45	47·0	128	64	32
4·4	187	44·3	46·0	125	62·5	31·2
4·45	183	43·4	45·0	122	61	30·5
4·5	179	42·8	44·2	119	59·5	29·7
4·55	174	41·5	43·5	116	58	29
4·6	170	40·9	42·8	113	56·5	28·2
4·65	166	40·2	42·0	111	55·5	27·7
4·7	163	39·4	41·4	109	54·5	27·2
4·75	159	38·6	40·7	106	53	26·5
4·8	156	38·1	40·0	104	52	26
4·85	153	37·5	39·5	102	51	25·5
4·9	149	36·6	38·8	99	49·5	24·7
4·95	146	36·0	—	97	48·5	24·2
5·0	143	35·5	—	95	47·5	23·7
5·05	140	34·8	—	93	46·5	23·2
5·1	137	34·2	—	91·5	45·7	22·8
5·15	134	33·5	—	89	44·5	—
5·2	131	32·9	—	87	43·5	—
5·25	128	32·3	—	85	42·5	—
5·3	126	31·9	—	84	42	—
5·35	124	31·4	—	82·5	41·2	—
5·4	121	30·8	—	80·5	40·2	—
5·45	118	30·2	—	78·5	39·2	—
5·5	116	29·7	—	77	38·5	—
5·55	114	29·3	—	76	38	—
5·6	112	28·9	—	74·5	37·2	—
5·65	109	28·3	—	72·5	36·2	—
5·7	107	27·8	—	71	35·5	—
5·75	105	27·3	—	70	35	—
5·8	103	26·9	—	68·5	34·2	—
5·85	101	26·5	—	67	33·5	—
5·9	99	25·9	—	66	33	—
5·95	97	25·5	—	64·5	32·2	—
6·0	95	25·2	—	63	31·5	—
6·05	94	24·9	—	62·5	31·2	—
6·1	92	24·5	—	61·5	30·7	—
6·15	90	24·0	—	60	30	—
6·2	89	23·7	—	59·5	—	—
6·25	87	23·3	—	58	—	—
6·3	86	23·1	—	57·5	—	—
6·35	84	22·7	—	56	—	—
6·4	82	22·2	—	54·5	—	—
6·45	81	21·9	—	54	—	—
6·5	80	21·7	—	53·5	—	—

NOTE.—The hardness numbers given for 2,000, 1,000, and 500 kg. are based on the assumption that the area of impression is proportional to the load, an assumption which is sufficiently correct for most practical purposes.

TABLE III.—Scleroscope Readings for Various Materials

In specifying the scleroscope value to be attained by material, it is advisable to allow a variation of 5 per cent. up or down in the reading. High speed steel requires an allowance of 10 per cent. The following are average values for common materials :—

Carbon steel (annealed ..	35–30	Cast-iron (grey)	35–40
High speed steel (annealed)	40–35	,, (small castings)	35–60
Brass (very hard)	45	Chilled cast-iron (sliding surfaces)	50–80
,, (soft)	10	Nickel steel (6–7 per cent. carbonised and hardened)	60–80
Bronze (hard)	25–50		
Brass (castings)	7–25		
Bronze	10–35		

Motor Work.

Frames (Nickel Chrome steel)	40–50	Transmission gears	80–85
,, (Carbon steel)	35–40	Gudgeon pins	80–90
Axles (0·35 carbon—nickel chrome)	40–45	Valve lifter roller pin	60–65
Springs (Vanadium steel)	65–80	Cams	70–85
,, (Carbon steel)	60–75	Valves	50–60
Crank shafts (0·35 carbon—nickel chrome)	45–55	Cones	70–80
		Keys (hardened)	75–80

In using any part of this table, reference should also be made to those chapters dealing with the above materials, where further test figures and information are given.

TABLE IV.—Comparison between Auto-Punch and Brinell Impressions*

Auto-Punch Impression, mm. diameter.	Brinell, 3,000 kg.		Auto-Punch Impression, mm. diameter.	Brinell, 3,000 kg.	
	Impression diameter, mm.	Hardness Number.		Impression diameter, mm.	Hardness Number.
1·260	2·50	600	1·694	4·10	217
1·272	2·55	578	1·708	4·15	212
1·284	2·60	555	1·721	4·20	207
1·294	2·65	532	1·735	4·25	202
1·306	2·70	512	1·745	4·30	196
1·318	2·75	495	1·760	4·35	192
1·332	2·80	477	1·780	4·40	187
1·345	2·85	460	1·798	4·45	183
1·360	2·90	444	1·815	4·50	179
1·375	2·95	430	1·827	4·55	174
1·390	3·00	418	1·829	4·60	170
1·405	3·05	402	1·852	4·65	166
1·420	3·10	387	1·865	4·70	163
1·434	3·15	375	1·878	4·75	159
1·448	3·20	364	1·890	4·80	156
1·460	3·25	351	1·912	4·85	153
1·475	3·30	340	1·925	4·90	149
1·489	3·35	332	1·940	4·95	146
1·504	3·40	321	1·953	5·00	143
1·518	3·45	311	1·966	5·05	140
1·534	3·50	302	1·979	5·10	137
1·548	3·55	293	1·995	5·15	134
1·563	3·60	286	2·010	5·20	131
1·578	3·65	277	2·030	5·25	128
1·591	3·70	269	2·050	5·30	126
1·603	3·75	262	2·070	5·35	124
1·615	3·80	255	2·085	5·40	121
1·627	3·85	248	2·100	5·45	118
1·640	3·90	241	2·115	5·50	116
1·652	3·95	235	2·135	5·55	114
1·664	4·00	228	2·160	5·60	112
1·680	4·05	223			

* As supplied by Messrs. Rudge-Whitworth, Ltd., Coventry.

TABLE V.—APPROXIMATE RELATIONSHIP BETWEEN THE BRINELL HARDNESS AND MACHINING HARDNESS OF STEELS

Brinell Values.		Tensile Strength, tons per sq. in.		Cutting Properties (approx.).			
Hardness Number.	Diameter of Impression, mm.	Carbon Steel.	Alloy Steel.	Single-point Tool.		Milling.	Drilling.
				Turning.	Planing.		
80	6·50	21·7	—	95	95	75	60
97	5·95	25·5	—	100	100	80	70
118	5·45	30·2	—	95	95	75	65
140	5·05	34·8	—	90	90	70	60
166	4·65	40·2	42·0	80	80	65	55
192	4·35	45·0	47·0	65	65	50	40
207	4·20	48·0	49·8	50	50	35	30
235	3·95	53·4	55·0	35	35	25	20
262	3·75	58·0	60·0	25	25	15	10
286	3·60	—	65·0	20	20	10	5
311	3·45	—	70·0	15	15	7	3
340	3·30	—	76·0	10	10	5	2
364	3·20	—	81·0	7	7	3	1
387	3·10	—	85·0	5	5	2	—
402	3·05	—	88·0	3	3	1	—
418	3·00	—	92·0	2	2	—	—
444	2·90	—	97·0	1	1	—	—
477	2·80	—	104·0	—	—	—	—
512	2·70	—	112·0	—	—	—	—

TABLE VI.—Hardness Tests of Brass (66:34)

See p. 89.

Ultimate Tensile Strengths and Hardness Numbers.

Thickness inch.	Ultimate Strength, tons per sq. in.	Scleroscope Number.	Brinell Number.			Ratio: Brinell to Scleroscope Number.		
			Load in kg. 3000	1000	500	Load in kg. 3000	1000	500
0·130	20·25	7·8	—	—	—	—	—	—
0·781	20·2	10·0	70·0	70·0	66·0	7·0	7·0	6·6
0·376	21·1	10·0	78·0	74·0	72·5	7·8	7·4	7·3
0·716	21·25	10·0	86·0	81·0	74·5	8·6	8·1	7·5
0·061	21·9	10·0	—	—	—	—	—	—
0·717	22·05	13·5	96·0	89·0	84·0	7·1	6·6	6·2
0·231	22·7	14·3	89·0	83·5	83·0	6·2	5·8	5·8
0·237	23·4	15·0	93·0	85·5	85·5	6·2	5·7	5·7
0·704	22·1	13·0	92·5	85·0	82·0	7·1	6·5	6·3
0·237	22·0	13·0	86·5	80·0	82·0	6·7	6·2	6·3
0·689	22·6	13·0	99·5	90·0	88·5	7·7	6·9	6·8
0·116	22·65	15·1	—	—	—	—	—	—
0·677	23·35	16·0	107·0	100·0	92·8	6·7	6·3	5·8
0·660	23·6	16·5	104·0	98·5	91·5	6·3	6·0	5·5
0·652	24·4	17·8	114·0	104·5	103·5	6·4	5·9	5·8
0·214	23·9	17·5	101·0	96·0	101·0	5·8	5·5	5·8
0·216	24·0	17·5	103·0	98·5	98·0	5·9	5·6	5·6
0·054	24·4	19·0	—	—	—	—	—	—
0·627	24·8	18·3	118·5	111·5	106·0	6·5	6·1	5·8
0·192	24·85	21·0	118·0	104·5	102·5	5·6	5·0	4·9
0·052	24·8	20·0	—	—	—	—	—	—
0·054	25·05	20·0	—	—	—	—	—	—
0·106	24·8	20·0	—	—	—	—	—	—
0·207	25·7	20·0	115·0	108·0	107·0	5·8	5·4	5·4
0·622	26·0	21·3	124·0	119·0	116·0	5·8	5·6	5·5
0·201	26·0	21·0	119·0	113·5	111·0	5·7	5·4	5·3
0·593	26·8	22·6	127	121·5	119·5	5·6	5·4	5·3
0·194	26·9	22·8	125·0	118·5	118·0	5·5	5·2	5·2
0·577	28·1	25·0	134·0	125·5	122·0	5·4	5·0	4·9
0·046	28·5	27·0	—	—	—	—	—	—
0·082	30·9	29·0	—	—	—	—	—	—
0·042	31·6	28·5	—	—	—	—	—	—
0·501	32·0	29·1	146·0	146·0	138·5	5·0	5·0	4·8
0·041	32·4	31·0	—	—	—	—	—	—
0·040	32·6	30·8	—	—	—	—	—	—
0·486	34·0	32·0	149·0	146·5	143·0	4·7	4·6	4·5
0·477	34·3	31·0	151·0	147·5	143·5	4·9	4·8	4·6
0·039	34·2	32·0	—	—	—	—	—	—
0·435	33·4	32·0	151·5	149·5	142·5	4·7	4·7	4·5
0·046	34·6	32·0	—	—	—	—	—	—
0·077	35·1	32·0	—	—	—	—	—	—
0·437	36·0	32·0	154·0	152·5	147·5	4·8	4·8	4·6
0·137	36·7	32·0	—	—	—	—	—	—
0·038	36·4	33·0	—	—	—	—	—	—
0·036	36·5	34·0	—	—	—	—	—	—
0·420	37·1	33·0	156·0	155·0	150·0	4·7	4·7	4·6
0·066	37·8	36·0	—	—	—	—	—	—
0·053	37·4	36·1	—	—	—	—	—	—
0·399	38·3	36·0	161·0	155·5	149·5	4·5	4·3	4·2
0·057	39·6	38·0	—	—	—	—	—	—
0·049	41·5	40·0	—	—	—	—	—	—
0·023	42·0	40·0	—	—	—	—	—	—

TABLE VII.—TONS PER SQUARE INCH EQUIVALENTS IN POUNDS PER SQUARE INCH.

One British ton = 2,240 lbs.

Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.
1	2,240	41	91,840	81	181,440
2	4,480	42	94,080	82	183,680
3	6,720	43	96,320	83	185,920
4	8,960	44	98,560	84	188,160
5	11,200	45	100,800	85	190,400
6	13,440	46	103,040	86	192,640
7	15,680	47	105,280	87	194,880
8	17,920	48	107,520	88	197,120
9	20,160	49	109,760	89	199,360
10	22,400	50	112,000	90	201,600
11	24,640	51	114,240	91	203,840
12	26,880	52	116,480	92	206,080
13	29,120	53	118,720	93	208,320
14	31,360	54	120,960	94	210,560
15	33,600	55	123,200	95	212,800
16	35,840	56	125,440	96	215,040
17	38,080	57	127,680	97	217,280
18	40,320	58	129,920	98	219,520
19	42,560	59	132,160	99	221,760
20	44,800	60	134,400	100	224,000
21	47,040	61	136,640	101	226,240
22	49,280	62	138,880	102	228,480
23	51,520	63	141,120	103	230,720
24	53,760	64	143,360	104	232,960
25	56,000	65	145,600	105	235,200
26	58,240	66	147,840	106	237,440
27	60,480	67	150,080	107	239,680
28	62,720	68	152,320	108	241,920
29	64,960	69	154,560	109	243,160
30	67,200	70	156,800	110	246,400
31	69,440	71	159,040	111	248,640
32	71,680	72	161,280	112	250,880
33	73,920	73	163,520	113	253,120
34	76,160	74	165,760	114	255,360
35	78,400	75	168,000	115	257,600
36	80,640	76	170,240	116	259,840
37	82,880	77	172,480	117	262,080
38	85,120	78	174,720	118	264,320
39	87,360	79	176,960	119	266,560
40	89,600	80	179,200	120	268,800

TABLE VIII.—Young's Modulus for Various Materials.

Aluminium alloy (castings)	10,000,000
,, Bronze	17,000,000
,, wire	18,500,000
Brass (cast)	13,000,000
Bronze	12,000,000
Copper (cast)	11,000,000
,, (wire)	17,600,000
Delta Metal	15,400,000
Duralumin	10,000,000
Gun metal	13,000,000
Iron (cast)	15,000,000
,, (wrought)	25,000,000
Lead (sheet)	800,000
Monel Metal	28,000,000
Muntz Metal	15,000,000
Nickel	31,000,000
Phosphor Bronze	14,800,000
Steel (castings)	31,000,000
,, (crucible)	29,500,000
,, (mild)	30,000,000
,, (3 per cent. Nickel, 1·3 per cent. Chromium)	36,100,000
,, (12·5 per cent. Chromium)	43,600,000
Timber	1,000,000 to 2,000,000
Tin (cast)	5,000,000
Zinc	11,500,000

TABLE IX.—Coefficients of Linear Expansion per Degree Centigrade (0° to 100°).

Aluminium	0·000022
,, Alloy castings	0·000026
Brass (cast)	0·000019
,, (wire or sheet)	0·000019
Copper	0·000017
Firebrick	0·0000049
Iron (cast)	0·000011
,, (wrought)	0·000012
Lead	0·000027
Nickel	0·000010
Steel (hard)	0·000012
,, (cast)	0·000011
Tin (cast)	0·000023
Water	0·000158
Zinc (cast)	0·000030

TABLE X.—Weights of Materials.

	Lbs. per cu. in.	Lbs. per. cu. ft.	Specific gravity.
Aluminium (rolled)	0·0964	167	2·67
,, (cast)	0·0925	160	2·56
,, alloy (12 per cent. Copper)	0·102–0·106	—	2·83–2·94
,, bronze	0·278	480	7·68
Babbit metal	0·2605	450	7·5
Brass (cast) (60 : 40)	0·302	524	8·40
Bronze (70 : 30)	0·3195	553	8·85
Chromium	0·2347	405	6·5
Copper	0·3190	553	8·87
Delta Metal (rolled)	0·3045	527	8·45
Duralumin	0·101	174	2·8
Gunmetal (90 : 10)	0·307	530·6	8·50
Iron (cast)	0·2605	450	7·21
,, (Pig No. 3)	0·2575	445	7·126
,, (Pig No. 1)	0·258	446	7·137
,, (wrought)	0·2834	489	7·85
Lead (cast)	0·4104	709	11·36
Manganese Bronze	0·301	520	8·3
Monel Metal (cast)	0·319	550	8·87
,, ,, (rolled)	0·323	558	8·98
Muntz metal (rolled)	0·303	524	8·4
Nickel	0·3177	549	8·8
Phosphor Bronze (cast)	0·3107	537	8·6
Steel (average)	0·2816	489·5	7·85
Tin (cast)	0·265	459	7·35
Zinc (cast)	0·2472	428	6·86

TABLE XI.—Melting Points of Metals and Alloys.

	Degs. C.	Degs. F.
Aluminium	659	1220
,, Bronze	1037	1900
Bronze (85 : 10 : 5)	980	1800
Babbit metal	227	440
Brass (naval)	855	1570
,, (yellow)	895	1640
Chromium	1510	2750
Copper	1083	1980
Gun metal (88 : 10 : 2)	995	1820
Iron (pure)	1530	2788
,, (pure white)	1135	2070
,, (grey pig)	1240	2280
,, (grey forge pig)	1220	2230
Lead	327	621
Magnesium	650	1200
Manganese	1230	2249
Manganese Bronze	870	1600
Monel Metal	1360	2490
Nickel	1452	2650
Phosphor Bronze	972	1800
Silver	961	1760
Steel (mild)	1510	2750
Tin	232	450
Zinc	420	790

TABLE XII.—Contraction of Castings.

Aluminium	$\frac{17}{64}''$ per foot
Brass (thin)	$\frac{1}{8}''$ in 9 inches
,, (thick)	$\frac{1}{8}''$ in 10 inches
Copper	$\frac{3}{16}''$ per foot
Cast-iron pipes	$\frac{1}{8}''$,,
Delta metal	$\frac{3}{16}''$,,
Gunmetal rods	$\frac{1}{8}''$ in 9 inches
Lead	$\frac{1}{4}''$ per foot
Malleable C.I. "white heart"	$\frac{3}{16}''$,,
,, ,, "black heart"	$\frac{1}{8}''$,,
Manganese Bronze	$\frac{1}{4}''$,,
Monel Metal	$\frac{1}{4}''$,,
Steel	$\frac{3}{16}''$,,
Tin	$\frac{1}{4}''$,,
Zinc	$\frac{5}{16}''$,,

TABLE XIII.—Specific Heat and Heat Conductivity of Metals and Alloys.

	Specific Heat at 0° C.	Heat Conductivity (Silver = 100).
Aluminium	0·2220	35·0
Brass	0·0890	—
Chromium	0·1023	—
Copper	0·1008	92·0
Gunmetal	0·0952	—
Iron (pure)	0·1054	16·0
,, (cast white)	0·1298	—
,, (cast grey)	0·1216	—
,, (wrought)	0·1146	—
Lead	0·0359	8·5
Magnesium	0·2500	34·3
Manganese	0·1204	—
Mercury	0·0334	5·3
Nickel	0·1095	14·0
Platinum	0·0312	37·9
Silver	0·0572	100·0
Steel, cast (hard)	0·1185	—
,, ,, (soft)	0·1166	—
Steel (mild)	0·1158	—
Tin	0·0683	15·2
Zinc	0·0877	26·3

TABLE XIV.—Table showing conversion of Tons per Square Inch into Kilogrammes per Square Millimetre.

Tons per sq. in.	Kilos per sq. mm	Tons per sq. in.	Kilos per sq. mm.	Tons per sq. in.	Kilos per sq. mm.
10·00	15·75	40·00	63·00	70·00	110·24
11·00	17·32	41·00	64·57	71·00	111·82
12·00	18·90	42·00	66·15	72·00	113·40
13·00	20·47	43·00	67·72	73·00	114·97
14·00	22·05	44·00	69·30	74·00	116·54
15·00	23·62	45·00	70·87	75·00	118·12
16·00	25·20	46·00	72·45	76·00	119·70
17·00	26·77	47·00	74·02	77·00	121·27
18·00	28·35	48·00	75·60	78·00	122·84
19·00	29·92	49·00	77·17	79·00	124·42
20·00	31·50	50·00	78·75	80·00	126·00
21·00	33·07	51·00	80·33	81·00	127·57
22·00	34·65	52·00	81·90	82·00	129·14
23·00	36·22	53·00	83·47	83·00	130·72
24·00	37·80	54·00	85·04	84·00	132·30
25·00	39·37	55·00	86·62	85·00	133·87
26·00	40·95	56·00	88·20	86·00	135·44
27·00	42·52	57·00	89·77	87·00	137·02
28·00	44·10	58·00	91·34	88·00	138·60
29·00	45·67	59·00	92·92	89·00	140·17
30·00	47·25	60·00	94·50	90·00	141·74
31·00	48·82	61·00	96·07	91·00	143·32
32·00	50·40	62·00	97·64	92·00	144·90
33·00	51·97	63·00	99·22	93·00	146·47
34·00	53·55	64·00	100·80	94·00	148·04
35·00	55·12	65·00	102·37	95·00	149·62
36·00	56·70	66·00	103·94	96·00	151·20
37·00	58·27	67·00	105·52	97·00	152·77
38·00	59·85	68·00	107·10	98·00	154·34
39·00	61·42	69·00	108·67	99·00	155·92
				100·00	157·50

Kilos per Square Mm.—Tons per Square Inch

Kilos.	Tons.	Kilos.	Tons.	Kilos.	Tons.	Kilos.	Tons.	Kilos.	Tons.	Kilos.	Tons.
10	6·35	26	16·44	41	26·03	56	35·56	71	45·08	86	54·50
11	6·98	27	17·07	42	26·665	57	36·195	72	45·72	87	55·20
12	7·62	28	17·70	43	27·30	58	36·85	73	46·35	88	55·70
13	8·25	29	18·34	44	27·935	59	37·48	74	46·99	89	56·40
14	8·89	30	19·05	45	28·57	60	38·10	75	47·62	90	57·15
15	9·51	31	19·68	46	29·25	61	38·75	76	48·26	91	57·60
16	10·14	32	20·32	47	29·845	62	39·39	77	48·89	92	58·30
17	10·77	33	20·95	48	30·47	63	40·00	78	49·52	93	58·90
18	11·40	34	21·58	49	31·11	64	40·64	79	50·16	94	59·60
19	12·03	35	22·21	50	31·75	65	41·27	80	50·80	95	60·20
20	12·70	36	22·96	51	32·38	66	41·91	81	51·50	96	60·80
21	13·30	37	23·48	52	33·02	67	42·54	82	52·00	97	61·40
22	13·90	38	24·10	53	33·65	68	43·18	83	52·60	98	62·00
23	14·56	39	24·73	54	34·29	69	43·81	84	53·30	99	62·80
24	15·20	40	25·40	55	34·92	70	44·45	85	53·80	100	63·50
25	15·875										

Tons × 1·575 = Kilos per sq. mm.
Kilos per sq. mm. × 0·6359 = Tons per sq. in.

TABLE XV.—TABLE OF CHEMICAL SYMBOLS AND ATOMIC WEIGHTS OF PRINCIPAL METALS, ETC.

Element.	Symbol.	Atomic Weight.
Aluminium	Al	27·1
Antimony	Sb	120·2
Arsenic	As	74·96
Bismuth	Bi	208·0
Cadmium	Cd	112·4
Carbon	C	12·0
Chromium	Cr	52·0
Cobalt	Co	58·97
Copper	Cu	63·57
Gold	Au	197·2
Hydrogen	H	1·008
Iridium	Ir	193·1
Iron	Fe	55·84
Lead	Pb	207·10
Magnesium	Mg	24·32
Manganese	Mn	54·93
Mercury	Hg	200·6
Molybdenum	Mo	96·0
Nickel	Ni	58·68
Nitrogen	N	14·01
Oxygen	O	16·00
Palladium	Pd	106·7
Phosphorus	P	31·04
Platinum	Pt	195·2
Potassium	K	39·1
Rhodium	Rh	102·9
Silicon	Si	28·3
Silver	Ag	107·88
Sodium	Na	23·00
Sulphur	S	32·07
Tin	Sn	119·0
Titanium	Ti	48·1
Tungsten	W	184·0
Vanadium	V	51·0
Zinc	Zn	65·37

APPENDIX I

TEST SHEETS

THE preparation of test sheet forms is often done in a very incomplete manner, with the result that the forms have to be revised subsequently to provide the extra information necessary for the departments concerned, or to set out the results in a more convenient form.

The schedule given below is intended to be used as a guide for the drawing up of new test sheets. It is realised that modifications will be necessary to give other information in some cases, and that in others, many of the headings will be found unnecessary, but in all essential particulars this form of test sheet will be found useful.

It is divided into five sections. The first section contains all particulars necessary for identifying the consignment from which the samples are taken, and will be filled in from the Delivery Note or Storekeeper's Book. The Material Mark is allocated by the laboratory on the results of the physical tests and analysis, but is included in this section because it is to be impressed on all the articles in the consignment, and therefore forms part of the description of the material.

The second section gives particulars of the number of test pieces required for each test. The practice of printing in all the headings and crossing out the tests not required, is deliberately discarded, as it is found in practice that the crossing out is neglected, and that this part of the sheet falls into disuse.

The third section contains all the test results. The calculated figures which are required for comparison with other tests, are kept well away from the observed results, so that there can be no confusion, and the specification figures are put close to the former for convenience and speed in making the necessary comparisons and references. It will be noted that provision is made for four sets of test results, but, of course, more spaces can be left, if required.

The fourth section gives the names of observers and witnesses (the latter is important when tests for other firms or Government Departments are made) and acts as an acceptance or rejection note for the Inspection Department (if necessary).

The dates of receipt, machining, testing, and accepting the consignment are also included, so that any delay in dealing with a series of tests can be easily detected and traced.

PHYSICAL TEST SHEET

No. *1365*
Date *14/8/19*
Order No. *A2160*
Bond No. *3349*
Material Mark *XY53*
Previous Test No. —
For Part No. *S179*
Shop Order No. *P412*

DESCRIPTION OF MATERIAL

Makers. *Red Forging & Stamping Co., B'ham.*
Kind of Material. *Steel Stampings (Prop. Shafts)*
Size and Shape.
Condition of Material. *Heat Treated*
Heat Treated by *Albion Heat Treating Co.*
Quantity. *100*

TEST PIECES

Tests required.	Tension.	Compression.	Impact.	Brinell.	Twist.	Bend.	Flatten.	Drift.	Fracture.
No. of Tests	*4*	—	*4*	*4*	—	—	—	—	*8*
Dia. of Test Piece—Ins.	*0·564*	—	*Std.*	—	—	—	—	—	—
Area of Test Piece—Sq. In.	*0·25*	—	—	—	—	—	—	—	—

Form of Part from which Test Piece is Cut. *End of Stamping*
Condition of Test Piece—(1) as Cut: *Heat Treated* (2) When Tested:
Date Machined (Finished). *15/8/19*

TEST RESULTS.

Specification No. *K1*

Actual Figures.				Test.	Calculated Figures.				Specification Figures.	Remarks.
13·15	*12·3*	*14·3*	*13·45*	Tension ~~Compression~~ Yield, Tons/☐″	*52·6*	*49·2*	*57·2*	*53·8*	*50*	
15·35	*14·65*	*16·3*	*15·85*	,, Ultimate ,,	*61·4*	*58·6*	*65·2*	*63·4*	*60*	
0·40	*0·44*	*0·36*	*0·40*	,, Elongation ,, ~~Compression~~ %	*20*	*22*	*18*	*20*	*17*	*on 2″*
0·425	*0·405*	*0·435*	*0·420*	,, Reduction ,, ~~Increase~~ of area %	*43*	*48*	*40*	*44*	*40*	
45	*58*	*38*	*35*	Impact, Ft.-Lbs.	*45*	*58*	*38*	*35*	*35*	
3·7	*3·8*	*3·5*	*3·5*	Brinell Impression, mm. dia.	*3·7*	*3·8*	*3·5*	*3·6*	*3·4–3·7*	
269	*255*	*302*	*286*	,, Number	*269*	*255*	*302*	*286*	*321–269*	
				Twist (No. of Turns, or Angle)						
				Bend, Radius						
				,, Angle						
				Flatten.						
				Drift.						
				Fracture.	*F*	*F*	*F*	*F*		

GENERAL REMARKS. *Fractures fibrous generally, but No. 4 shows signs of overheating.*

Tests Made by *P. T. Sherlock*
,, Witnessed by *T. M. Withers*
,, Passed by *L. Boyne*

Date *16/8/19*
Material Accepted / ~~To be Re-treated and Re-tested~~ / ~~Rejected~~
Signed *R. F. Wakeman,* Inspector
Date *16/8/19*

INDEX

INDEX

PRINTED IN GREAT BRITAIN BY
WILLIAM CLOWES AND SONS, LIMITED,
LONDON AND BECCLES.