MATERIALS ENGINEERING
of Metal Products

By

NORMAN E. WOLDMAN, Ph.D.

Consulting Metallurgical Engineer
Also Member of Faculty:
The Cooper Union School of Engineering, and
Stevens Institute of Technology Graduate School

REINHOLD PUBLISHING CORPORATION
330 WEST FORTY-SECOND STREET, NEW YORK, U.S.A.

Printed in U.S.A. by
Norwood Press, Norwood, Mass.

Preface

This volume was written as a companion book to "Metal Process Engineering," published early in 1948. The latter book was concerned with the different metallurgical and mechanical processes for fabricating metal parts such as casting, forging, rolling, powder metallurgy, joining of metals, heat treatment, machining of metals, etc.

This volume presents the materials used in various types of industries and different applications in an attempt to correlate the metallurgy of the material with engineering design and service applications. It has been written to meet the needs of engineering students, professional engineers and production engineers who can use the correlated and interpreted information in part or as a whole with their professional work.

To the production and manufacturing engineers processing problems are very closely related to materials selection. The relation between the design of a product and the materials of which it is made is close, and designers and materials engineers are coming to recognize the relationship more and more. "Materials engineering" is the broad technical function of applying engineering materials to product manufacture. Sound materials engineering includes and correlates (1) applicability of materials in the finished product, (2) processing behavior (workability, weldability, hardenability, machinability, etc.) of the materials to be used, and (3) best fabricating and processing methods for each material.

This book is divided into five main sections: (1) Materials for Lightweight Construction, such as aluminum alloys, magnesium alloys, high strength-low alloy steels and stainless steels; (2) Materials for Mechanical Products, such as gears, springs, bearings and threaded fasteners; (3) Materials for Electrical Industries, such as magnetic materials, electrical contacts, thermostat metals, and electrical resistance alloys; (4) Materials for Special and Severe Service, such as corrosion-resistant materials and high-temperature alloys; and (5) Testing of Materials, such as mechanical testing and non-destructive testing. An Appendix of tabulated properties and characteristics of materials is included.

Free use of manufacturers' bulletins, standard books, and published literature was made to obtain the necessary information, and thanks are due to their authors. In some cases items or even whole paragraphs have been copied verbatim from these references. Where a record was kept of the original references or sources of information, due acknowledgment has been made in the text. However, owing to the many sources from which detailed information was obtained, a complete acknowledgment has been difficult. In these cases the author may be accused of plagiarism. But forgiveness is requested of these unacknowledged authors, since one does not always keep a record of the original sources of all the information obtained through readings and studies made. Actually, since this text covers so many different and specialized fields of activity in engineering, it would have been unwise for the author not to have taken advantage of the knowledge and experience of manufacturers and recognized authorities in each field covered. No one individual can be a true authority on all the phases of metallurgical and design engineering.

More detailed information on any particular subject may be obtained from the list of references at the end of each chapter. For more specific information regarding any particular metal or alloy it is recommended that the reader refer to the manufacturers of said material.

The author wishes gratefully to acknowledge the assistance rendered by several of his former associates in writing parts of certain chapters. These men concentrated in these different fields under the author's supervision while working for the same corporation. Due credit is to be given to the following: to Mr. David Sinizer for assistance in writing the chapter on Bearing Materials; to Mr. Albert Merwin for assistance in writing the chapter on Corrosion and Its Prevention; and to Mr. Fred Barrett for assistance in writing the chapter on Magnetic Materials.

In addition, due acknowledgment should be made to the following engineers and companies for proof-reading the chapter on their particular specialty and offering their comments, criticisms, corrections and additions. The original manuscript was greatly improved by incorporating their suggestions.

The mention of alloys by their trade-names or trade-marks, whether registered or unregistered, is not to be understood by such presentation herein to denote generic or descriptive names and words for general use.

Aluminum Alloys: Aluminum Company of America
Corrosion and Its Prevention: F. L. LaQue, Head of Corrosion Engineering Division, International Nickel Co.
Electrical Contact Materials: E. I. Larsen, Chief Metallurgical Engineer, P. R. Mallory & Co.
Electrical Resistance Alloys: F. E. Bash, Ass't. Vice President, Driver-Harris Co.
High-nickel Alloys: International Nickel Co.
High-temperature Alloys: Howard Avery, Research Metallurgical Engineer, American Brake Shoe Co.
Low Alloy-High Strength Steels: H. H. Smith, Manager of High Strength Steels, Youngstown Sheet & Tube Co.
Magnesium Alloys: Dow Chemical Co.
Magnetic Materials: Bell Telephone Laboratories
Spring Materials: F. P. Zimmerli, Chief Engineer, Barnes-Gibson-Raymond, Inc.
Threaded Fasteners: W. C. Stewart, Technical Adviser, American Institute of Bolt, Nut and Rivet Manufacturers.

N. E. Woldman

New York, N.Y.
March 15, 1949

Contents

Section I: Materials for Light-Weight Construction

Section II: Materials for Mechanical Products

Section III: Materials for the Electrical Industries

Section IV: Materials for Special and Severe Service

Section V: Testing

Section I

Materials for Light-weight Construction

Chapter I

Material for Light-weight Structures

The constant demand throughout the development of the aircraft industries has been for stronger and lighter alloys. This has become more apparent as airplanes have been built larger and heavier. The efficiency of an airplane, at least from a commercial viewpoint, is measured by its pay load or the useful weight which it can lift and transport. The lower the dead weight of a plane of a given design the more passengers and freight it can carry. The efficiency and ease of maneuvering planes are affected by the total weight. For the same horsepower rating, the lighter the plane the greater the maneuverability.

Railway companies are confronted constantly with the problem of lowering the costs of transportation. Light-weight cars decrease the operating cost and increase the pay load. Steamship companies are likewise concerned with reduction of operating costs, and so are the bus and truck companies. Light-weight construction allows more cargo and therefore increased revenue.

There are three classes of materials suitable for light-weight structures:

(A) Light metals such as aluminum and magnesium alloys.
(B) High strength-low alloy steels.
(C) Austenitic stainless steels.

The relative densities of these materials to various other metals are shown in Table 1.

TABLE 1. *Relative Densities*

	Specific gravity	Lb. per cu. in.
Magnesium	1.74	0.063
Aluminum	2.71	0.098
Zinc	7.1	0.258
Cast Iron	7.2	0.260
Steel	7.6–7.9	0.276–0.282
Stainless Steel	7.92	0.283
Brass	8.4–8.8	0.302–0.319
Bronze	8.8	0.318
Monel	8.9	0.323
Copper	8.94	0.322

Magnesium alloys are the lightest structural materials yet developed, being two-thirds the weight of aluminum and one-fourth the weight of iron and steel. Both aluminum and magnesium alloys in the wrought and heat-treated conditions have high strength-weight ratio, which means that on equal weight basis their strength is equal or superior to that of most other metals.

Aluminum alloys were introduced extensively during the early stages of the aircraft industry. Owing to their density, high mechanical strength and great durability, great savings in weight resulted. The fuselage, the wings, the tail, the rudder, the propeller and many of the engine parts are made from rolled, drawn, forged and cast aluminum alloys. Later there were introduced the alloys of magnesium which were lighter than aluminum and just as strong in the cast condition, but not as strong in the wrought and heat-treated condition.

High strength-low alloy steels were put into effective use in the construction of railway cars, ships and buses. Their higher strength and greater resistance to corrosion than standard carbon steels enables thinner sections to be used, thus decreasing overall weight.

Stainless steels of the austenitic 18–8 type are used extensively in construction of railway, bus and truck bodies, and also to a certain extent in the fuselage and wings of airplanes. The greater stiffness, strength and corrosion resistance of austenitic stainless steel permits decreasing the thickness of the sheets and plates to such an extent as to equal the gross weight of similar construction in aluminum alloys.

Thus in all forms of transportation every pound saved without sacrificing strength and endurance means increased pay load, increased speed or performance, quicker starting, easier braking, reduced inertia and friction or wear, savings in fuel or power, or combinations of these.

Factors which affect the selection of the alloy are original cost of material, ease of fabrication, such as machining, forming, welding, etc., and final physical properties to enable the part to withstand service operation.

The suitability of materials for structural purposes has been judged mostly by the tensile properties, largely because of convenience and precedent. This practice is satisfactory as long as the material is structurally isotropic. However, the demand for light-weight structure is causing the increased use of cold-reduced metals in which the tensile and compressive properties are often unequal, and also variable relative to the rolling direction of the material.

The properties which affect the life and performance of structures and machinery are strength, ductility, resistance to sudden shock or impact, rigidity, resistance to wear and abrasion, and resistance to heat and corrosion.

Most machinery, equipment and structures are subject to periods of overstressing, at least occasionally, throughout their life. For this reason a material should not be selected solely on the basis of strength. Rigidity or stiffness is one property that is not improved by the use of alloying elements in the base metal, since it is a function of the modulus of elasticity, which is approximately the same for all compositions of the same base metal.

Regardless of the inherent capabilities of the metal, the price of lightness is ingenuity of design. The extent and nature of the stresses having once been determined, the design of the structures becomes a process of selecting appropriate sections. These are closed members, designed for the dual purpose of utilizing thin material and efficient joining within the structure. One very important development in design is the evaluation of thin metal used in compression members.

Another expedient is to provide flat plates with corrugations running parallel to the principal compression or shear stresses. This also stiffens the panel against loads normal to the surface. For instance, the metal in the roof covering of certain automobiles is only 0.022 inch thick, yet no damage results when a man walks on it.

The design of light-weight structures is mainly concerned with the strength of compression members, which are inherently less strong than tension members due to (1) secondary failure by local instability of thin sections, and (2) primary column failure in general.

Weight saved in the structure reduces bending moment and this, in turn, permits further reduction of structure; the cumulative effect then relieves the load on the body, and here too, additional pounds may be saved.

When weight is an important factor developments in new designs represent different methods of attacking and solving the problem of procuring light weight and strength. In one design the engineer may resort to light metals such as aluminum or magnesium alloys, in another to corrosion-resisting steels, and lastly to high strength-low alloy steels.

The biggest factor that adds weight to ordinary steel railroad equipment is the necessity of providing additional thickness to sheets and structural members to compensate for the loss of thickness due to corrosion. By the use of better corrosion-resistant material this extra thickness is not required.

As stated by H. Knerr, when using a metal for structural purposes the designer is interested mainly in how many pounds of it will be required to do the job, that is, to withstand a certain load in tension, compression, bending, etc. If the metal is weak, more of it will be required to withstand the load. If a so-called "light" metal, of low specific gravity, is weak, it will in effect be a heavy material of construction. Conversely, a "heavy" metal may truly be light if it is strong. Plainly then, design materials cannot be compared on the basis of specific gravity (density) or strength alone: both factors must be taken concurrently. The inherent lightness of a material depends upon its strength for a given weight. A simple means of evaluation is a number obtained by dividing the strength in pounds per square inch by the specific gravity of the metal. This number is called the "strength-weight" factor (S.W.F.) or ratio. As previously stated, the four materials that are considered as important light metals of construction are magnesium alloy, aluminum alloy, high strength-low alloy steel and stainless steel.

Methods of joining have an important influence on the overall lightness of a fabricated structure. Here steel takes the lead over its non-ferrous competitors, because alloy steel structures are commonly joined by welding, affording a light, rigid joint, whereas high-strength magnesium and aluminum alloys must be riveted, which necessitates overlapping of metal with consequent excess weight.

It is interesting to note that when a material is made stronger, as by alloying or by heat treatment or both, the effect is actually to make it lighter, since less of the metal is required to do the job. The strength-weight factors of some typical metals are given in Table 2. Note that pure commercial aluminum, in the annealed state, is actually a heavy material of construction, having a strength-weight factor of only 4.8. Soft iron, having a strength-weight factor of 5.1, is also heavy, but definitely lighter than the annealed aluminum.

TABLE 2. *A Few Characteristic Strength-Weight Factors*

(Strength-weight factor (S.W.F.) equals ultimate strength in pounds per square inch divided by specific gravity)*

	Tensile strength	Sp. gr.	S.W.F.
Commercial aluminum 2S alloy annealed	13,000	2.7	4.8
Armco iron, annealed	40,000	7.8	5.1
Mild steel, rolled, A.I.S.I. 1025	60,000	7.8	7.7
High strength-low alloy steel	80,000	7.8	10.3
Magnesium alloy, M-1 alloy, annealed	34,000	1.8	18.8
Alloy steel, heat-treated, medium strength, A.I.S.I. 3130	150,000	7.8	19.3
Aluminum alloy, 24S–T4, rolled	62,000	2.8	22.1
Alloy steel, heat-treated, high strength, A.I.S.I. 3140	180,000	7.8	23.0
Stainless steel, 18–8 type, rolled	200,000	7.9	25.3
Magnesium alloy, AZ80, rolled	50,000	1.8	27.7
Aluminum alloy, 75S–T6, rolled[1]	82,000	2.8	29.2

* Typical mechanical properties.

[1] Values given for sheet. Extrusions will have strengths about 8–10 per cent higher.

An interesting case is presented by the three important light metals of construction: magnesium alloy, aluminum alloy and stainless steel. Although their specific gravities are approximately 1.8, 2.85 and 7.9, respectively, these metals are almost equally light, their strength-weight factors all lying between 23 and 29. Characteristic tensile strength values of the various metals are used in Table 2. All alloys are in the heat-treated state. Obviously, some design value other than tensile strength might be used, such as the yield point or yield strength, the endurance limit, etc. The materials can be compared equally well on such a basis, provided that the same character is used throughout.

If the fatigue or endurance limit of the metals of low specific gravity, such as magnesium or aluminum alloy, is used for comparison, they are shown to be decidedly heavier than steel because the ratio of endurance limit to ultimate strength of such metals is lower than with heat-treated alloy steels.

Naturally many factors enter into the choice of a construction material besides its strength-weight value, such as modulus of elasticity, machining or fabricating characteristics, first cost of the raw material, resistance to corrosion, etc. The problem of choice is a complicated one, but where lightness of structure is important, strength-weight factor should be given primary consideration.

Chapter II

Aluminum Alloys

Light weight, ease of fabrication, high resistance to atmospheric corrosion, good thermal conductivity, and high metallic luster are characteristics which have helped make aluminum a commonly used structural material. Aluminum weighs only about one-third as much as most of the common metals, but is one and a half times as heavy as magnesium.

Commercially pure aluminum, in the annealed condition, is very ductile when cold and can be drawn to greater depths than can copper, brass or steel. Although commercially pure aluminum in the annealed condition has a tensile strength only about one-fourth that of structural steel, the strength can be markedly increased by cold-working the metal. This gain in strength is accompanied by a loss in ductility, and as a result the ease of forming is decreased as the amount of cold-working is increased.

There are two types of wrought aluminum-base alloys.[5] In one type the harder tempers with increased tensile properties are produced only by cold-working, *i.e.*, strain-hardening. In the second type the higher strengths are produced by heat-treatment processes, or by a combination of heat treatment and strain-hardening. Several alloys of these types, covering a wide range of physical properties and forming qualities, are commercially available in the forms into which metals are usually fabricated.

Hard tempers of the common, non-heat-treatable aluminum-base alloys are produced by cold-working. Of these alloys, commercially pure aluminum alloy 2S is the most easily worked. For many purposes the strengths of the non-heat-treatable alloys in the cold-worked condition are entirely adequate, and their use offers the advantage of lower cost and greater ease of fabrication than do the heat-treatable alloys.

Normal use of the strong heat-treatable alloys is in the heat-treated condition, as in the annealed condition they have mechanical properties comparable with those of certain of the common alloys. Their maximum properties are obtained by heating at 860 to 980°F. and quenching in cold water, after which they are allowed to age for several days at room temperature or several hours at 250 to 375°F. Hardening of heat-treatable alloys produced by cold-working is accompanied by a loss of ductility.

In all the heat-treatable alloys, plasticity and workability are better directly after the solution heat-treatment than after age-hardening. The annealed temper of these alloys is best for severe cold-working operations, such as bending, drawing and forming.

Many of the wrought aluminum alloys are heat-treatable and can be obtained in different hardnesses and tempers. A valuable combination known as "Alclad" consists of a strong aluminum alloy clad with about 5 per cent of high purity, corrosion-resistant aluminum or aluminum alloy on each side. The wrought alloys range in tensile strength from 13,000 psi for the annealed commercially pure aluminum to over 82,000 psi for the best heat-treated alloy. Cold-working readily doubles the strength of commercial aluminum, and the addition of alloying elements together with utilization of certain thermal treatments increases the strength of aluminum more than six times, so that it competes with steel structurally.

Hard temper material, obtained by strain-hardening, is a very stiff, springy, cold-rolled product intended for flatwork only. It is not suitable for bending with or against the grain. Half-hard temper is a moderately stiff cold-rolled product suitable for easy bending, capable of being bent to a 90° angle across the grain around a radius equal to the thickness of the material. Quarter-hard temper is a medium soft, cold-rolled product, suitable for forming, bending and easy drawing. It is capable of being bent flat upon itself across the grain, and of being bent with the grain to a 90° angle around a radius equal to the thickness of the material, but not less than 0.010 inch. Soft temper is a soft, ductile, cold-rolled product, suitable for fairly deep drawing where no sign of surface disturbance such as drawing strain is permissible. It is capable of being bent flat upon itself with or across the grain. It is also called the annealed temper.

In the second group of alloys depending on heat treatment for final hardening and strength, maximum physical properties are produced by a solution heat treatment followed by aging. The annealed temper is designated by "O" and the fully hardened by "T"; for example 24SO and 24ST. The number after the "T" indicates the type of heat treatment. The intermediate temper, after solution treatment, is designated by "W," and it is necessary then to artificially age this alloy at elevated temperatures to obtain "T" temper. However, several aluminum alloys are capable of natural aging at room temperature. Artificial aging at elevated temperatures will result in full hardness and strength in a shorter time than natural aging at room temperature.

Alloying Elements

Of the elements used in the production of commercial wrought aluminum alloys, copper, silicon, iron manganese, magnesium, zinc, chromium, and nickel are the most common. They may be used singly or in combination. Some of the high-strength alloys are quite complex and contain as many as six intentionally added elements, as well as silicon and iron which may be present in controlled amounts as impurities.

Copper up to 5.5 per cent improves dynamic fatigue and elastic properties. It increases the strength and hardness but impairs the ductility. It improves machinability and castability, but decreases corrosion resistance. It helps maintain properties at elevated temperature, and most of all it makes the resulting alloy respond to age-hardening heat treatment for optimum physical properties.

Magnesium up to 3 per cent increases strength, hardness and machinability. It may increase corrosion resistance to salt spray and mild alkaline solutions slightly, but lowers resistance to dilute acids. Aluminum-magnesium alloys have poorer castability than other aluminum alloys, but are better in this respect than pure aluminum.

Manganese up to 1.5 per cent increases mechanical properties without impairing corrosion resistance. It is a mild hardener, increasing strength but decreasing ductility. It improves properties at elevated temperatures and improves machinability.

Zinc up to 6 per cent is added always in combination with copper or magnesium. It increases strength and hardness with little loss of ductility.

Nickel up to 2.5 per cent increases strength and hardness, but lowers ductility. It impairs corrosion resistance but aids in maintaining strength at elevated temperatures. Nickel is never used except with copper. It is found only in several grades of casting and forging alloys in high-temperature service.

Chromium is used up to 0.3 per cent. It acts as a grain refiner, increases physical properties at elevated temperatures, and improves corrosion resistance.

Bismuth and lead up to 0.5 per cent each improve machinability. They are found only in the free-cutting bar stock used in the automatics.

Titanium improves response to heat treatment for the casting alloys.

Silicon up to 1 per cent in conjunction with copper and magnesium improves the alloy's response to heat treatment.

Alloys

The common alloys[4] derive their increased strength in the annealed condition from the alloying elements employed. Further increases in the strengths of these alloys can be obtained only through the introduction of cold work, such as cold-rolling, cold swaging, tube drawing and the like. They are not amenable to hardening by thermal treatments. Examples of these alloys in general use are 2S, 3S, and 52S.

The high-strength alloys respond to heat treatment for great increases in hardness and strength properties. These alloys are hardened by a solution heat treatment followed by an aging treatment at a lower temperature. Examples are 14S, 24S, 61S, 75S, R301 and R303.* The 17S alloy (the original heat-treatable alloy) has been practically replaced by the 24S and 61S alloys due to their superior properties.

Table 3 shows the nominal chemical composition of the commercial wrought aluminum alloys.

TABLE 3. *Nominal* Chemical Composition*

Alloy	Cu	Si	Mn	Mg	Zn	Cr	Al
2S	0.2 max.	†	0.05 max.	—	0.1 max.	—	99.0 min.
3S	0.2 max.	0.6 max.	1.0–1.5	—	0.1 max.	—	Bal.
24S	4.5	—	0.6	1.5	—	—	Bal.
52S	—	—	—	2.5	—	0.25	Bal.
61S	0.25	0.6	—	1.0	—	0.25	Bal.
75S	1.6	—	—	2.5	5.6	0.3	Bal.
R301 (core)	4.5	1.0	0.8	0.4	—	—	Bal.
R303	1.3	—	—	2.5	6.5	0.25 (0.1 Ni)	Bal.

* Unless otherwise specified.
† Iron plus silicon—1.0 per cent max.

Alloys 2S and 3S are inexpensive, and are generally used where workability or finish is important and tensile strength is of little or no concern. These alloys are readily drawn, easily finished and very weldable. They also have excellent resistance to corrosion. Alloy 3S has slightly higher strength than 2S, but has similar welding characteristics.

Alloy 52S is used where greater strength is required than can be obtained from alloy 3S. The tensile and yield strengths are about double those of 3S in corresponding tempers. It also has high resistance to corrosion, especially to sea water. This alloy is readily drawn, but work-hardens more rapidly than 3S, and therefore requires more frequent intermediate anneals during cold reduction.

Alloys 24S and R301 are high-strength materials and have been primarily used for aircraft and surface transportation construction where excellent workability and high strength are required.

Alloy 61S is a general-purpose product for structural application and is the least expensive of the heat-treated alloys. The mechanical properties are intermediate between those of the common alloys (2S, 3S and 52S) and the heat-treated, high-strength alloys 24ST and 75ST. Alloy 61S is characterized by a high yield strength, yet it is fairly workable, readily welded and has excellent corrosion resistance.

---

* All numbered alloys followed by the letter "S" are those of the Aluminum Company of America, while those numbered alloys preceded by the letter "R" are those of the Reynolds Metals Company.

Alloys 75S and R303 are the highest-strength aluminum alloys commercially available. They are finding increased use where maximum strength, hardness, and wear resistance are important.

Due to their poorer forming characteristics in the fully hardened condition, alloys 24S, 75S, R301 and R303 must be formed in the annealed condition and the parts heat-treated after forming. In order to improve corrosion resistance, these alloys are generally used for sheet in the clad form. The "Alclad" products are characterized by their superior resistance to perforation by corrosion. They consist of a surface layer of one aluminum alloy metallurgically bonded to another possessing the desired mechanical properties. The surface coating, which is applied to either one or both sides of sheet products, is chosen so that it will be anodic to the core. In this manner cathodic protection is provided at the metal surface and the structural integrity of the core material is maintained. The "Alclad" products now available are 3S (sheet and tubing), 14S, 24S, 75S plate and sheet, and 56S wire. The clad R301 and R303 are also available.

Standard clad sheet products are fabricated with each film thickness amounting to approximately 5 per cent of the total thickness of the sheet. As a result the tensile and yield strengths are approximately 10 per cent lower than corresponding values for the uncoated alloys. The actual cladding thickness varies with the gage.

Properties

All aluminum alloys have rather low strength values in the cast or annealed condition. Cold-working the non-heat-treatable alloys increases the tensile strengths from an average low of 13,000 psi for the soft 2S alloy to an average high of 41,000 psi for the hard-drawn 52S alloy, with a corresponding decrease in ductility from 35 to 7 per cent elongation. The

TABLE 4. *Typical Physical Properties of Non-heat-treatable Alloys*

Alloy and temper	Tensile strength (psi)	Yield strength (psi)	Elongation (% in 2") (Sheet 1/16" thick)	Shearing strength (psi)	Brinell hardness
2S-O	13,000	5,000	35	9,500	23
2S-H12(¼H)	15,500	14,000	12	10,000	28
2S-H14(½H)	17,500	16,000	9	11,000	32
2S-H16(¾H)	20,000	18,000	6	12,000	38
2S-H18(H)	24,000	22,000	5	13,000	44
3S-O	16,000	6,000	30	11,000	28
3S-H12(¼H)	19,000	17,000	10	12,000	35
3S-H14(½H)	21,000	19,000	8	14,000	40
3S-H16(¾H)	25,000	22,000	5	15,000	47
3S-H18(H)	29,000	26,000	4	16,000	55
52S-O	27,000	12,000	25	18,000	45
52S-H32(¼H)	34,000	27,000	12	20,000	62
52S-H34(½H)	37,000	31,000	10	21,000	67
52S-H36(¾H)	39,000	34,000	8	23,000	74
52S-H38(H)	41,000	36,000	7	24,000	85

yield strength, shearing strength and hardness increases with increase in tensile strength. Age-hardening of the heat-treatable alloys will increase the tensile strengths from an average low of 18,000 psi for the soft-annealed 61S alloy to an average high of 82,000 psi for the fully hardened 75S–T6(T) alloy in sheet form.

Typical physical properties of the important wrought aluminum alloys in the various tempers are shown in Tables 4 and 5. It is to be noted that the yield strengths of the 75S–T and the R303–T alloys are higher than those of normal structural steels.

TABLE 5. *Typical Physical Properties of Heat-Treatable Alloys*

Alloy and treatment	Tensile strength (psi)	Yield strength (psi)	Elongation (% in 2") (Sheet 1/16" thick)	Shearing strength (psi)	Brinell hardness
24S–O	27,000	11,000	19	18,000	47
24S–T3(T)	70,000	50,000	16	41,000	120
24S–T4(T)	68,000	48,000	20	41,000	120
24S–T36(RT)	73,000	57,000	13	42,000	130
"Alclad" 24S–O	26,000	11,000	19	18,000	—
"Alclad" 24S–T3(T)	64,000	44,000	15	40,000	—
"Alclad" 24S–T4(T)	64,000	42,000	19	40,000	—
"Alclad" 24S–T36(RT)	67,000	53,000	11	41,000	—
61S–O	18,000	8,000	22	12,500	30
61S–T4(W)	35,000	21,000	22	24,000	65
61S–T6(T)	45,000	40,000	12	30,000	95
75S–O	33,000	15,000	17	22,000	60
75S–T6(T)	82,000	72,000	11	49,000	150
"Alclad" 75S–O	32,000	14,000	17	22,000	—
"Alclad" 75S–T6(T)	76,000	67,000	11	46,000	—
R 301–O	25,000	10,000	22	18,000	—
R 301–W	62,000	41,000	19	40,000	—
R 301–T	68,000	60,000	10	43,000	—
R 303–O	30,000	15,000	24	——	—
R 303–T	77,000	71,000	14	47,500	150

Values for R303 alloy are for bar stock.
Elongation values for R301 alloys are 1/2" diameter rod.

The typical shear and fatigue properties of these wrought alloys are shown in Table 6 as follows:

TABLE 6. *Typical Shear and Fatigue Properties*

Alloy and temper	Shear strength (psi)	Fatigue strength (psi)
2S–O to 2S–H18(H)	9,500–13,000	5,000– 8,500
3S–O to 3S–H18(H)	11,000–16,000	7,000–10,000
52S–O to 52S–H38(H)	18,000–24,000	17,000–19,000
24S–O to 24S–T36(RT)	18,000–42,000	13,000–18,000
61S–O to 61S–T6(T)	12,500–30,000	9,000–13,500
75S–O to 75S–T6(T)	22,000–49,000	—— 21,000
R303–O to R303–T	—— 47,500	—— 22,500
R301–O to R301–T	—— 43,000	—— 12,500

The endurance (fatigue) limit varies from about 5,000 psi for the common 2S–O alloy to more than 21,000 psi for the high-strength 75S–T6(T) alloy; the shear strength varies from an average of 9,500 to 49,000 psi.

The compressive yield strengths of the aluminum alloys are slightly less than the corresponding tensile yield strengths for products that are straightened or flattened by stretching. Otherwise, they are substantially the same.

Table 7 is a tabulation of the guaranteed physical property specifications[8] for sheet and plate of 2S, 3S and 52S wrought alloys in various tempers and gauges.

TABLE 7. *Guaranteed Physical Property Specifications Sheet and Plate (2S, 3S, and 52S)**

Grade and temper	Tensile strength (psi minimum)	Elongation in 2" (% minimum) (Thickness 1⁄16")					
		0.013–0.019	0.020–0.031	0.032–0.050	0.051–0.113	0.114–0.161	0.162–0.249
2S–O	15,500 †	15	20	25	30	30	30
2S–H12(¼H)	14,000	3	4	6	8	9	9
2S–H14(½H)	16,000	2	3	4	5	6	6
2S–H16(¾H)	19,000	1	2	3	4	4	—
2S–H18(H)	22,000	1	2	3	4	4	—
3S–O	19,000 †	20	20	23	25	25	25
3S–H12(¼H)	17,000	3	4	5	6	7	8
3S–H14(½H)	19,500	2	3	4	5	6	7
3S–H16(¾H)	24,000	1	2	3	4	4	—
3S–H18(H)	27,000	1	2	3	4	4	—
52S–O	31,000 †	15	18	20	20	20	20
52S–H32(¼H)	31,000	4	5	5	7	9	9
52S–H34(½H)	34,000	3	4	4	6	7	7
52S–H36(¾H)	37,000	3	3	4	4	4	—
52S–H38(H)	39,000	3	3	4	4	4	—

* Physical properties for plates in the annealed (O) temper will be substantially the same as for the heavier sheet gauges. The physical properties for "as rolled" (H temper) plates will vary somewhat, and are not guaranteed.

† Maximum.

The modulus of elasticity of aluminum alloys[1] varies somewhat, depending on the composition of the material; in general it increases with increasing percentages of alloying elements from about 10,000,000 to about 10,800,000 psi. For practical purposes, however, the modulus may be taken as 10,300,000 psi.

The modulus of rigidity is 3,900,000 psi corresponding to a value of 0.33 for Poisson's Ratio. The modulus of resilience varies with the square of the elastic strength of the alloy, and therefore differs for different aluminum alloys, as well as for similar alloys in different tempers.

The increase[4] in strength obtained by alloying other elements with aluminum, and by heat-treatment and cold work is accompanied by changes in other properties of the metal. These changes, other than strength, frequently are very important and require careful consideration in design.

The increased deflection of the aluminum alloys, caused by lower modulus of elasticity, is offset by their increased ability to resist impact without permanent set, and to reduce stresses produced by fixed deflections. Their ability to resist energy from dynamic loads is even greater. As an example, for equal elastic strengths, the strong aluminum alloys on a weight basis will resist approximately eight times as much energy as steel. By volume, the energy resistance of aluminum is three times as great as that of steel.

Aluminum alloys,[7] like other metals, when subjected to elevated temperatures, have lower tensile strengths, yield strengths, and moduli of elasticity, and higher per cent elongations. When exposed to sub-zero temperatures, the mechanical properties, including the per cent elongation of aluminum, increase.

Overaging or improper aging of the heat-treatable alloys may occur on prolonged exposure to elevated temperatures, resulting in impaired resistance to corrosion of some of the alloys or changes in mechanical and physical properties.

Table 8 shows the typical changes in tensile properties of two aluminum wrought alloys[1] after prolonged heating at testing temperature.

Table 8. *Typical Tensile Properties of Aluminum Alloys at Elevated Temperatures.*

Alloy	Property	75°F.	300°F.	400°F.	500°F.	600°F.
3S–O	T.S. (psi)	16,000	11,000	8,000	6,000	4,000
	Yield strength	6,000	5,000	4,500	3,500	2,500
	Elongation (%)	40	47	50	60	60
3SH14 or 3SH24 (3S–½H)	T.S. (psi)	21,500	17,500	14,000	10,000	5,000
	Yield strength	19,000	12,500	8,000	4,000	3,500
	Elongation (%)	16	17	22	25	40
3SH18 or 3SH28 (3S–H)	T.S. (psi)	29,000	22,500	16,500	10,000	4,000
	Yield strength	26,000	14,500	6,500	4,000	2,500
	Elongation (%)	10	12	15	25	55
52S–O	T.S. (psi)	27,000	20,000	15,000	11,000	7,500
	Yield strength	12,000	10,500	9,000	7,000	4,500
	Elongation (%)	30	55	65	100	105
52SH36 (52S–¾H)	T.S. (psi)	39,000	32,000	24,000	12,000	8,000
	Yield strength	34,000	27,000	11,000	8,000	4,500
	Elongation (%)	10	16	35	80	100

The new age-hardenable high-strength aluminum alloys are characterized by relatively low elongations, reduced impact resistance, increased notch sensitivity, increased ultimate strength, and a yield strength that is much more nearly equal to the ultimate strength than is true with the conventional unaged aluminum alloys.

Working

The wrought alloys can be hot- or cold-worked by rolling, forging, pressing, extruding and drawing. Structural shapes, such as I-beams, H-beams, channels and angles may be either rolled or extruded.

An extruded shape is produced by forcing hot metal through a die in which there is an opening corresponding in shape to the desired cross-section. This process frequently provides more efficient utilization of metal than rolled shapes, and it permits production of many shapes that cannot be rolled.

Cold-rolling is performed to accomplish any or all of the following purposes: (1) to improve surface; (2) to obtain dimensional accuracy relative to thickness; (3) to produce degrees of temper.

During cold-rolling, commercial aluminum (2S) can be reduced 90 to 95 per cent without damage to the material, but the alloys of aluminum can be reduced only 50 to 75 per cent, when they must be softened by heating before further cold reduction can be performed. Cold-working results in strain-hardening the metal, but by proper annealing the metal can be softened again.

Relative ease of cold-forming the various grades and tempers, as well as the amount of work that can be done, varies with the nature of the operation and the equipment employed. In general, the forming characteristics of these materials are very good in the annealed condition, fair to good after solution heat treatment, but poor to very poor in the aged conditions.

Aluminum alloys having a wide range between the tensile and yield strengths generally have a larger capacity for cold work than those with a narrow range. Those with high elongation values can be given deeper draws than those with low elongations if the strength values are sufficiently high to prevent rupture.

The 52S alloy work-hardens (strain-hardens) more rapidly than either 2S to 3S alloys, and as a result can be given a less drastic reduction and must also receive more intermediate anneals.

The chief requirement for successful cold-forming is that the tools shall permit a suitable radius for bending and drawing operations. The required radius depends on the alloy, temper, and thickness of the material. Usually somewhat more liberal radii are required for the strong aluminum alloys than those necessary for drawing steel.

For the ultra-strong aluminum alloys such as 75S and R303, the bend radius is ½ to 3 times the sheet thickness for annealed stock and 2 to 10 times the sheet thickness for solution-treated and aged stock. The minimum bend radius will naturally be determined by the alloy composition, temper and sheet thickness.

In general, "Alclad" 75S–T sheet is less workable than "Alclad" 24S–T sheet, and this is reflected in certain changes in working procedure. The bend radii must be increased by at least 1T and possibly 2T (T = thickness) over those used for "Alclad" 24S–T. Also a different allowance for springback is required for 75S–T than for 24S–T.

Hot-forming[8] has only limited application among the alloys whose tempers are produced by definite amounts of strain-hardening, as by cold work. In the soft tempers all the alloys have good forming qualities; if they are heated in the harder tempers, care must be taken to avoid heating to the annealing temperature. At temperatures above 600° F. they are quite plastic, but on cooling to room temperature they are practically in the annealed state. Much improvement in bending and forming qualities is obtained when working at 300 to 400° F., in which temperature range there is little loss in strength and hardness on cooling.

By heating the material to 250 to 300° F. for the bending operation, the minimum bend radii may be substantially reduced without any appreciable reduction in mechanical properties.

Forming and reworking of materials[6] are shop problems, but they also merit careful consideration by designers. The introduction of aged super-alloys has made these problems more acute when forming of any kind is necessary after the final heat treatment. The aging heat treatment greatly increases the yield strength, so that the amount of springback from forming and similar operations is larger, and greater loads and better tools are required to do the work. The aging treatment increases the yield strength more than it does the ultimate strength, so that the gap between the two is sharply reduced. As the forces required in these forming operations must necessarily stress the material past its yield strength—indeed almost to its ultimate strength—there is great danger of failure in the form of cracked parts. In some cases the ratio of yield strength to ultimate strength can be as high as 95 per cent.

Wherever possible, forming of the age-hardenable alloys should be done on material in the fully heat-treated and aged condition. When this is not possible, it should be done promptly after heat-treating, when the metal is in a more workable condition than it is after aging. The parts can then be aged to obtain full strength and hardness.

Much of the forming and blanking work[1] is done on hydraulic presses fitted with a rubber pad on the ram. Drop hammers use zinc alloy dies and lead punches cast in the die cavity. Sheet panels having a very slight double curvature are sometimes formed by stretching them over a metal or hardwood form. Rough spots or poor lubrication can cause particles of aluminum to tear out of the work and build up on the tool surface. This condition is cumulative and, once started, becomes progressively worse. In addition to marring the surface of the metal, it may even cause fracture because the metal is unable to slip easily over the tool surfaces.

Soluble oils are sometimes used as lubricants, but more often a mineral oil, tallow, paraffin or a mixture of tallow and paraffin is better for the more severe forming operations.

Heat Treatment

All the heat-treatable wrought alloys require two stages in the hardening process.[4] First, a high-temperature solution treatment, followed by a drastic quench in a cooling medium; and secondly, an aging treatment at a lower temperature than that of the solution treatment. Some alloys are capable of aging rapidly at room temperature, but the time required for aging can be decreased by increasing the temperature.

The solution heat treatment of aluminum alloys involves bringing the material to a prescribed temperature, holding it there for a prescribed length of time, and then promptly quenching it. Either a fused salt bath or an air furnace is used. It is important that the specified temperature limits be maintained. When the temperature is too low, optimum mechanical properties are not attained, and when it is too high, the quality of the material is impaired by melting at the grain boundaries. A rapid cold water quench is essential to produce material with highest resistance to corrosion. This is true for 24S and 75S alloys, but not for 61S alloy.

The purpose of the solution treatment [1] is to bring about solid solution of the alloying constituents in the aluminum at the elevated temperature and to prevent its precipitation in accordance with the lower solubility at room temperature by very rapid cooling. The strength and hardness are thus increased over those of the annealed material.

After the alloy has remained at room temperature following solution heat treatment, aging occurs by a gradual precipitation of the insoluble constituents from the supersaturated solid solution, with a resulting further increase in strength and hardness, accompanied by loss in ductility and corrosion resistance. This precipitation and corresponding strengthening effect can be accelerated by heating the material to an elevated temperature below the previous quenching temperature. In general, the tensile properties and the hardness increase to values substantially higher than those developed by aging at room temperature.

The rate of increase in mechanical properties on aging depends not only on the time and temperature of aging but also on the composition and the method of fabrication of the alloy prior to heat treatment. Some alloys are more responsive to age-hardening heat treatments than others; and in addition, some alloys are affected in their response to aging heat treatment by the amount of cold work to which they have been subjected. The mechanical properties of 24S and R301 alloys, in most cases, are greatly improved by cold work prior to the aging heat treatment; while the properties of 75S and R303 alloys are not affected. Table 9 shows the recommended heat treatments for the soft-annealed 24S, 61S and 75S alloys.

TABLE 9. *Heat Treatment of Aluminum Alloys*

	Solution treatment			Precipitation (aging) treatment		
Annealed temper	Heat to ° F.	Quench	Resulting temper	Heat to ° F.	Hold for hours	Resulting temper
24S-O	910-930	cold water	24S-T4 *	375 †	11-13	24S-T81
				375 †	8-10	24S-T84
						24S-T86
61S-O	960-980	cold water	61S-T4	315-325	16-20	61S-T6
				345-355	6-10	61S-T6
75S-O	870 ‡	cold water	75S-W	245-255 §	22-26	75S-T6

Note: In heat-treating clad 24S and 75S alloys, hold at temperature for shortest period of time.

In quenching, submerge in cold water as quickly as possible after removal from furnace.

* For extrusions, the correct temper designation is T42.

† Cold-working subsequent to the solution heat treatment and prior to the precipitation treatment is necessary to secure the required properties.

‡ Sheet may also be heat-treated at higher temperatures (up to 925° F.) if desired.

§ A two-stage treatment comprising 4 to 6 hours at 210° F. followed by 8 to 10 hours at 315° F. may be used for sheet, but anyone using it may wish to consult his patent counsel regarding U.S. Patent No. 1,858,092.

The newer high-strength alloys, such as R303 and 75S, require three steps in the thermal hardening process: first a high-temperature solution heat treatment, and then a drastic quench; second, a two-stage aging process. If it is desirable to maintain the workability to aid in forming, the material is held at a low temperature after quenching, since lower temperatures will retard the rate of aging.

The strain-hardening,[1] which results from cold-working aluminum alloys, may be removed by annealing, *i.e.*, by heating to allow recrystallization to take place. The rate at which recrystallization occurs is greater, the higher the temperature and the more severely the metal has been worked before annealing. Complete softening is practically instantaneous for 2S and 52S at temperatures over 650° F., and for 3S at temperatures over 750° F. Heating for longer times at somewhat lower temperatures will accomplish similar results.

Since the greater the degree of cold-working the lower the recrystallization temperature, it becomes evident that the harder the temper the lower the annealing temperature.

In the case of heat-treatable alloys, the metal must be raised to a temperature which will permit recrystallization (annealing) to remove the strain-hardening; but at the same time the temperature must be maintained as low as possible to avoid heat-treatment effects which would prevent complete softening of the alloy. Heating these alloys to 650° F. is sufficient to remove the strain-hardening which results from cold-working.

Machining

Wrought aluminum alloys generally have good machining characteristics. In general, tools for machining aluminum should have appreciably more side rake and top rake than are required for cutting steel. High speeds and fine to medium feeds are desirable. The cutting edges of the tools must be keen, smooth and free from grinding scratches. The finer the feed, the higher the speed.

These alloys can be machined without a lubricant with high-carbon steels, high-speed steel or cemented carbide. However, the application of a cutting lubricant is always recommended at the point of cutting. Mineral-base lubricant oils thinned with kerosene frequently are used for most machining operations.

Some aluminum alloys tend to form a built-up edge[2] on the cutting lip of the tool, consisting of welded particles which have been partially melted under the heat generated in cutting. This is most pronounced with the softer alloys, though it may arise with the harder ones also. It may be minimized by use of proper coolants and cutting compounds and by attention to the quality of tool surfaces.

The non-heat-treatable alloys give continuous chips which may be directed away from the stock by generous side and top tool rake angles. These alloys offer little resistance to cutting, and tool pressure in machining is low. However, they are inclined to be gummy in the soft-annealed condition and their machinability is improved by cold-working to their hard tempers.

The strong heat-treatable alloys can be machined to a good finish with or without a lubricant, although the use of a good lubricant is recommended for most operations. Since they have higher physical properties than the non-heat-treatable alloys, the resistance to tool penetration is greater and the resulting chips are long, continuous curls. More power is required to machine these alloys in the fully age-hardened condition than in the annealed condition, although a better surface finish is obtained in the fully age-hardened condition.

Welding

One of the two most critical factors in the welding[2] of aluminum is oxidation. Though aluminum derives its corrosion-resistant qualities from this oxide, it must be removed before sound welds can be made. Its removal is complicated by the fact that it has a higher melting point than the base metal. In the various forms of fusion welding, this difficulty is overcome by the use of fluxes, which combine chemically with the oxide to form a fusible slag. The other critical factor is the apparent weakness of aluminum alloys at high temperatures. Many are partially molten over wide ranges of temperature, and when temperatures at which partial melting occurs are reached in welding, the alloys show a tendency to collapse.

Aluminum alloys may be welded by the torch, electric arc or electrical resistance methods. In fusion welding the equipment is the same as that used for welding steel, but in electrical resistance welding, machines of slightly different design and greater electrical capacity are required. The metal arc method generally makes stronger welds than the torch method. In the latter the neutral flame of either oxyhydrogen or oxyacetylene may be used. The oxyhydrogen flame generally produces a cleaner and more satisfactory joint than the oxyacetylene.

The metallic arc welding process is particularly applicable in certain classes of work, since there is less buckling and warping. Temper of the sheet is less affected during arc welding than during torch welding, since the heat is more concentrated and the weld is made more rapidly. It is not considered good practice, however, to use the metal arc on thicknesses less than $\frac{1}{64}''$.

For metal arc electrodes, and filler rods for torch welds of the strong alloys, a flux-coated 5 per cent silicon-aluminum alloy is used. For torch welds of the common alloys such as 2S and 3S, especially if a polished surface is desired, commercial aluminum (2S alloy) filler rod is used. Generally the same alloy is recommended for filler rod as the parent metal to be welded.

A flux is used in all fusion welding. In the metal arc process, the flux is best applied as a heavy coating on the electrodes.

A particularly interesting method of joining aluminum employs an argon-shielded tungsten arc. No flux is utilized when this type of welding is used on aluminum. Therefore, considerably more latitude is allowable in designing joints, since there is no danger of entrapping corrosive flux in faying surfaces. Welds can be made in any position and weld bead is smooth, sound and free from spatter.

Surfaces must be cleaned for spot welding, especially the oxide coating, to avoid surface heating when contact is made with the welding electrode.

A welded joint, except in fully annealed material, will have somewhat lower mechanical properties than those of the unwelded metal. The heat of welding has an annealing effect on the alloys. In some cases, it also affects the corrosion resistance adversely. Heat treatment of the strong alloy welds will partially recover these losses of properties.

Riveting *

Riveting[1] is a common method of assembling aluminum structural members. Standard rivet alloys are A17ST, 17ST and 24ST. Rivets of A17ST alloy are more widely used than of the other two alloys, and are regularly driven in the fully heat-treated and aged condition. Joints requiring greater strength are made with 17ST or 24ST rivets, in which case the rivets are usually solution heat-treated so that they can be driven before age-hardening has progressed very far. Rivets of 53S alloy are used more generally in structures other than aircraft.

Satisfactory driving characteristics are maintained at room temperature (70° F.) for about an hour after quenching in the case of the 17ST rivets, and for about ten minutes in the case of the 24ST rivets. To avoid the necessity for continually heat-treating fresh material, 17ST rivets may be driven after about 24 hours if they are held at the temperature of melting ice (32° F.). Packing in Dry Ice (CO_2) is recommended, especially for 24ST rivets, as lower temperatures will retard age-hardening still more. When the rivets are returned to room temperature age-hardening proceeds in the normal manner.

For rivets over ½" diameter, A17S–T4 rivets are driven cold by squeeze riveters, or 53S rivets are driven hot where pneumatic hammers must be used.

The riveting operation ordinarily is done cold. The spacing of rivets in any joint depends upon the proportions of the members joined. Three times the nominal rivet diameter is the recommended minimum spacing.

Riveting as a method of joining is usually desired for the strong age-hardened aluminum alloys, since these materials cannot be welded without sacrifice in strength. However, care must be exercised in riveting the aged 75S–T and R303T alloys since the increased notch sensitivity of these materials may result in cracks when riveting is done near deep scratches or notches.

Failure of a rivet may occur in either of two ways: by shearing on one or more planes, or by crushing the metal at the point where the rivet bears against the plate.

---

* Excerpts from "Riveting Aluminum," a copyrighted booklet of the Aluminum Company of America.

Corrosion Protection *

All aluminum alloys are relatively resistant to ordinary exposure to industrial atmospheres. Alloys 2S, 3S and 52S are more resistant to corrosion than other aluminum alloys. Alloy 52S, however, is more resistant to salt water, both from the standpoint of appearance and retention of mechanical properties. Alloy 61S compares favorably with 2S, although the surface will exhibit more superficial pitting action in some corrosive atmospheres. The clad high-strength alloys, 24ST and 75ST, have nearly the same corrosion resistance as 2S, but the bare material is inferior to it.

Although all aluminum alloys exhibit relatively good resistance to corrosion, some of the high-copper, heat-treated and aged, strong alloys are considerably less resistant to corrosion than aluminum of high purity. To combine the great strength of these strong alloys with the excellent corrosion resistance of the pure metal, the clad products, called "Alclad" or "Pureclad," were developed.

In contact with moist air, aluminum quickly acquires a thin, impervious film of aluminum oxide which serves as a protective barrier against further attack. A thicker oxide film can be formed electrolytically where greater resistance to corrosion is required. This process is referred to as *anodic oxidization* or *anodizing.*

Anodic oxidation provides a hard, adherent oxide surface film having excellent corrosion resistance and abrasion resistance. It also provides an excellent paint base.

There are two recognized methods commonly used today for electrolytic anodic oxidation (anodizing) of aluminum: the chromic acid anodizing process and the sulphuric acid (Alumilite) anodizing process. The process using chromic acid electrolyte can be used on aluminum alloys containing less than 5 per cent copper; while the process using sulphuric acid electrolyte can be used on all aluminum alloys. Both processes, including the sealing process described in the following paragraph, are included in the patented Alumilite procedure.

The porous aluminum oxide film produced by both processes can be sealed by immersion in boiling water or in a 5 per cent potassium dichromate solution for 30 minutes. This additional treatment increases the film's resistance to corrosion still further.

Where aluminum alloys are assembled in wet contact with other metals there is danger of galvanic attack of the aluminum. To prevent this electrolytic action, it is best to insulate the dissimilar metals with bituminous paint, fiber strips, or asphalt-saturated felt.

---

* Excerpts from "Finishes for Aluminum," a copyrighted booklet of the Aluminum Company of America.

Since aluminum is anodic to a large number of alloys, special care should be taken to avoid contact with dissimilar metals or alloys. Where these must be used in connection with aluminum, however, both the dissimilar metal and the adjacent faying surface of the aluminum alloy should be coated thoroughly with zinc chromate primer before assembly. Insertion at the faying surface of a non-hygroscopic insulating material is advantageous under severe conditions.

Almost any kind of paint can be used on aluminum, although the materials more commonly employed are synthetic lacquers, synthetic enamels and aluminum paints.*

Many aircraft structures have been made of unprotected "Alclad" material and after several years of active service, it was found to be in excellent condition. Thus the material may generally be used without paint protection as far as the maintenance of structural integrity is concerned.

Design

Because of the lower value of the modulus of elasticity compared with that of steel, it is desirable to use deeper sections in aluminum alloys where it is necessary to maintain the same deflection characteristics when they are loaded as beams. Such redesign can be made to produce a structure having the same deflection under load and possible higher ultimate strength than would be obtained with structural steel, and at the same time to bring about substantial saving in weight.

The lower modulus of elasticity is an asset when impact loads are to be resisted since, other things being equal, the lower the modulus, the greater the ability to resist energy without permanent set. The lower modulus is also advantageous in reducing stresses produced by misalignment, settlement of supports, or other fixed deflections.

Rigidity is an important factor in converting from steel to aluminum. For structural applications, it is impractical to make direct size substitutions of aluminum for steel in many instances. To provide an equivalent structure, it is necessary to increase the thickness of the aluminum flat sheet and plate from 20 to 40 per cent. By proper selection of the alloy, the aluminum part will have greater strength and resistance to local denting than the steel part, and will weigh 50 to 60 per cent less.

If tensile strength is the primary consideration, any thickness increase will depend upon the aluminum alloy chosen.

In using aluminum for design where it occurs together with steel, it must be borne in mind that the coefficient of thermal expansion is slightly more than twice that of steel.

There is very little to choose between the strength-weight ratios of the high-tensile steels and light aluminum alloys, but there are many cases in

---

* See von Fischer, "Paint and Varnish Technology," Reinhold Publishing Corp., 1948.

which the full advantage of steel cannot be realized, because the steel section would be so thin that it would fail by local crippling before the full strength of the material could be utilized.

The high tensile yield strength of the new high-strength aluminum alloy products generally cannot be used in members designed for tension loads, as the ratio of yield to tension exceeds the two-thirds value. But since the compressive yield strength is approximately equal to the tensile yield strength, these products are admirably suited for compression members.

Sheet aluminum, corrugated and V-crimp, has been marketed with a typical tensile strength of 37,000 psi, a yield strength of 35,000 psi, and an elongation in 2 inches of 4 per cent. A low-cost utility sheet aluminum for general sheet-metal work, ventilating, heating and air-conditioning ducts, hoods, gutters and down spouts, has a typical tensile strength of 21,000 psi, a yield strength of 19,000 psi, and an elongation in 2 inches of 6 per cent.

Figure 1 shows a 100-foot aluminum bridge span which was installed late in 1946 on the Grasse River Bridge at Massena, New York. This bridge

(Courtesy Aluminum Co. of America, Pittsburgh, Pa.)

Figure 1. Aluminum bridge span.

is constructed primarily of aluminum plate and rolled stock, although the flange angles, 8″ × 6″ × ⅝″, as well as the T-sections used for lateral bracing, were extruded.

References

1. Aluminum Company of America bulletins.
2. Reynolds Metals Co. bulletins.
3. Permanente Metals Corporation bulletins.
4. Anon, "Working of Aluminum Alloys," *American Machinist*.
5. Miller, R., "Shop Aspects of the New High Strength Aluminum Alloys," S.A.E. reprint, October, 1945.
6. Nock, J., "75S–New High-Strength Aluminum Alloy," *Metals and Alloys* (October, 1945).
7. Ziegler, P., "Aluminum Alloys and Their Applications," *Light Metal Age* (December, 1945).
8. Mitchell, O., "Wrought Aluminum Alloys," *Materials and Methods* (February, 1946).

Chapter III

Magnesium Alloys

Because of their great chemical stability, ease of fabrication, and good strength-weight ratio magnesium alloys have become strong contenders in the highly competitive field of structural alloys.

Magnesium-base alloys have characteristics which place them in a separate class from other base alloys. They are the lightest structural alloys yet known, being two-thirds the weight of aluminum and one-fourth the weight of iron and steel. Some of the cast and wrought alloys respond to age-hardening heat treatment, which gives them greater physical strength. They also possess excellent machinability, toughness and fatigue endurance. They have a high strength-weight ratio, which means that on an equal weight basis their strength is equal or superior to that of most other structural metals.

Magnesium alloys are available in a number of commercial wrought forms. A variety of these alloys have been developed to meet specific demands for strength, ease of fabrication, workability, corrosion resistance, welding properties and other factors of importance.

These alloys are well adapted for use in structures which can be easily fabricated from extrusions, plates, sheet, castings, and forgings. Their ultra-light weight permits the design of structures which have equal stiffness and strength with lower weight than is obtainable with other metals.

Replacement of heavier metals with magnesium alloys may involve certain changes in design. Where steel has been used because of its greater strength, a part made from magnesium alloy must provide a greater cross-section. Strength increases in direct ratio to any increase in thickness, assuming constant width, but stiffness increases as the cube of the increase in thickness. Consequently, weight may be reduced, strength maintained and stiffness increased with greater resistance to bending, buckling, and elastic deformation and stress.

The weight-strength ratio favors certain magnesium alloys, as do the ratios of weight-stiffness, weight fatigue resistance, and other pertinent ratios in which light weight is the essential component.

There are a number of alloys of varying physical characteristics in sheets, both in annealed and hard-rolled tempers. The annealed material is used for parts requiring some forming and subject to little or no load, while the rolled material is used for parts with moderate or no forming and requiring higher yield strength.

Wrought magnesium alloys provide a very light structural metal for use in such applications as oil and fuel tanks, aircraft wings, bus and trailer bodies. In the form of sheets and plates these alloys are used for parts, such as cover plates, engine cowling, bus trailer and truck roofs, and side panels, aircraft wings and ailerons, floor plates, seats, conveyors and other applications. Magnesium extrusions are used for applications such as floor beams, moldings, stiffener elements in aircraft structures and frame sections, bus and trailer body frames and other structural members.

Since wrought magnesium alloys[4] have excellent strength-weight ratios they are used in many highly stressed structures. In castings, tensile strengths of 35,000 to 45,000 psi are reached, and in the wrought condition the tensile strengths may be 45,000 to 55,000 psi. In many cases weight savings up to about one-third can, therefore, be realized by changing from aluminum to magnesium alloys. Compared to most ferrous alloys, the weight saving may be about one-half, or even higher.

Alloying Elements

Alloying elements such as aluminum, manganese and zinc are added to give magnesium strength, corrosion resistance, weldability and formability.

Aluminum is the most important alloying element in magnesium-base alloys. It imparts hardness and increases tensile, yield and compressive strengths. With increasing content of aluminum, the grain structure becomes more refined, the strength and hardness increase, and the ductility diminishes. Alloys with more than 13 per cent of aluminum are too brittle for structural uses. Those containing 6 to 10 per cent of aluminum can be age-hardened with corresponding great increase in strength and hardness.

Manganese has little effect on the mechanical properties. It does increase resistance to corrosion and tends to improve weldability of the magnesium alloys. It is sometimes added alone, at other times together with aluminum.

Zinc, usually 1 to 3 per cent, primarily adds to the corrosion resistance of the alloy under saline conditions. It is an important alloying element for products which are to possess high strength, although in practice it is not used alone but in combination with aluminum.

Alloys

Table 10 lists the typical chemical composition of wrought magnesium alloys used in structures.

The AZ31X alloy is used for extrusions, plates, sheets and strips; AZ80X

Table 10. *Typical Chemical Composition of Magnesium Alloys*

ASTM Alloy *	Aluminum	Zinc	Manganese	Magnesium
AZ31X	3.0	1.0	0.3	bal.
AZ61X	6.5	1.0	0.2	bal.
AZ80X	8.5	0.5	0.2	bal.
M1	—	—	1.5	bal.

* All alloy designations not under the ASTM system of numbering are those of the Dow Chemical Company.

for heat-treated extrusions and forgings; AZ61X for extrusions and forgings; and M1 for extrusions, forgings, plate, sheet and strip.

Magnesium sheet is currently available in two commercial alloys: ASTM alloy M1 and ASTM alloy AZ31X. The former, also known as M alloy, is used where good weldability, maximum formability, low cost and moderate strength are required. ASTM alloy AZ31X, also known as FS–1 alloy, has better formability than J1 or M1 alloy, and also has good shear and tensile strength. This alloy has maximum impact resistance.

Magnesium sheet in the hard-rolled condition will have maximum yield strength at the expense of some ductility. Annealed material will have a lower yield strength but greater ductility than hard-rolled sheet. Consequently annealed sheet is used for applications requiring maximum formability.

The M1 alloy is usually used in the annealed condition and only in special cases is it used in the hard-rolled condition. The FS–1 alloy has superior bendability and slightly inferior drawability than M1 alloy sheet. In addition, the FS–1 alloy sheet is not generally used for welded assemblies except where stress-relieving treatment may be given after welding, owing to its tendency to crack from welding stresses set up in restricted joints. The hard-rolled sheet is used where high strength combined with toughness is required.

All magnesium structural shapes are produced by the extrusion press. Extrusion permits the use of shapes that are impossible to make by rolling. Of the four extrusion alloys ASTM alloy M1 is the cheapest and is used for general purposes where strength is secondary and shape is the major consideration. ASTM alloy AZ31X has the best combination of cost and properties and is the general-purpose structural alloy. It combines maximum strength and toughness. ASTM alloy AZ61X is slightly stronger but more expensive than the AZ31X alloy. ASTM alloy AZ80X (also known as O–1 alloy) is the strongest magnesium structural alloy, particularly in the extruded and aged condition. It is used where maximum strength is required but is not recommended for applications subjected to excessive shock or rough handling.

The O–1 alloy is the only wrought magnesium alloy that reacts to heat treatment, and it is commercially furnished in the as-extruded or as-forged condition and in the aged condition. Tensile strength in the as-worked condition will be about 50,000 psi with a yield strength of about 30,000 psi. After aging 10 hours at 350° F. following working, the tensile strength increases slightly and the yield strength will approach 35,000 psi.

Properties

Unlike steel, but similar to aluminum alloys in this respect, magnesium alloys do not exhibit sharp yield points when subjected to the usual tensile tests. There is a very gradual breaking away from the modulus line. Yield strength in these alloys is accepted as the point where the stress-strain curve deviates 0.2 per cent from the modulus line.

The modulus of elasticity of magnesium alloys is 6,500,000 psi, a value much lower than that of other structural metals. In spite of this, a magnesium sheet is over twice as stiff in flexure as an aluminum sheet of the same weight, and eighteen times as stiff as a steel sheet of the same weight. In resiliency, or capacity for elastic shock absorption, magnesium alloys excel because of their lower modulus of elasticity.

The modulus of rigidity or modulus of shear is about 2,400,000 psi, and the value of Poisson's Ratio is approximately 0.35.

Typical mechanical properties of sheets are shown in Tables 11 and 12. The properties, of course, will vary with the thickness and temper of the sheet.

TABLE 11. *Typical Mechanical Properties of Magnesium Alloys*

ASTM Alloy	Condition	Tensile strength (psi)	Yield strength (psi)	Elongation (% in 2 in.)	Brinell hardness
AZ31X	Annealed	37,000	22,000	21	56
AZ31X	Hard-rolled	43,000	33,000	11	73
M1	Annealed	33,000	15,000	17	48
M1	Hard-rolled	37,000	29,000	8	56

TABLE 12. *Typical Mechanical Properties of Magnesium Alloys*

ASTM Alloy	Condition	Compression yield strength (psi)	Shear strength (psi)	Fatigue strength (psi)
AZ31X	Annealed	16,000	21,000	12,000
AZ31X	Hard-rolled	26,000	23,000	14,000
M1	Annealed	12,000	17,000	9,000
M1	Hard-rolled	20,000	17,000	1,000

Typical mechanical properties of extruded products are shown in Tables 13 and 14. The mechanical properties of extrusions vary not only with the alloy composition, but also with the shape and size of the extrusions.

The AZ80X alloy (or O-1 alloy) can be strengthened by aging after extrusion. In this condition (designated as O-1HTA) minimum tensile prop-

TABLE 13. *Typical Mechanical Properties of Extruded Products*

ASTM Alloy	Tensile strength (psi)	Yield strength (psi)	Elongation (% in 2 inches)	Brinell hardness
		Bars and Rods		
AZ31X	40,000	30,000	15	49
AZ61X	45,000	32,000	15	58
AZ80X	49,000	33,000	11	65
M1	38,000	26,000	10	42
		Shapes		
AZ31X	38,000	26,000	15	50
AZ61X	44,000	28,000	16	64
AZ80X	46,000	29,000	9	67
M1	34,000	20,000	9	46
		Tubing		
AZ31X	36,000	21,000	16	46
AZ61X	40,000	21,000	9	50
M1	33,000	21,000	9	42

TABLE 14. *Typical Mechanical Properties of Extruded Products*

ASTM Alloy	Compressive yield strength (psi)	Shear strength (psi)	Fatigue strength (psi)
	Bars and Rods		
AZ31X	17,000	19,000	14,000
AZ61X	10,000	19,000	18,000
AZ80X	22,000	20,000	18,000
M1	14,000	16,000	9,000
	Shapes		
AZ31X	15,000		
AZ61X	19,000		
AZ80X	22,000		
M1	11,000		
	Tubing		
AZ31X	15,000		
AZ61X	15,000		
M1	9,000		

erties of 48,000 psi strength and 33,000 psi yield are obtained in bars. Typical properties for this grade of material are a tensile strength of 54,000 psi, a tensile yield of 39,000 psi, a compressive yield strength of 36,000 psi and an elongation of 8 per cent.

Heating will reduce tensile and yield strengths and increase ductility; therefore, proper design factors must be used at elevated temperatures. At temperatures over 400° F., magnesium alloys for structural purposes are not recommended. At subnormal temperatures magnesium alloys undergo only negligible changes of strength.

The curves in Figure 2 show how tensile strength and elongation vary with temperature for 0.040 to 0.060-inch sheets in the annealed condition.[6] The FSa alloy is equivalent to ASTM alloy AZ31X, the Ja alloy is equivalent to ASTM alloy AZ51X, and the Ma alloy is equivalent to ASTM alloy M1, all being in the annealed condition as indicated by the "a" after the alloy identification letter.

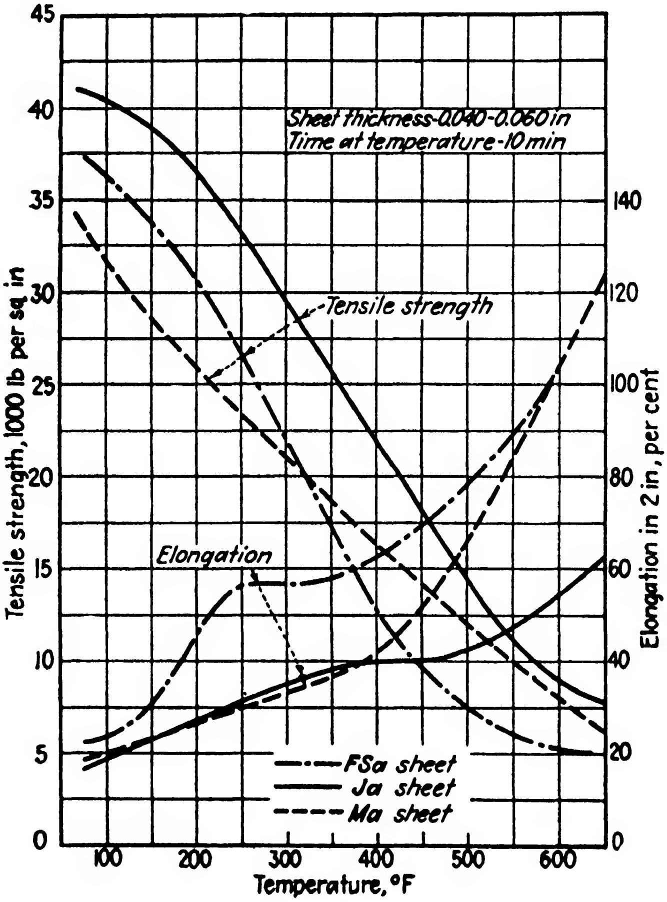


Figure 2. Curves showing how tensile strength and elongation vary with Temperature for "Dowmetal" sheets

The curves in Figure 3 show how tensile strength and elongation vary with temperature for 0.040 to 0.060-inch sheets in the hard-rolled condition.[6] The "h" after the alloy identification letter indicates the hard-rolled condition.

All magnesium alloys, whether cast or wrought, have higher damping capacities than any of the aluminum alloys. This property is particularly pertinent to applications involving reciprocating motion or moving parts, as the stresses on adjacent equipment or parts through vibration are smaller with magnesium alloys than with aluminum and its alloys. Magnesium alloys are very resilient and possess a high resistance to shock loads. Resilience of a material for a given applied stress is inversely proportional to its modulus of elasticity. Owing to its low modulus, magnesium alloys within their elastic range possess greater resilience than aluminum or steel, and as a consequence can absorb more shock by energy loads without undergoing damage.

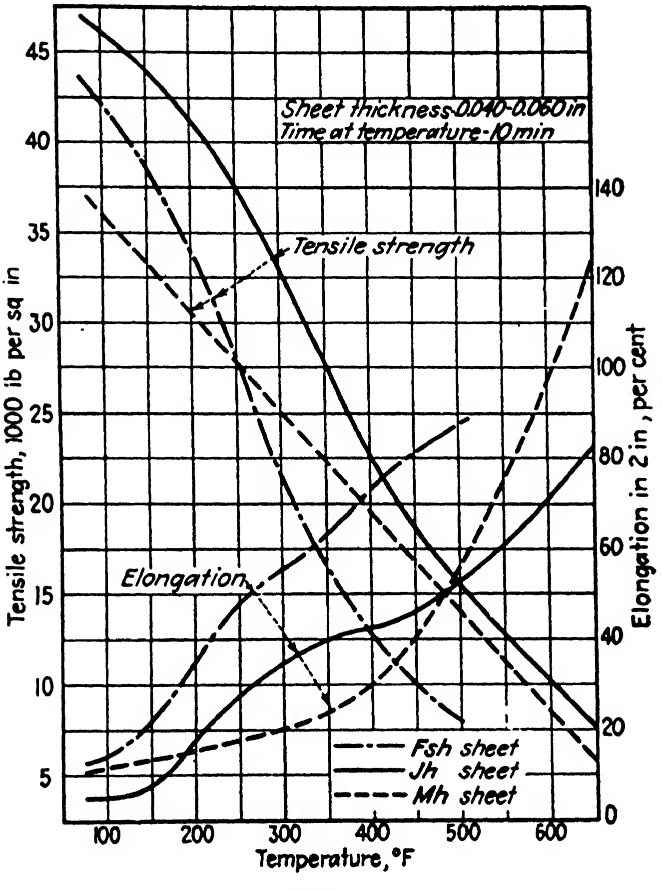


Figure 3. Curves showing how tensile strength and elongation vary with temperature for "Dowmetal" sheets.

Heat Treatment

The heat treatments to which magnesium alloys are subjected include annealing, quenching, solution treatment, aging and stabilizing.

Sheet and plate are annealed at the rolling mill. Annealing gives a lower yield strength but greater ductility than is obtained in hard-rolled sheet. The solution heat treatment is given for the purpose of putting into solid solution as much of the alloying ingredients as possible. It results in high tensile strength and maximum ductility. Aluminum and zinc are much more soluble in magnesium at elevated temperatures than at room temperature, and it is this fact which makes magnesium alloys (the same is true of certain aluminum alloys) susceptible to heat treatment. The properties of the alloys may be changed by controlling the quantities of solid solution and constituents precipitated at the grain boundaries. The solution heat treatment involves treatment at temperatures in the range of 700 to 800° F., depending on the exact alloy composition.

Working

Magnesium alloys have been developed which can be mechanically worked, rolled, extruded and drawn, thereby causing marked improvement in their physical properties. Rolled sheet can be made in thicknesses down to 0.005 inch.

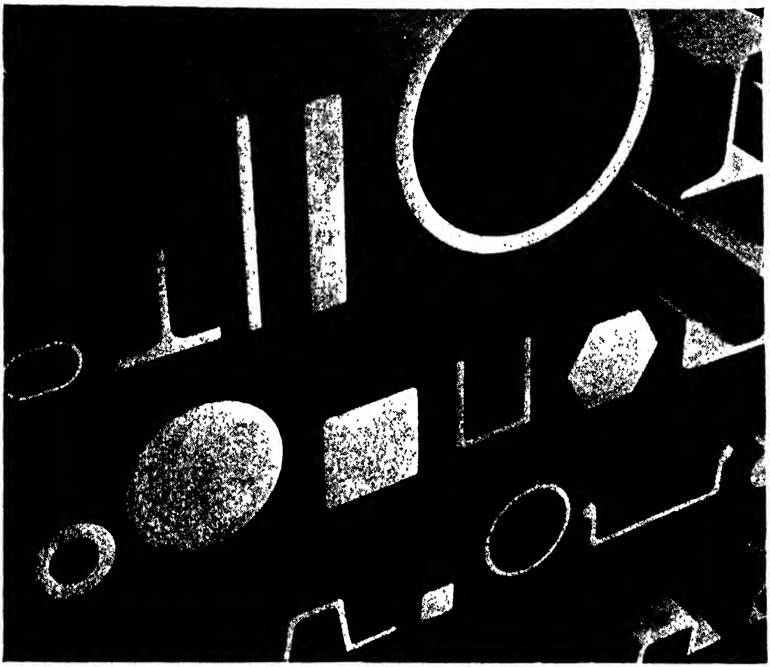
Sheet rolling methods employ an initial breakdown of rather large cast ingots or extruded slabs at elevated temperatures (about 750 to 900° F.), followed by the cold-rolling operations necessary to impart the desired physical properties and surface finish to the alloy. It is necessary to anneal the sheet quite frequently during cold-rolling operations.

Magnesium alloy sheet plate and extrusions can be fabricated in much the same way as other metals, with one important provision: the work usually must be done at elevated temperatures. The crystal structure is such that the alloys work-harden rapidly at room temperature. Therefore, working is usually done from 450 to 600° F.

Extrusions can be made in a wide variety of plain and intricate shapes (Figure 4). Extrusions are relatively inexpensive since the operation and necessary dies are low in cost.

Magnesium alloys have less favorable cold-forming properties than such metals as iron, copper and aluminum. They work-harden rapidly when formed at room temperature; hence their cold-working possibilities are limited. Cold-forming should be done slowly and, in designing forming tools, the relatively high springback must be taken into account. However, there is no springback during hot-forming.

Cold-working is usually confined to bending. Sheet stock is used in this operation and the predominant stress is tensile. Since cold magnesium sheet is incapable of even a moderate elongation without rupture, any attempt to deep draws, sharp bends, or severe pressing and spinning on cold sheet would result in failure. A limited amount of cold-working is possible, but liberal radii should be allowed.



(Courtesy Dow Chemical Co., Midland, Mich.)

Figure 4. "Dowmetal" extrusions.

Minimum cold-bending radius for sheet alloys in the soft temper is approximately four to five times the sheet thickness; in the hard tempers, eight to ten times. When hot-bent, the minimum bending radius is reduced to approximately twice the thickness. Radii of bends are determined by the alloy composition, its temper and the temperature of working. However, by heating the materials to elevated temperatures their workability is greatly improved.

Working magnesium metals at elevated temperatures and at speeds coincident with the recrystallization rate has several advantages over cold-working. The parts can often be formed, shaped or drawn in one operation without the necessity of drawing, annealing and redrawing, thus reducing not only the time involved for making the part, but also eliminating the necessity of additional die equipment for deep-drawn parts. Another advantage is that the allowance for "springback" is not required.

With proper equipment, magnesium alloy sheets can be formed at elevated temperature to nearly any shape commonly formed in aluminum alloy. Hard-forming, press-forming, rubber-forming or roll-forming utilize equipment and methods of the same types as are used for other metals.

Perhaps the most widely used process for working magnesium alloy sheet into shapes requiring only comparatively shallow forming and slight drawing action is the Guerin process, which has found much favor in pressings, etc. In adapting this process to magnesium alloy forming, it is customary to use heated dies. This is accomplished by placing the dies on a heated platen or hot plate or, for more complicated dies, by inserting heating elements in the die itself. Materials for very large parts should be preheated before being placed into position on the dies.

When parts are to be made in large quantities or where extreme accuracy is required, steel die equipment should be used.

When the temperature relation of sheet and dies is properly maintained, magnesium can be as readily drop hammer-formed as aluminum. Parts must be hot-formed perfectly on the form block to avoid the necessity of cold-forming afterward. Hard-rolled alloys should be used only where forming is moderate.

The top limit for single draws is given in Figure 5 as a function of temperature.[3] The drawability factor *D–d/D* is the ratio obtained by dividing the blank diameter minus the draw diameter by the blank diameter. The M1 alloy has better drawability than the FS–1, while the J1a alloy has the lowest drawability. Lubricants are employed for all drawing operations.

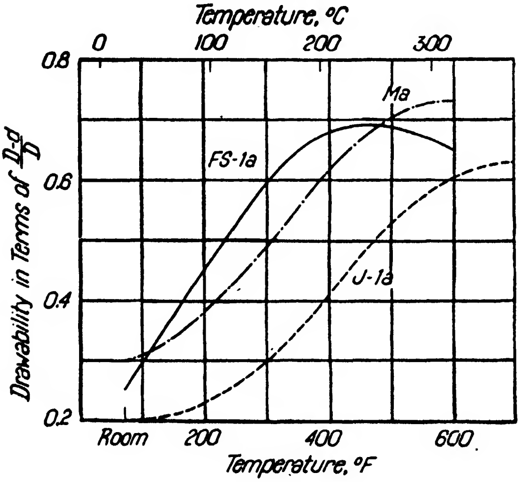


Figure 5. Limits for hot-drawing magnesium alloy sheet in a single operation.

Most successful forming of magnesium alloys is accomplished at elevated temperatures between 300 and 650° F., depending on the alloy used, gauge of material, temper of material and severity of forming. Slow forming produces better results than rapid forming. The slower the rate of forming and the more accurate the tools, the better the results.

Machining

Magnesium cast and wrought parts have excellent machining characteristics. There is no tendency toward dragging or tearing, and the metal readily takes a smooth surface and finish. Chips readily clear the work and the cutting tool. Magnesium alloys allow higher cutting speeds, greater feeds and deeper cuts than any other metal. For equal volumes of metal removed, the power consumption in machining magnesium is lower than that of any other metal. Power requirements for magnesium alloys are about one-sixth those for mild steel.

Magnesium can be machined without a lubricant because of the ease of cutting and the small amount of frictional heat generated with sharp and properly designed tools. Cutting tools should have smooth faces, large rake angles, small areas of tool in contact with the work, and large chip spaces. It is very important to keep the cutting edges as sharp and smooth as possible, and free from grinding wheel scratches. Tools should be designed to dispose of the chip rapidly and smoothly without jamming and developing frictional heat. Under any frictional conditions, the low heat capacity of the metal will produce higher temperatures in the tool, chips and work than will other metals.

Magnesium chips can be ignited if frictional heat developed during cutting rises too high. This sometimes occurs when fine chips are produced in light finishing cuts at high speeds, or when the cutting tools become dull. If such light cuts cannot be avoided it may be desirable to use a mineral oil coolant for such operations.

Welding

Magnesium alloy parts can be joined by arc welding, gas welding, and electrical resistance seam and spot welding. All these methods are applicable to magnesium structural assemblies, although each has its particular advantage for certain classes of work.

The most satisfactory method of welding magnesium is by means of the electric arc with tungsten electrodes in helium or argon gas atmosphere. A standard d-c arc-welding generator is used to strike an arc between the work and tungsten electrode. The molten metal area is shielded during welding by means of a small cup which surrounds the tungsten electrode. No flux is needed, and substantially complete protection is obtained against oxidation of the metal. The magnesium alloy filler rod used should be of approximately the same composition as the material being welded.

Alternating-current welding using superimposed high frequency and argon shield is becoming more and more popular and will probably be used almost exclusively on plate over 1/8 to 3/16 inches thick.

Because the flux used in gas welding is likely to cause corrosion if it is entrapped in the weld, all gas welding on magnesium alloys is limited to butt joints. Oxyacetylene, oxyhydrogen, or oxycarbohydrogen gas can be used, but the latter is preferable. Depending on the thickness of the material being welded, the work should be tack-welded at intervals of 1½ to 6 inches, the closest spacing of tacks being required for thin materials.

Resistance welding offers advantages of economy and freedom from corrosion possibilities, but it is not recommended for heavily stressed joints. Spacing of spot welds is important. The minimum spacing varies from ¼ to 2 inches with the sheet thickness and nature of the joint. Different magnesium alloys can be welded to each other but not to other metals.

In preparing for the welding operation, the area to be welded should be carefully cleaned free of oxides and non-metallic inclusions, so that the weld metal and the parent metal coalesce to form a sound weld.

The use of arc welding[9] in preference to gas welding is often dictated by the type of joint required. While gas welding must be limited to butt-type joints to insure removal of the corrosive flux used, arc welding which utilizes an inert gas shield to prevent oxidation of the material instead of a flux, can be used on lap joints, fillet joints and all other joints such as those commonly used in steel welding. As multipass welds are permissible, there is no top limit on the material thickness which may be welded as there is in gas welding. Generally, arc welding is preferred to gas welding in material over 0.1 inch thick because of the faster welding rate obtainable. It is very difficult to weld the M1 alloy to the aluminum-containing alloys, although the latter alloys can be welded to each other.

When fastening with screws, coarse threads are preferred to the finer types. Thread length in the magnesium part should be two to three times the diameter of the screw. To insure most favorable stress distribution, screws should be more closely spaced than in similar assemblies using ferrous alloys. To hold galvanic corrosion to a minimum, steel screws should be either zinc- or cadmium-plated. Under vigorous corroding conditions, screws should be dipped in zinc chromate primer or in a joint-sealing compound.

Corrosion Resistance

Years ago the objection to magnesium alloys was their lack of stability in sea water, and even to some extent in fresh water. Magnesium alloys corroded very rapidly, developing pits and a grayish-white incrustation. The current magnesium alloys are reasonably stable under most atmospheric conditions. This has been attained by careful purification and the addition of manganese and zinc. However, in saline atmospheres, they are somewhat subject to pitting and roughening. Nevertheless, where corrosion does occur during protracted exposure, the slight loss in strength is equivalent to the loss in area. There is no loss in ductility or strength that can be attributed to intercrystalline corrosion in present commercial alloys.

It is interesting to note that the corrodibility of magnesium in dry air is much less than the corrosion of carbon steel in the same atmosphere, and that magnesium is highly resistant to alkalies. One of the important factors contributing to magnesium corrosion has been entrapped flux that was used in melting or casting operations. Dry air at room temperature has little effect on magnesium, but the rate of attack increases materially as the relative humidity increases.

Surface attack occurs as a uniform etching, the metal gradually darkening and acquiring a thin film of magnesium oxide, hydroxide or carbonate. The film retards rather than prevents subsequent attack.

While the best of the present commercial magnesium alloys have satisfactory corrosion resistance under ordinary inland atmospheric conditions, it is advisable to give magnesium parts a protective treatment. These protective films, in addition to fulfilling their prime purpose of resistance to corrosion, also provide an excellent surface for painting.

Chemical treatments and certain recommended paint systems are used to protect magnesium alloys against the corrosive effects of weathering and many corrosive atmospheres. Chemical treatments provide a passive surface layer which inhibits corrosion. Most chemical treatments do not furnish complete protection, but serve primarily as paint bases. For the majority of structural uses paints, covering a suitable primer coating, supply ample surface protection.

Parts are usually given an anticorrosive treatment known commercially as a "chrome pickle." This is nothing more than a quick dip (20 to 60 seconds) in a solution of sodium dichromate, nitric acid and water. This produces an iridescent, yellow coating of sparingly soluble chromic chromates on the surface, which is intimately bonded to the metal. It also provides a good base for subsequent painting and has definite anti-corrosive properties.

The nature of the recommended system of paint protection will vary with the corrosive conditions and alloys. Generally, the success of a paint coating will depend on: (1) the application of one of the chemical treatments, (2) the preparatory cleaning treatment, and (3) the use of a correct priming coat. For chloride-containing atmospheres or media zinc chromate pigmented primers provide the best protection. But for general use a variety of pigmented systems may be used.

Under conditions where magnesium is assembled with dissimilar metals and where moisture is likely to penetrate into the joint, care must be taken to insulate the contacting surfaces to prevent galvanic corrosion by using primers, sealing compounds, and gasket materials.

Galvanic corrosion can be very damaging to magnesium under severe exposure conditions, inasmuch as it is the least noble of all structural alloys. Proper design to prevent electrolytic retention and careful selection of materials in galvanic contact is essential where exposure conditions are severe.

The treatment that provides the most resistance to salt water is immersion for 5 minutes in a 15 to 20 per cent solution of hydrofluoric acid followed by immersion for 30 minutes in a boiling 10 to 15 per cent sodium dichromate solution saturated with magnesium fluoride or calcium fluoride.

Parts can be galvanically oxidized (anodized) in a sodium dichromate-ammonium sulphate solution at 120–140° F. The oxide coating thus produced by anodic oxidation is an excellent dielectric; hence it is effective as an insulator in preventing galvanic corrosion when magnesium parts are brought into contact with dissimilar metals. However, this process has not been used commercially to any extent.

Design

The design of structural parts is not as simple as with castings, nor are the weight savings obtained quite as large, for two fundamental reasons: (1) the mechanical properties of wrought magnesium alloys do not compare as favorably with aluminum or steel as do the properties of castings; and (2) the low modulus of elasticity becomes a significant factor, because structural components are, as a class, much more slender and less stocky than castings. Thus the effect of the low modulus must be considered, not only to limit deflections to a reasonable magnitude but because allowable stresses, particularly in compression members, are greatly influenced by the stability of the member as a unit as well as locally.

When magnesium[4] is used instead of other structural metals for structures built up from extruded shapes, sheet, plate and tubing, the amount of weight saving which can be effected depends to a large extent on the loading conditions. When magnesium members are used in bending, and space limitations are not stringent, substantial weight savings can be effected. When stressed in direct tension, magnesium members are little or no lighter than those of other suitable structural materials. The same applies to very short columns.

Although allowable design stresses may vary greatly with the type of design and application, a good general rule is to select a design stress equal to one-half the minimum yield strength. For repeated loads the fatigue strength of the material may govern the selection of design stress, and for columns the column strength of each particular member will govern. Thus, for structural shapes of all magnesium alloys except the M1 grade, design stresses in static tension vary from 11,500 to 15,000 psi, and design stresses in static compression and flexure from 8,000 to 12,000 psi, depending on the yield strength of the particular alloy used.

In shear, a design stress of one-quarter of the typical ultimate shear strength has in many cases been found satisfactory. A value of one-third to one-half the tensile strength is usually adequate for the bearing design stress. If the structure is subjected to heavy impact loading, all design stress values for static loading should be reduced by one-half. At elevated temperatures, they must be further reduced in accordance with the decrease in mechanical properties with increase in temperature.

Since the mechanical properties of structural magnesium alloys vary with the method of fabrication, different design stresses are used for extruded shapes, tubing and sheet.

Magnesium members with thin sections, such as webs and outstanding flanges, are more subject to failure by elastic local buckling than are identical sections of a material with a higher modulus of elasticity—a consideration which may make additional strengthening of such members necessary and which in turn makes larger weight savings possible.

Since both the modulus of elasticity and the compressive yield strength are lower in structural magnesium alloys than in other structural metals, the strength of magnesium columns is proportionately lower. Available data indicate that the compressive yield strengths for magnesium alloys used for structural purposes vary from 11,000 to 27,000 psi, depending upon the alloy, heat treatment, cross-section, and method of fabrication.

The yield strength in compression of most wrought magnesium alloys is about 60 to 70 per cent of the yield strength in tension. However, the aged O-1 alloy has a yield strength in compression nearly equal to that in tension. This fact is important in the design of members which depend on the yield strength in compression, such as short columns and compression flanges or beams.

If yield strength alone is the determining factor, a nominal gain results from substituting magnesium for some other metal.[3] However, in members subjected to bending, substantial weight saving results because a deeper section can be used with magnesium.

While the weight increases as the first power, the strength increases as the square, and the rigidity as the cube. Thus the somewhat lower mechanical properties and the considerably lower modulus of elasticity are simultaneously accounted for, and an equal strength member obtained with an appreciable weight saving.

Table 15 illustrates the comparative yield strengths of some commonly used materials.

TABLE 15. *Comparative Yield Strengths of Metals*

	Yield strength (psi)	Specific yield strength (Y.S./Sp.Gr.) (psi)
Magnesium FS-1 hard	33,000	18,330
Magnesium O-1 HTA	39,000	21,670
Aluminum 24ST	41,000	15,180
Aluminum 75ST	72,000	26,670
High strength-low alloy steel		
(hot-rolled)	55,000	7,000
(heat-treated)	125,000	15,840
Austenitic stainless steel		
(hard-rolled)	150,000	19,000

Wherever rigidity[10] is the controlling factor in a structural magnesium member, either in some of its parts or in its entirety, an increase in section depth is the most efficient way of increasing stiffness to compensate for the low modulus of elasticity, since stiffness in bending is proportional to the modulus of elasticity and to the moment of inertia of the section.

Other properties and conditions of interest to the designer which are influenced by the low modulus of elasticity of magnesium are: resilience, column strength, collapsing strength of tubing, straightening characteristics, springback in forming, and deflection in machining.

Magnesium alloys have good resistance to fatigue but—in common with other metals, but to a higher degree in some forms and to some notches—are sensitive to the effect of notches and other stress-raising factors, which reduce their endurance limits considerably.

Notches, sharp corners, abrupt changes and similar conditions, all of which cause concentration of stresses, should be avoided in the design of magnesium structures. Magnesium alloys are sensitive to stress concentration, hence conditions tending to cause such should be avoided.

In practice,[2] necessary fabrication methods frequently will not permit attainment of ideal stress distribution in a given part. Absence of sharp corners and notches, generous fillets, beading of holes, rounding of sharp corners, careful blending of joints of sections and carefully driven rivets are the factors necessary if stress concentrations are to be avoided and the structure is to have maximum fatigue strength.

Magnesium alloys for sheet, plate and strip can be obtained in the annealed or in the hard-worked condition. In selecting a suitable alloy for a specific purpose, the correct temper must be considered.

High strength properties are obtained in magnesium sheet by cold-working it in the rolling process at the mill. When hard-rolled sheet is used in highly stressed parts, the parts must be designed to permit forming at temperatures which do not result in excessive annealing. Parts which are not highly stressed or which require severe deformation are made in annealed sheet, which may be heated to high temperatures without affecting inherent metal properties.

The minimum cold-bend radius to which sheet may be subjected varies with alloy, temper, thickness, the type of bending equipment employed, the rate of bending, and the relation of the axis of the bend to the grain of the sheet. In making 90° bends, a bending radius of 4 to 5 times the sheet thickness for annealed stock 0.040 to 0.064 inch thick appears to be satisfactory. In the hard temper the minimum bending radii should be at least doubled.

The light weight of magnesium-base alloys makes possible the use of stiffeners, large fillets or thicker webs without undue weight penalty.

The low modulus of elasticity can easily be compensated for by increasing depth of sections, inasmuch as the stiffness of sections increases as the cube of the depth.

Magnesium alloys are slightly softer than other structural alloys, and are therefore more susceptible to mechanical injury. Where parts are subjected to abrasive wear, the surface affected should be protected by a harder metal, leather, fiber, rubber, etc., depending on the nature of the application.

Complete structures[8] can be built from magnesium alloy with a considerable saving in weight and an increase in stiffness if O–1 magnesium alloy extrusions in the heat-treated and aged conditions are used for concentrated members instead of aluminum. However, there is some question as to whether the weight saving in severely formed members is sufficient to balance the extra expense and complications required for hot-forming. Consideration can be given, then, to the use of aluminum alloy for ribs and other severely formed members, with magnesium alloy sheet covering them.

Riveting

Riveting[4] is widely used for joining magnesium alloys where particularly high strength of the joints is required. In order to minimize the possibility of galvanic corrosion in the joints, rivets of aluminum alloy 56S are used, because the electrolytic potential between alloy 56S and magnesium is comparatively low. Magnesium alloy rivets have not been found satisfactory because of their low shear strength and the necessity for driving hot, even in small sizes.

Other aluminum rivet compositions, namely, A17ST, 53S and 3S can be

(*Courtesy Dow Chemical Co., Midland, Mich.*)

Figure 6. Rolling magnesium alloy sheet.

used, but with danger of contact corrosion. All rivets should be anodized. The possibility of contact corrosion when using other than 56S alloy may be reduced by coating rivets with zinc chromate primer.

Proper design[2] of riveted joints is essential if maximum strength is to be obtained. The bearing strength of magnesium alloy sheet is 60,000 to 70,000 psi. Based on a single shear value of 8,000 psi for alloy 56S rivets, a rivet diameter of 2½ times the sheet thickness will give a balanced design. To avoid local stressing of the sheet, rivets should not be placed too close together; minimum spacing between rivets should be three times rivet diameter.

Rivet holes should be drilled rather than punched, especially when exposed to water or sea air.

Satisfactory joints or connections can be made in magnesium[3] with bolts, studs or screws. Washers should be used under nuts at all times and under bolt or stud heads when the bolt or stud is under tensile loading. Bolts, studs and washers made from anodized aluminum alloy and zinc- or cadmium-plated steel are preferred. The use of brass or nickel alloys is not recommended because of the possibility of galvanic corrosion.

Figure 6 shows the rolling of magnesium alloy sheet in a two-high mill, and Figure 7 shows the magnesium alloy sheet as it comes from the roller.

(Courtesy Dow Chemical Co., Midland, Mich.)

Figure 7. Rolling magnesium alloy sheet.

References

1. Dow Chemical Co. bulletins.
2. American Magnesium Corp. bulletins.
3. Anon., "Working of Magnesium Alloys," *American Machinist* (May 1, 1940).
4. Woldman, N., "Magnesium in Aircraft," *Metals and Alloys* (October, 1940).
5. Winkler, J., "Survey of Wrought Magnesium Alloy Fabrication," A.S.M. Preprint No. 8, 1944.
6. Resos, E., "Hot Forming of Magnesium Alloy Sheets," *Iron Age* (July 27, 1944).
7. Ashburn, A., "How to Work Magnesium Alloys," *American Machinist* (November 7, 1946).
8. DuMond, T., "Magnesium Alloys," *Materials and Methods* (May, 1947).
9. "Magnesium," American Society for Metals, 1946.
10. "Designing with Magnesium," American Magnesium Corporation.

Chapter IV

High Strength-Low Alloy Steels

High strength-low alloy steels are used where light weight is desirable, as in busses, trucks, trailers, street cars, road machinery, mine cars, railroad equipment, ships, and other transportation units. As such equipment is subjected to severe stresses and sudden shocks, whether used for railroads or on the highways, ductility in the materials used for its construction is essential. To permit the safe use of thin sections in stressed members, steel with a high degree of corrosion resistance is necessary; otherwise the loss of strength due to corrosion would be critical.

High strength-low alloy steels are proving economical also in applications which are difficult to keep protected by paint coatings, such as coal-hopper cars, coal-mine cars, parts of truck bodies and some industrial structures and roofing. They are used extensively in bridges, buildings and other steel structures; in the oil and chemical industries, and in power generation.

High strength-low alloy steels are a specific class of steels, in which enhanced mechanical properties and, in most cases, good resistance to atmospheric corrosion are obtained by incorporating moderate proportions of one or more alloying elements, other than carbon. These steels are generally intended for applications where savings in weight can be effected by their greater strength, and where better durability is obtained because of their other desirable characteristics.

These steels are supplied to minimum mechanical properties and are normally furnished as-rolled, as-annealed, as-normalized, or as-stress-relieved. They are intended for use without further heat treatment except for preheating, postheating or stress-relieving operations, which are sometimes used in conjunction with welding.

Some of the elements which impart strength to steel also increase corrosion resistance, as for example copper, nickel, phosphorus, silicon, chromium and molybdenum. Two or more of these elements in small percentages, combined with low carbon and various proportions of manganese, constitute the chemical compositions of the principal steels now included in this group.

Requirements

Requirements for lighter and more efficient structures are:

(a) Greater strength to permit a substantial increase in unit stresses, and thereby make possible a proportionate decrease in section modulus. This means the employment of lighter gauges.

(b) Greater degree of resistance to corrosion so that the rate of attack will be retarded sufficiently to warrant the reductions made in the sections employed.

(c) A composition that can be formed easily, hot or cold, readily welded without heat treatment, and generally without the need of subsequent annealing or stress-relieving.

(d) The above properties to be provided in the as-rolled condition of the steel, because obviously large structures such as railroad freight and passenger cars cannot be subjected to heat treatment after fabrication.

(e) All these improved properties to be integrated in a steel of relatively low cost, because structures built from them must be comparable in cost to ordinary steel.

The main requirements[3] of a high strength-low alloy steel are high yield and ultimate strengths; high elastic ratio (ratio of yield strength to tensile strength) without undue loss of ductility; high resistance to fatigue and impact; good weldability with standard equipment; better atmospheric corrosion resistance than mild carbon steel; and low air-hardening properties when welded or gas-cut.

These special steels provide engineers and production men with ductile, low-alloy materials that do not necessitate radical changes in part or equipment design, in shop equipment, or in shop methods. They can be easily worked, either hot or cold, do not change characteristics during normal cooling, but can be heat-treated if desired. They are high-strength steels that are easily welded, sawed, sheared, punched, drilled, reamed and machined.

Alloying Elements

Copper. The copper content of an ordinary steel determines its degree of resistance to atmospheric corrosion, and as the proportion of copper increases to about 0.25 per cent, a progressive improvement is shown; 0.25 per cent of copper in steel is sufficient to increase its resistance to atmospheric corrosion to twice that of carbon steel containing no copper. In most high-strength steels the copper content ranges up to 1.0 per cent, however, because the value of copper as a strengthening alloy is not effective below 0.7 per cent.

In copper steels only about 0.35 per cent of copper is held in solid solution at room temperature if the steel is slowly cooled, and the copper in excess of this amount may precipitate from solution, unless other elements, such as nickel or molybdenum, are present to hold it in solution. When the copper content is greater than 0.70 per cent and the steel is heated to about 900 to 1000° F. for 1 to 4 hours and cooled, the yield and ultimate strengths of the steel are greatly increased, but with a decrease in impact strength.

It has been established[1] that in the same atmosphere steels of 0.20 per cent minimum copper content have approximately double the resistance to corrosion of ordinary carbon steels containing no copper. The more resistant high-strength steels have from 4 to 6 times the corrosion resistance of ordinary steel.

Nickel also has been used extensively as an alloying element in steel to impart corrosion resistance, to improve the physical properties and to refine the grain structure. For most atmospheric corrosion resistance purposes, nickel contents up to 2 per cent are generally used in the commercial high strength-low alloy steels, together with other elements such as copper and chromium.

The influences of both nickel and copper in a steel are additive, and are beneficial to both the physical properties and the corrosion resistance.

Phosphorus up to as much as 0.15 per cent has been observed to exert a considerable effect in improving atmospheric corrosion resistance, particularly in steels containing small amounts of other elements, such as copper, chromium and nickel. The addition of phosphorus alone is not always practical from the standpoint of the physical properties desired in many applications, but it is successfully employed in some of the proprietary high strength-low alloy steels, in addition to other elements.

Silicon has a somewhat beneficial effect on atmospheric corrosion resistance up to about 1 per cent. Like phosphorus, however, silicon is not commonly used alone for this purpose, but is employed in the high strength-low alloy steels. At temperatures of from 1200 to 1500° F., silicon up to 4 per cent greatly increases the oxidation resistance of low-carbon steels, especially when used as a supplement to chromium.

Chromium in small proportions toughens steel and increases its strength, elastic limit and impact resistance. In larger percentages it forms hard carbides, giving greater wear resistance. It is generally used with nickel or copper.

Molybdenum, usually associated with nickel, increases resistance to shock and impact. It also raises the ultimate strength, hardness and toughness. Molybdenum goes into solid solution in the iron, but when other elements are present it forms hard carbides which increase wear resistance.

Carbon. The carbon content is generally kept low, ranging from 0.08 to 0.25 per cent. Naturally, the higher carbon content produces steel of increased yield and ultimate strengths, but as carbon is a most active hardening element, it affects the air-hardening quality markedly. The lower the carbon content the greater the ductility, weldability and corrosion resistance of the steel. However, higher carbon contents give greater resistance to abrasion.

The atmospheric corrosion resistance of high-strength steels varies with the combination and content of those alloying elements most effective in building up this resistance.

Alloys

The commercial high strength-low alloy compositions are marketed by their manufacturers under various proprietary names and trade marks. The chemical compositions of some of these alloys are shown in Table 16. It is to be noted that in all cases the carbon content is not over 0.25 per cent and the total alloy content in each is less than 4 per cent.

TABLE 16. *High Strength-Low Alloy Compositions*

	Alloying Elements (%)									
Alloy Type	C	Mn	P	Si	Cu	Ni	Cr	Mo	Zr	Al
1	0.12 max.	0.15–0.40	0.08–0.15	0.35–0.75	0.35–0.60	—	—	0.16–0.28	—	—
2	0.12 max.	0.20–0.50	0.07–0.15	0.25–0.75	0.25–0.55	0.65 max.	0.50–1.25	—	—	—
3	0.12 max.	0.50–1.00	0.04 max.	—	0.50–1.00	0.50–1.10	—	0.10 min.	—	—
4	0.20 max.	1.25 max.	0.100 max.	0.30 max.	0.60 max.	1.00 max.	—	0.10 max.	—	—
	0.12 avg.	0.75 avg.	0.080 avg.	0.05 avg.	0.40 avg.	0.60 avg.	—	0.08 avg.	—	—
5	0.12 max.	0.50–0.90	0.05–0.12	0.15 max.	0.95–1.30	0.45–0.75	—	0.08–0.18	—	0.12–0.27
6	0.25 max.	1.40 max.	0.045 max.	0.25 max.	0.30–0.60	0.50–1.00	—	—	—	—
7	0.12 max.	0.50–1.00	0.08–0.12	0.10–0.50	0.50–0.70	0.25–0.75	0.40–1.00	—	—	—
8	0.08–0.15	0.50–0.75	0.04 max.	0.60–0.90	0.25 max.	0.10–0.25	0.50–0.65	0.15 max.	0.05–0.15	—
9	0.15 max.	0.90–1.40	0.08–0.13	0.10 max.	0.30 min.	Resid.	Resid.	—	—	—
10	0.15 max.	0.75 max.	0.10 max.	0.30 max.	0.75–1.25	1.50–2.00	—	—	—	—
11	0.12 max.	0.50–0.70	0.10–0.15	0.30 max.	0.90–1.25	0.45–0.65	—	—	—	—
12	0.25 max.	1.10–1.60	0.045 max.	0.30 max.	0.20 min.	—	—	—	—	—

Properties

Typical tensile properties for the alloys shown in Table 16 are given in Table 17. The data given are for plate ½ inch thick in the hot-rolled condition.

TABLE 17. *Typical Mechanical Properties*

Alloy Type	Yield pt., min. (psi)	Ten. str., min. (psi)	Min. elong. in 2″
1	50,000	70,000	22
2	50,000	70,000	23
3	50,000	70,000	22
4	50,000	65,000	25
5	50,000	70,000	22
6	50,000	70,000	22
7	50,000	70,000	22
8	50,000	70,000	23
9	50,000	70,000	25
10	50,000	70,000	22
11	55,000	70,000	20
12	50,000	75,000	20

Two English alloys analyzing 0.30 carbon, 1.0 manganese, 1.1 chromium, 0.5 copper and 0.20 carbon, 1.35 manganese, 0.47 chromium, 0.9 silicon show tensile strengths of 83,000 to 97,000 psi, yield strengths of 51,000 to 65,000 psi, elongations of 17 to 21 per cent and reductions of area of 40 to 54 per cent. They are used in trams, busses, railroad cars, and ship deck and side plating.

Characteristics

These high-strength steels[3] are better than ordinary steels in notch toughness; this superiority is reflected in superior performance in actual service. A structure built of high-strength steel, as compared with a similar and correspondingly heavier one of ordinary steel, will exhibit higher resistance to fracture under overload at notches, re-entrant angles, or under other conditions of restraint.

Wherever elastic buckling is objectionable from the standpoint of appearance, the flat sheets are commonly stiffened with corrugations or reinforced with light stiffening agents to prevent the formation of buckles. These stiffening agents are usually cold-formed angles, zees, channels or hat sections, and in many instances it is possible to utilize them as integral parts of the stress-carrying members.

This material also has remarkable resistance to fatigue. The importance of fatigue corrosion resistance cannot be overemphasized when designing light-weight construction parts which are subject to vibration or repeated reversals of stress. Truck-body panel sheets, railroad-car side sheets, and other types of steel sheets and sections do not need the excessive weight necessary for stiffness when made from such highly fatigue-resistant steels.

Another advantage in using these steels for weight saving is that their ratios between yield strength and ultimate strength are very high—about 70 per cent instead of 60 per cent, as in straight-carbon steels. They also possess a ratio of proportional limit—yield strength of around 90 per cent. These two features allow the designer to use much higher working stresses, and thus take greater advantage of the alloy's tensile strength in reducing weight in the various types of construction where weight saving is of prime importance.

One of the popular alloys is No. 10 (called "Yoloy" by the manufacturer). The following discussion of this material is indicative of the characteristics and properties of the other proprietary steels being used for lightweight construction. The improved properties of this alloy[4] are obtained by the addition of nickel and copper and are due to the grain-refining influence of these elements. They appear to best advantage when compared to those of plain-carbon steels.

"Yoloy" has 50 per cent greater tensile strength than plain-carbon steels of the same carbon content, and 65 to 75 per cent greater yield strength. Its ductility is better, hardness is the same, and impact strength is 20 to 30 per cent greater than the corresponding values of carbon steels of the same strength. "Yoloy" has a typical Charpy impact value of 120 foot-pounds and a typical endurance limit of 45,000 psi. In addition, it has remarkable impact properties at low temperatures, as indicated in Table 18, comparing the Charpy impact value at various temperatures with those obtained for SAE-1035. This high resistance to shock greatly increases the usefulness of this steel in applications involving high strength and resistance to shock, in widely varying temperature ranges.

Table 18

Alloy	Tens. str. (psi)	Charpy impact strength in ft.-lbs. at						
		70° F.	32° F.	0°	−25° F.	−50° F.	−75° F.	−100° F.
SAE-1035	79,000	55	44	25	15	10	8	5
Alloy No. 10	78,000	130	130	128	125	115	95	70

"Yoloy" steels are generally furnished for use in the rolled condition to meet the minimum physical properties shown in Table 19. A normalizing treatment improves its strength and hardness, and an annealing operation its ductility. "Yoloy" sheets can be furnished by special arrangements with the producer to meet physical properties higher than those shown in Table 19. For these applications higher-carbon grades with or without modified heat treatments are also furnished. An increase of approximately 15,000 to 20,000 psi in both yield strength and ultimate strength may be

TABLE 19. *Physical Properties of Hot-rolled "Yoloy" (Alloy No. 10)*

Per cent carbon	Size of rolled material	Size of test specimen	Yield point (psi)	Tensile strength (psi)	Elongation per cent		Reduction of area (per cent)	Impact Charpy (ft.-lbs.)	Rockwell hardness "B"
					2 in.	8 in.			
0.08	¾" Round	Full Section	58,000	71,000	—	28.5	58	—	—
	¾" Round	0.505" Round	61,000	75,000	32.0	—	60	43	84
	⅞" Plate	1½" × ⅞"	53,000	70,000	—	27.0	—	—	—
	¼" Plate	1½" × ¼"	58,000	71,000	—	24.0	—	—	—
	⅛" Strip	½" × ⅛"	63,000	76,000	24.0	—	—	—	—
	14 Ga. Strip	½" × 14 Ga.	68,000	78,000	26.0	—	—	—	—
0.15	¾" Round	Full Section	60,000	77,000	—	25.5	60	—	—
	¾" Round	0.505" Round	64,000	82,000	28.5	—	60	41	85
	⅜" Plate	1½" × ⅜"	61,000	80,000	—	22.0	—	—	—
	¼" Plate	1½" × ¼"	65,000	83,000	—	23.0	—	—	—
	8 Ga. Strip	½" × 8 Ga.	65,000	84,000	26.0	—	—	—	—
0.22	¾" Round	Full Section	64,000	91,000	—	24.5	—	27	90
	¾" Round	0.505" Round	68,000	93,000	27.0	—	57	—	89
	¾" Plate	1½" × ¾"	66,000	90,000	—	22.0	—	—	—
	½" Plate	1½" × ½"	69,000	95,000	—	22.5	—	—	—
	¼" Plate	1½" × ¼"	69,000	94,000	—	21.5	—	—	—
	⅛" Strip	½" × ⅛"	71,000	98,000	20.0	—	—	—	—
	14 Ga. Strip	½" × 0.074"	81,000	100,000	19.5	—	—	—	—

TABLE 20. *Typical Physical Properties of N-A-X Steel*

Property	½" Plate as-rolled	3/16" Plate as-rolled	14-ga. Sheet as-rolled	20-ga. Sheet cold-rolled and annealed
Tensile strength (psi)	75,500	76,500	78,000	75,330
Yield strength (psi)	52,000	53,000	56,000	50,500
% Elongation in 8"	27	25	25	23

16 Gauge Hard Cold-rolled Sheets

Tensile strength	129,900
Yield strength	125,700
% Elongation in 2"	8
% Elongation in 8"	4

Physical properties of 1" round bar heat-treated by quenching from 1630° F. and tempering at indicated temperatures:

	Temper 400° F.	Temper 800° F.	Temper 1100° F.
Tensile strength (psi)	170,000	140,000	104,000
Yield strength (psi)	127,000	105,000	85,000
% Elongation in 2"	12	16	26
Reduction of area	36	54	67
Izod impact	38	53	98

obtained by heating to 900–950° F. for 4 to 4½ hours, followed by air-cooling. Although the lower-carbon grades of "Yoloy" are not generally heat-treated by quenching and tempering, the higher-carbon grades may be made to produce still better physical properties by quenching from 1550° F. and tempering.

Another manufacturer's grade of high strength-low alloy steel (Alloy No. 8 in Table 16) contains about 0.5 per cent chromium and about 0.1 per cent zirconium. Claims for the properties[9] of this material known as "N–A–X High Tensile" are shown in Table 20.

Alloy No. 11 (Table 21), known commercially as "Hi-Steel," shows the following properties as compared to ordinary structural steels.

Inland "Hi-Steel" has a working stress nearly twice that of ordinary structural steel, a fatigue strength approximately one-third greater, four to five times the resistance to corrosion, and high abrasion resistance. An even higher yield point can be achieved in many applications by precipitation-hardening, a simple low-temperature heat treatment.

TABLE 21. *Tensile Properties (¼" Plate)*

	Inland "Hi-Steel"	Ordinary structural steel
Yield strength (psi)	62,000	37,000
Ultimate strength (psi)	74,000	66,000
% Elongation in 8"	24	24
% Reduction in area	60	53

Endurance Limit

Fatigue strength	49,000	33,000

Charpy Impact Resistance

Temperature (° F.)	Inland "Hi-Steel" (ft.-lbs.)	Ordinary structural steel (ft.-lbs.)
80	55.3	36
32	43.1	33
15	39.5	29
0	36.3	26
−10	36.8	16
−25	33.7	6
−50	30.4	2

Physical Properties for Rivet Design

	Inland "Hi-Steel"	Ordinary structural steel
Shear strength (psi)	66,000	44,000
Bearing strength (psi)	115,000	95,000

"Mayari-R" corresponds in composition to Alloy No. 7 in Table 16. Typical properties[6] of this alloy in sheets and plates are given in Table 22.

"Dynalloy," "Otiscoloy," "Cor-Ten" and "Man-Ten" are other com-

TABLE 22. *Properties of "Mayari-R"*

Size	Yield point (psi)	Tensile strength (psi)	Elongation (% in 8 in.)	Brinell number	Bend test
14 ga.	52,600	70,400	23.3	145	flat
3/16 in.	57,600	71,900	28.0	137	flat
3/8 in.	58,200	78,400	28.0	156	flat
1/2 in.	54,900	78,400	25.5	152	flat

mercial alloys of this type. "Dynalloy" corresponds to Alloy No. 4 in Table 16, while "Otiscoloy" corresponds to Alloy No. 9, "Cor-Ten" to Alloy No. 2, and "Man-Ten" to Alloy No. 12.

U.S.S. "Cor-Ten" is sold to minimum mechanical properties[8] as shown in Table 23.

TABLE 23. *Properties of "Cor-Ten"*

Property	1/2" and under	Over 1/2" to 1" incl.	Over 1" to 2" incl.
Yield strength (psi)	50,000	47,000	45,000
Tensile strength (psi)	70,000	67,000	65,000
% Elong. in 2"	22		22
% Elong. in 8" (3/16" and heavier)	$\frac{1{,}500{,}000}{\text{T.S.}}$	$\frac{1{,}500{,}000}{\text{T.S.}}$	$\frac{1{,}500{,}000}{\text{T.S.}}$
Cold bend	180° D = 1*t*	180° D = 2*t*	180° D = 3*t*

U.S.S. "Man-Ten" is a manganese-copper high-strength steel[8] and is sold to minimum mechanical properties as shown in Table 24.

TABLE 24. *Properties of "Man-Ten"*

Property	1/2" and under	Over 1/2" to 1" incl.	Over 1" to 2" incl.
Yield strength (psi)	50,000	47,000	45,000
Tensile strength (psi)	75,000	72,000	70,000
% Elong. in 2"	20		20
% Elong. in 8" (3/16" and heavier)	$\frac{1{,}500{,}000}{\text{T.S.}}$	$\frac{1{,}500{,}000}{\text{T.S.}}$	$\frac{1{,}500{,}000}{\text{T.S.}}$
Cold bend	180° D = 1*t*	180° D = 2*t*	180° D = 3*t*

Forming

Despite their high yield points these alloys can be satisfactorily cold-formed and cold-worked. However, because of their greater strength they generally require more force to produce a given amount of permanent set in sections of equal thickness. When working with high-strength steel, somewhat greater allowance for springback must be provided in the forming dies.

The changes in practice necessary for cold-forming high-strength steel consist chiefly in making provision for more liberal radii of bends, slightly increasing die clearances, and allowing for more back spring. It is recommended that, for cold-forming, the inside radius of the bend be at least equal to the thickness of the material up to 1/16 inch inclusive; at least twice the thickness of material for thicknesses over 1/16 to 1/4 inch inclusive, and three times the thickness of material for thickness over 1/4 inch to 1/2 inch inclusive. High-strength steels of drawing quality can be worked with somewhat smaller radii than those recommended above.

High-strength steels[3] are readily hot-formed, and this practice is universally recommended for all thicknesses in excess of 1/2 inch. Temperatures of 1450 to 1600° F. at the dies usually give most satisfactory results. Because of their low alloy content, these steels do not harden appreciably upon cooling from hot-forming temperatures, either in air or by the quenching action of the cold die surfaces. The mechanical properties of these steels are only slightly affected by hot-forming; hence, no subsequent heat treatment is necessary to restore their original properties.

Corrosion Resistance

The constructional high strength-low alloy steels, by virtue of the presence of relatively small amounts of a number of elements, have superior strength and elastic properties and better atmospheric corrosion resistance than either mild-carbon steel or ordinary steels containing residual copper.

Service experience and an exhaustive testing of samples in various atmospheres have demonstrated clearly that the superior atmospheric corrosion resistance of certain high-strength steels is due to the more dense, tightly adherent, and highly protective rust coat, or oxide film which forms on their surfaces. This film is uniform and is particularly free from spalling and the formation of tubercules which aggravate pitting and cause corrosion to progress steadily. This oxide film is harder than that on carbon steel and adheres more tenaciously to the base metal.

Paints and other protective coatings[3] possessing good atmospheric corrosion resistance, such as zinc and certain enamels, adhere better to high-strength steels than to ordinary steels. Galvanized high-strength steels are sometimes required in special applications where corrosion is severe, as when chlorides are present. These steels, when galvanized, are much more resistant to salt conditions than galvanized copper-steel, which in turn is superior to galvanized ordinary steel.

Figure 8 shows time-corrosion curves[3] for steels typical of their classes after exposure to industrial atmospheres. The higher the copper content of the steel, the lower the corrosion rate. The commercial high strength-low alloy steels show remarkably greater corrosion resistance than ordinary carbon structural steels containing no copper or just residual copper.

The Inland Steel Company[5] has published a series of corrosion-time charts as shown in Figure 9. Curves A and B show the per cent loss in

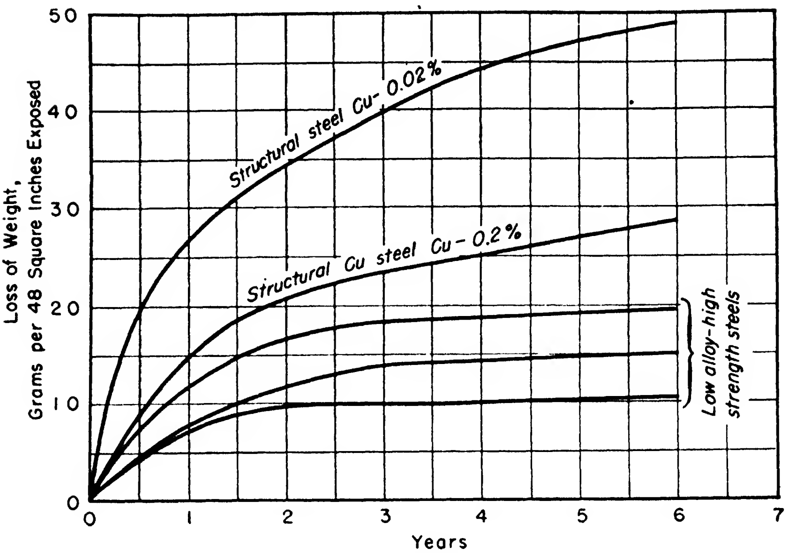


Figure 8. Time-corrosion curves for steels typical of their classes after exposure to industrial atmosphere.

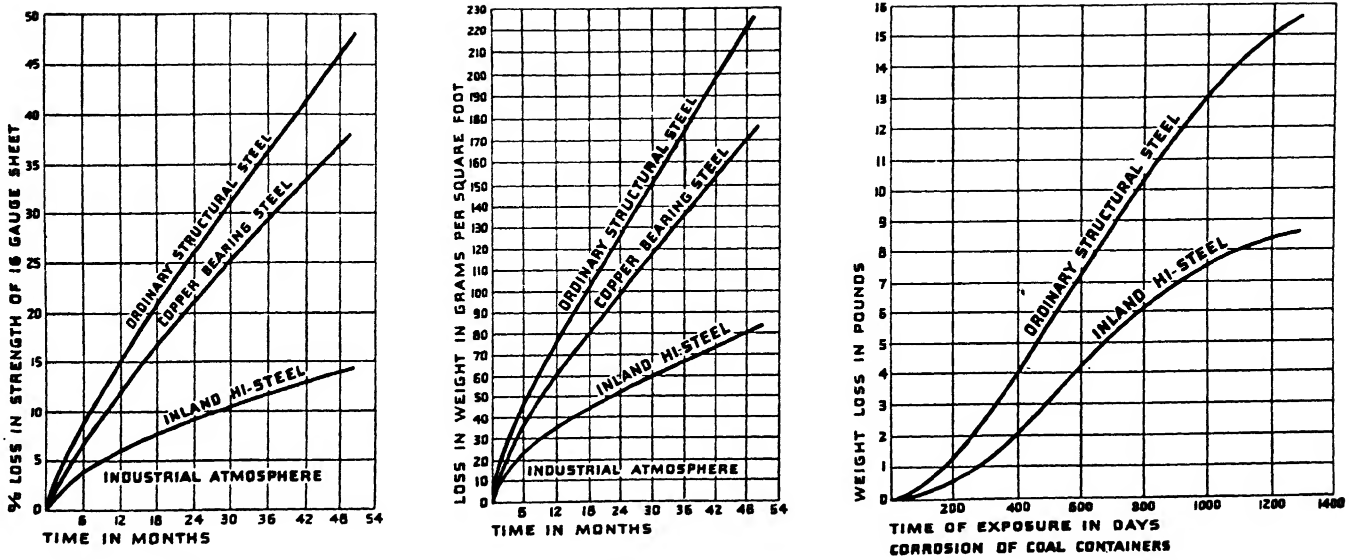
strength and in weight due to corrosive action on "Hi-Steel," copper-bearing steel, and ordinary structural steel, while curves C record corrosion of coal containers and show that the advantage of "Hi-Steel" increases with duration of exposure.

Welding

High strength-low alloy steels are as readily weldable as mild carbon steels, and may be welded by the electric arc, resistance or gas processes with a minimum of hardening or embrittlement. They can readily be welded to each other and to ordinary steel. Though their weldability is excellent, variations may result from differences in chemical composition, metallurgical characteristics, physical properties, type of electrode and welding technique employed, treatment prior to welding, and treatment after welding. Low-carbon steels, in general, are relatively easy to weld.

All these alloys undergo structural changes as a result of the welding operation. These changes are a function of the chemical composition of the material, the temperature obtained during the welding operation, and the rate of cooling from the molten state.

For good weldability high strength steels should have a carbon content below 0.20 per cent. As a result they do not air-harden, are easily welded, and the resulting welds have good physical properties in the "as-welded" conditions. Steels with carbon content over 0.20 per cent should be pre-



(A) (B) (C)

(*Courtesy Inland Steel Co., Indiana Harbor, Ind.*)

Figure 9. Corrosion time charts. Curves showing per cent loss in strength and loss in weight due to corrosive action on "Hi-Steel," copper-bearing steel, and ordinary structural steel. These curves record corrosion of coal containers and show that the advantage of "Hi-Steel" increases with duration of exposure.

heated before welding and subsequently heat-treated for most satisfactory results.

Shielded-arc electrodes of the same alloy as the base metal are generally used to weld these materials. The resulting welds have physical properties very close to those of the annealed base metal.

Design

High strength and corrosion resistance[1] make possible three different approaches to the problem of light weight construction: (1) to design the structure to have the same life as one built of ordinary copper steel but with a substantial weight saving; (2) to design for the least dead weight to secure the greatest economic advantages, but at the risk of a somewhat shorter service life; and (3) to use the same thickness of sections as in ordinary steel and secure greater strength and longer service life.

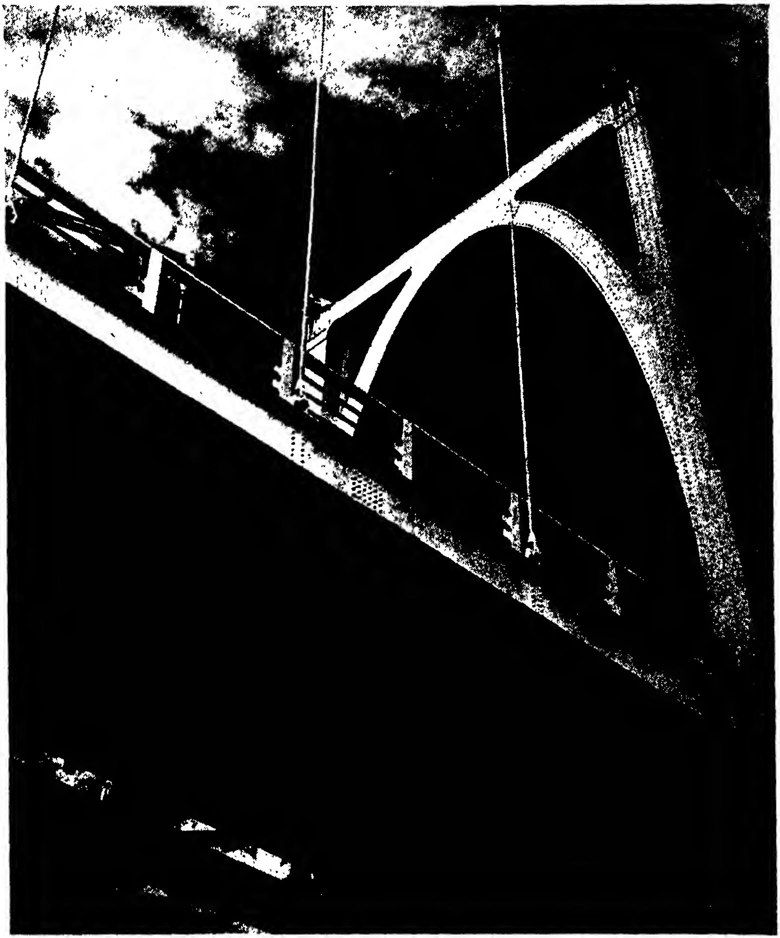
Because of their greater strength, toughness, fatigue limit and corrosion resistance, the high tensile-low alloy steels ordinarily permit reduction in sectional thickness of as much as 25 per cent. This means 33⅓ per cent more units per ton of steel, with actual improvement in the strength and durability of the finished products; and because they have exceptional ductility for high-strength steels, they can be deep-drawn and formed into intricate shapes.

In applications[2] where reduction in weight is important the high strength of these alloys permits weight savings proportional to the comparative strengths of the alloy and mild steel, provided due consideration is given the engineering principles involved. Where the stresses are in tension only, direct reduction of sections can be made in proportion to the increased strength of the alloy over that of mild steel.

Where a combination of stresses resolving themselves into bending are involved, load-carrying capacity can be increased, but deflections will increase directly. Direct substitution of thinner or lighter sections must be attended by a certain amount of caution, because only certain applications exist where weight can be saved proportional to the increase in strength without risk of buckling or crumpling. These dangers may be overcome by redesigning the section so that full weight-saving advantage of the alloy's high strength can be realized. A more efficient distribution of the metal in a section will allow a reduction in weight and increase its load capacity without sacrificing rigidity.

High strength-low alloy steels[5] offer two great advantages to designers and users of mobile steel equipment and steel structures: (1) their remarkable resistance to corrosion and (2) their great strength combined with high ductility, which permits either lighter weight construction without sacrifice of strength and safety, or increased strength without added weight.

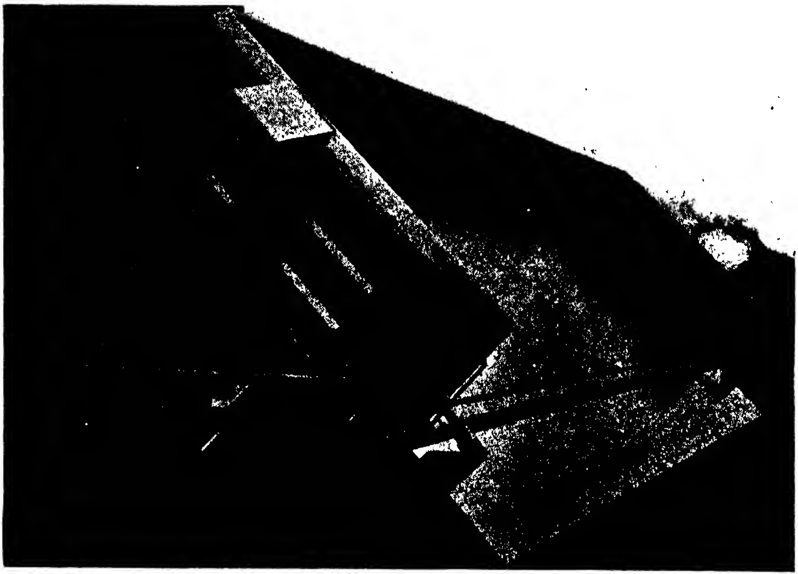
Designers realize that the factors[6] governing allowable working stresses in a material are the yield point and the endurance or fatigue limit, rather than the ultimate tensile strength. These alloys have been developed with a high yield strength and a correspondingly high endurance limit—almost double that of common low-carbon steel. As a result, they permit high working stresses.



(Courtesy Bethlehem Steel Co., Bethlehem, Pa.)

Figure 10. Suspension bridge.

Figure 10 shows the Orleans suspension bridge on highway 96 spanning the Klamath River, Humboldt county, California. The two girders for the 360-ft. span are made of 30-in., 108-lb. "Mayari R" sections. These girders were fabricated as chords of the dead-load camber curve and were fully spliced at 36-ft. lengths. The total weight of these girders is 87,000 pounds. Girders of equivalent strength fabricated from ordinary structural steel would have weighed 119,000 pounds, or 27 per cent more than those of "Mayari R." The bridge was designed by the State of California and was fabricated by the Judson-Pacific Company.



(Courtesy Carnegie-Illinois Steel Co., Pittsburgh, Pa.)

Figure 11. Air dump car.

Figure 11 shows an air dump car where appreciable reduction in weight without loss in strength is attained by the U.S.S. "Man-Ten" steel.

The proprietary names indicated in this section for the various commercial high strength-low alloy steels are registered trade marks of the following manufacturers:

"Aldecor": Republic Steel Corp., Cleveland, Ohio
"Cor-Ten": Carnegie-Illinois Steel Corp., Pittsburgh, Pa.
"Dynalloy": Alan Wood Steel Co., Conshohocken, Pa.
"Hi-Steel": Inland Steel Co., Indiana Harbor, Indiana
"Man-Ten": Carnegie-Illinois Steel Co., Pittsburgh, Pa.
"Mayari R": Bethlehem Steel Co., Bethlehem, Pa.
"N-A-X High Tensile": Great Lakes Steel Corp., Detroit, Mich.
"Otiscoloy": Jones and Laughlin Steel Co., Pittsburgh, Pa.
"Yoloy": Youngstown Sheet and Tube Co., Youngstown, Ohio

References

1. Knerr, H., "Material Selection on Strength-Weight Factors," *Automotive Industries* (April 19, 1923).
2. Gibson, A., "Nickel-Copper High Strength Steels Meet Specifications of Welded Construction," *Steel* (January 25, 1937).
3. Anon., "Low Alloy-High Strength Steels," *Materials and Methods* (July, 1947).
4. "Yoloy," Youngstown Sheet and Tube Co. bulletin.
5. "Hi-Steel," Inland Steel Co. bulletin.
6. "Mayari R," Bethlehem Steel Co. bulletin.
7. "Otiscoloy," Jones and Laughlin Steel Corp. bulletin.
8. "Cor-Ten and Man-Ten," Carnegie-Illinois Steel Co. bulletin.
9. "N-A-X High Tensile," Great Lakes Steel Corp., Division National Steel Corp., Detroit, Michigan.

Chapter V

Stainless Steel

Of the many possible elements which may be alloyed with iron or steel, chromium is the only one yet found that has the unique property of imparting to them remarkable resistance to corrosion and oxidation at a reasonable cost. It fortifies the entire body of metal against attack by destructive agents.

The amount of chromium required to produce true stainless characteristics is determined largely by the analysis of the iron or steel to which it is added, especially with respect to the carbon content. Theoretically, slightly more than 10 per cent of chromium will give definite stainless properties to pure iron; for maximum corrosion resistance with minimum chromium, a low carbon content is desirable. However, where the nature of the application demands greater hardenability, a higher carbon content is essential. Gradual increases in chromium yield progressive though not proportional increases in corrosion and heat resistance, and also cause fundamental changes in the physical characteristics and structure of the steel.

In combination with chromium, other elements may be alloyed with iron to obtain special characteristics. The most important of these elements is nickel. When both nickel and chromium are added, the resulting alloy, of which the well-known 18–8 is a type, is extremely ductile, highly resistant to corrosion and particularly well adapted to cold-forming operations. Elements such as molybdenum and sulphur impart special characteristics. Variation of the combination and proportion of the alloying elements results in the many different grades of stainless steel.

Classification

Stainless steels may be divided into two classes: (1) chromium-nickel grades and (2) straight-chromium grades. Most types of chromium-nickel stainless steels are essentially austenitic in grain structure, non-magnetic, and non-hardenable by heat treatment, but hardenable by cold-working. Straight-chromium stainless steels may be subdivided into two groups: those ferritic in grain structure, magnetic, and non-hardenable by heat treatment; and those martensitic in grain structure, and hardenable by heat treatment.

Although many different grades of stainless steel have been developed for various purposes, those best suited for cold-rolling to produce high strength are the austenitic chromium-nickel compositions. Only the non-hardenable austenitic steels are used extensively for light weight, high strength construction owing to their superior resistance to corrosion, good workability and excellent weldability, combined with high strength and excellent ductility.

The stainless steels are designated by American Iron and Steel Institute (AISI) type numbers in accordance with their chemical composition, as shown in Table 25. The austenitic grades are typed in the 300 series, the straight-chromium grades (above 11.5 per cent chromium) are typed in the 400 series, while the low-chromium grades (between 4 and 6 per cent chromium) are typed in the 500 series for differentiation and designation.

TABLE 25. *Chemical Composition of Some Wrought Stainless Steels*

Alloy type	Carbon	Chromium	Nickel	Manganese	Silicon	Other elements
301	0.08/0.20	16.0/18.0	6.0/8.0	2.0 max.	0.75 max.	
302	0.08/0.20	17.0/19.0	8.0/10.0	2.0 max.	0.75 max.	
302B	0.08/0.20	17.0/19.0	8.0/10.0	2.0 max.	2.0/3.0	
303	0.15 max.	17.0/19.0	8.0/10.0	2.0 max.	2.0/3.0	P or S or Se 0.07 min. Ti or Mo 0.60 max.
304	0.08 max.	18.0/20.0	8.0/10.0	2.0 max.	2.0/3.0	
308	0.08 max.	19.0/21.0	10.0/12.0	2.0 max.	2.0/3.0	
309	0.20 max.	22.0/24.0	12.0/15.0	2.0 max.	2.0/3.0	
310	0.25 max.	24.0/26.0	19.0/22.0	2.0 max.	1.50 max.	
316	0.10 max.	16.0/18.0	10.0/14.0	2.0 max.	0.75 max.	Mo- 2.0/3.0
317	0.10 max.	18.0/20.0	11.0/14.0	2.0 max.	0.75 max.	Mo 3.0/4.0
321	0.10 max.	17.0/19.0	8.0/11.0	2.0 max.	0.75 max.	Ti 5 × C min.
329	0.20 max.	23.0/28.0	2.5/5.0	2.0 max.	0.75 max.	Mo 1.0/2.0
347	0.08 max.	17.0/19.0	9.0/12.0	2.0 max.	0.75 max.	Cb 10 × C min.
403	0.15 max.	11.5/13.0		1.0 max.	1.00 max.	
405	0.08 max.	11.5/13.5		1.0 max.	1.00 max.	Al 0.10/0.30
410	0.15 max.	11.5/13.5		1.0 max.	0.75 max.	
416	0.15 max.	12.0/14.0		1.0 max.	0.75 max.	Same as type 303
420	over 0.15	12.0/14.0		1.0 max.	0.75 max.	
430	0.12 max.	14.0/18.0		1.0 max.	0.75 max.	
430F	0.12 max.	14.0/18.0		1.0 max.	0.75 max.	Same as type 303
431	0.20 max.	15.0/17.0	1.25/2.50	1.0 max.	0.75 max.	
440A	0.60/0.75	16.0/18.0		1.0 max.	0.75 max.	Mo .75 max.
440B	0.75/0.95	16.0/18.0		1.0 max.	0.75 max.	Mo .75 max.
440C	0.95/1.20	16.0/18.0		1.0 max.	0.75 max.	Mo .75 max.
442	0.35 max.	18.0/23.0		1.0 max.	0.75 max.	
443	0.20 max.	18.0/23.0		1.0 max.	0.75 max.	Cu 0.90/1.25
446	0.35 max.	23.0/27.0		1.5 max.	0.75 max.	
501	over 0.10	4.0/6.0		1.0 max.	0.75 max.	
502	0.10 max.	4.0/6.0		1.0 max.	0.75 max.	
414	0.15 max.	11.5/13.5	2.5 max.	1.0 max.	0.75 max.	
431	0.20 max.	15.0/17.0	2.5 max.	1.0 max.	0.75 max.	

Alloying Elements

In both the straight-chromium and chromium-nickel compositions, additive elements[9] are included to modify the properties of the original stainless steel composition. Thus such elements as silicon, copper, manganese, molybdenum, selenium, sulphur, titanium, columbium, tungsten, etc., are added in varying percentages, the amount depending upon the effectiveness of the alloying component and the desired properties of the composition. The effects of these elements in a regular stainless steel composition may be enumerated as follows:

(1) Both tungsten and molybdenum increase the strength at high temperatures. Tungsten may be added up to 3 per cent, and molybdenum up to 4 per cent.

(2) Silicon and aluminum improve the resistance to scaling. Silicon can be added up to 3 per cent and aluminum to from 3 to 4.5 per cent.

(3) Columbium or titanium stabilizes the austenitic stainless steels against carbide precipitation and minimizes the tendency toward intergranular corrosion. Columbium, being a carbide former, is added to the minimum amount of 10 times the carbon content, while titanium, also a carbide former but a more effective one, is added in the amount of 4 to 6 times the carbon content.

(4) Sulphur or selenium improves the machinability of both the straight-chromium steels and the austenitic 18–8 type. They are added with either manganese or molybdenum as the balancing component.

(5) Other elemental additive agents are either manganese, copper or nickel. Manganese is added up to 2.0 per cent to improve the hot-working characteristics of the austenitic alloys; the copper additions may vary from 1 to 4 per cent to improve the resistance to corrosion from chlorides; and nickel up to 2 per cent to certain grades of straight-chromium steels to improve hardenability and also resistance to salt-water corrosion.

Straight-Chromium Steels

The straight-chromium steels are classified according to their hardenability; thus those compositions that are hardenable when subjected to a normal heating and quenching cycle are known as the martensitic stainless steels, because of the normal martensitic structure that is obtained in hardening; the non-hardenable types are termed ferritic stainless steels, since the normal structure obtained upon any type of heating and cooling is ferritic.

The degree of hardenability is dependent upon the chromium and the carbon content. In the hardenable grades the former may be as high as 16 per cent. The ferritic types of straight-chromium steels usually have a higher chromium content—over 16 per cent—accompanied by a carbon range of from 0.12 to 0.35 per cent.

The two grades of straight-chromium steels which may be used for members in certain types of structures are less weldable and less corrosion-resistant than the austenitic chromium-nickel steels. Type 410, containing 11.5 to 13.5 per cent chromium, can be hardened by heat treatment to high physical properties. It is suitable for use where good physical properties are desirable and exacting corrosion problems, such as stain resistance, are not paramount. The best corrosion resistance is obtained in the heat-treated condition. Type 430, containing 14 to 18 per cent chromium, cannot be hardened by heat treatment. This alloy can be welded, which leads to grain growth with some loss in ductility and toughness. For this reason, it is not recommended for welded sections which will be exposed to shock or vibration in service.

The 12 per cent chromium alloys in normal atmosphere will become slightly discolored by the formation of a visible film on the surface of the metal, but this film will protect the metal from any further attack. Thus, the 12 per cent chromium steels find wide application for resisting service conditions which are not too severe, and where a slight discoloration of the surface during service can be tolerated.

The addition of 16 to 18 per cent chromium to iron produces a steel which under atmospheric conditions forms a sufficiently protective film without any discoloration of the surface of the metal. The addition of nickel improves the stability of this film and renders its formation easier. About 2 per cent nickel in a 16 per cent chromium steel makes the alloy respond to a hardening heat treatment.

Chromium-Nickel Steels

When added in sufficient quantity to the ferritic straight-chromium steels, nickel changes the structure from ferrite to austenite; and with this change increased ductility, toughness and strength at normal and elevated temperatures are obtained. Over the range of composition from 16 to 20 per cent chromium and 6 to 12 per cent nickel a wide variety of different types of austenitic stainless steels can be obtained by properly proportioning the amounts of carbon, chromium and nickel. These vary from material with a high rate of work-hardening, which can be cold-rolled into high-tensile sheets, to steels with a very low rate of work-hardening that lend themselves readily to spinning and deep-drawing operations. The commercial classifications do not take this variation in mechanical properties with composition into account, and therefore where specific compositions are necessary to obtain desired results, restricted composition under a given type must be used. Thus, more than one grade is made under some of the types of stainless steel, in order to obtain the composition best suited for various applications, such as drawing or spinning stock or high-tensile cold-rolled sheet.

The austenitic steels are therefore iron-chromium-nickel steels in which nickel exceeds about 6 per cent, and nickel plus chromium exceeds about 24 per cent, with or without moderate additions of other elements. These steels in the annealed condition are normally non-magnetic. While they cannot be hardened by quenching, they may be hardened materially by cold-working and in such case become slightly magnetic. In the annealed condition they possess greater ductility and toughness than ordinary steels. Included in this group are the 17–7, 18–8, 16–12 Mo, 18–8 Ti, 18–10 Cb, 25–12 and 25–20 grades.

Grade 17–7 (Type 301) is an austenitic chromium-nickel stainless steel used for both inside and outside trim and for structural purposes where no welding or other heating will involve the effects of the precipitation of intergranular carbides. It is a general utility stainless steel that is easily cold-worked and meets the requirements of a number of forming and drawing operations where good corrosion resistance, combined with ductility, is required. Its relatively high carbon content makes it sensitive to carbide precipitation.

Grade 18–8 (Type 302) possesses the best combination of resistance to corrosion and desirable mechanical properties. The composition is so proportioned that the steel has the proper degree of work-hardening to make what is considered to be the best deep-drawing steel of all the stainless grades. Because of its great ductility and exceptional toughness, it can be severely drawn, spun, rolled, machined or otherwise worked in the cold state.

Grade 18–8, Type 303, is similar to Type 302. The only difference is that elements which aid machinability have been added to the regular Type 302 composition. These additions detract to some extent from the corrosion resistance. Type 303 is known as the "free-machining" or "free-cutting" grade of austenitic stainless steel.

Grade 19–9 (Type 304) is similar to Type 302 except that the carbon content is held at a maximum of 0.08 per cent. This grade is weldable with less danger of intercrystalline corrosion or embrittlement. The lower carbon content minimizes the susceptibility to intergranular corrosion, which may result from the carbide precipitation that takes place in the higher carbon 18–8 alloys when the metal is heated within the temperature range of 800 to 1600° F. This low-carbon grade is not ordinarily required for welded construction subject only to atmospheric conditions.

Grade 16–12–2 (Type 316) has superior resistance to chemical corrosion. The addition of 2 per cent molybdenum to "18–8" combats pit type corrosion owing to aqueous solutions containing chloride ions. The molybdenum also acts somewhat as a stabilizing agent, thereby slightly decreasing the tendency toward carbide precipitation and susceptibility to intergranular corrosion. In this composition the addition of molybdenum together with the slight increase in nickel over the Type 304 grade improves the strength and corrosion resistance.

Grade 18–12–3 (Type 317) has higher alloy content than Type 316 for increased strength and corrosion resistance.

Grade 18–8 Ti (Type 321) is an "18–8" type stabilized against intercrystalline corrosion and embrittlement due to welding. The alloy is stabilized with a minimum percentage of titanium equal to four times the carbon content to prevent carbide precipitation at the grain boundaries.

Grade 18–10 Cb (Type 347) is a stabilized "18–8" stainless steel for welded structures. The alloy is stabilized with a minimum amount of columbium equal to ten times the carbon content to render it immune to intergranular corrosion and to weld decay. The addition of columbium prevents harmful carbide precipitation. It is used principally for welded equipment which cannot be annealed and quenched after welding and where service conditions are severe.

Grade 20–10 (Type 308) has a higher content of chromium and nickel than standard 18–8 stainless steel. It is used when a greater corrosion resistance than "18–8" metal is needed.

Grade 25–12 (Type 309) combines high scaling resistance and good strength. It is used for elevated temperature applications. A special grade of Type 309 with lower carbon content permits welded fabrication with a minimum of carbide precipitation. Both grades are ductile, easily welded, machinable, and have excellent corrosion resistance.

Grade 25–20 (Type 310) is similar to "25–12" stainless, but with higher nickel content for greater resistance at welding temperatures. Types 308, 309 and 310 are primarily heat resistant grades in which the chromium content is usually high enough to obtain resistance to scaling up to approximately 2000° F., with sufficient nickel to keep the alloy in an austenitic condition. Type 310 is the most stable of these three grades.

All austenitic chromium-nickel stainless steels of the 18–8 type, when heated in the temperature range from approximately 800 to 1600° F. precipitate chromium carbides at the grain boundaries and, as a result of this depletion of the chromium, are susceptible to rapid disintegration by intergranular corrosion when they come into contact with certain liquid corrosive media. To avoid this, the regular austenitic alloys must be given a heat treatment which consists of rapid cooling from a sufficiently high temperature to put the carbides into solid solution and prevent them from precipitating during cooling. When these stainless steels are properly alloyed with either columbium or titanium, they are no longer susceptible to intergranular corrosion since the carbides are stabilized.

Properties

The non-hardenable austenitic stainless steels in general have a tensile strength of 80,000 to 100,000 psi in the annealed condition and excellent ductility. This strength cannot be increased by heat treatment, but can be materially increased by the cold-working of thin sections. It is possible to secure as high as 200,000 psi in cold-rolled sheet and strip, and as high as 300,000 psi in cold-drawn wire. They do not suffer any great loss in impact strength or ductility at very low temperatures.

These steels, being susceptible to work-hardening, develop excellent resistance to abrasion or surface rubbing. They are capable of taking a ground and polished surface in a wide variety of finishes and lusters, ranging from a dull gray or silvery pickled finish, through the popular ground satin finish up to the highly polished mirror finish.

In Table 26 are given the typical physical and mechanical properties of annealed 18–8 Type 302 stainless steel.

Table 26. *Physical Properties, Annealed 18–8 Steel*

Tensile strength (psi)			75,000 to 95,000
Yield point (psi)			30,000 to 40,000
Elongation in 2″ (%)			55 to 60
Reduction of area (%)			65 to 75
Brinell			130 to 170
Charpy			100
Izod impact strength (ft.-lb.)			75 to 115
Thermal conductivity (Btu/sq. ft./hr./° F./in.)			
	200° F.	113	
	1000° F.	150	
Specific gravity			7.94
Specific heat			0.118
Melting point (° F.) (begins to melt)			2,550
Specific electrical resistance (microhms per cu. in.)			
	70° F.	29	
	210° F.	35	
	930° F.	41	
	1470° F.	44	
Coefficient of linear expansion (per ° F.)			
	0–200° F.	0.000009	
	0–600° F.	0.000009	
	0–1000° F.	0.000010	
	0–1500° F.	0.000011	
Modulus of elasticity			28,000,000 to 30,000,000

The mechanical properties of 18–8 stainless steel in the various cold-worked tempers are described in various specifications, of which a typical example[4] is shown in Table 27.

TABLE 27. *Physical Properties of 18-8 Stainless Steel*

Class and physical condition	Tensile strength (psi)		Yield strength at 0.2% set (psi)	Elongation in 2 inches (min.)		
				Thickness up to 0.015 in.	Thickness 0.016 to 0.030 in.	Thickness 0.031 in. and over
Class 1 (Low Ductility)	Min.	Max.	Min.	(%)	(%)	(%)
(A) Annealed	75,000	100,000	30,000	40	40	40
(B) ¼ Hard	125,000	—	75,000	12	12	12
(C) ½ Hard	150,000	—	110,000	7	8	8
(D) ¾ Hard	175,000	—	135,000	3	5	7
(E) Hard	185,000	—	140,000	3	4	4
Class II (High Ductility)						
(A) Annealed	75,000	100,000	30,000	40	40	40
(B) ¼ Hard	125,000	—	75,000	25	25	25
(C) ½ Hard	150,000	—	110,000	15	18	18
(D) ¾ Hard	175,000	—	135,000	10	12	12
(E) Hard	185,000	—	140,000	8	9	9

Test specimens must withstand cold bending in any direction relative to rolling direction through the angle indicated in the following table and on a diameter equal to *n* times the thickness of the specimen without cracking.

BENDING PROPERTIES

Composition and physical condition	Thickness 0.030 inch and under		Thickness 0.030 to 0.050 inch		Thickness 0.050 inch and over	
	Angle in degrees	*n*	Angle in degrees	*n*	Angle in degrees	*n*
(A) Annealed	180	1	180	1	180	1
(B) ¼ Hard	180	1	180	1	90	2
(C) ½ Hard	180	2	180	2	90	2
(D) ¾ Hard	180	3	90	2½	–	–
(E) Hard	180	4	90	3	–	–

By permission of the American Rolling Mill Co., Middletown, Ohio.

Table 28 shows the typical range of properties of the grades of austenitic stainless steels usually used for structural design. The range varies from the annealed stock to the hard-rolled or hard-drawn stock. The very low ratio of yield strength to tensile strength of the annealed stock and the high ratio of yield strength to tensile strength of the hard-rolled stock should be noted.

TABLE 28. *Typical Range of Properties of Stainless Steels*

Type	Tensile strength (psi)	Yield strength (psi)	% Elongation in 2 inches	Reduction of area (%)	Izod impact	Brinell hardness
302, 304	85–300,000	30–280,000	60–5	70–55	115–40	140–425
303	85–150,000	35–135,000	55–10	65–40	85–60	150–300
309	95–190,000	45–175,000	50–5	65–50	110–75	170–350
316	80–225,000	35–200,000	55–5	70–55	100–40	150–375
321, 347	80–190,000	30–175,000	55–5	70–50	100–40	135–350
410	75–190,000	40–150,000	35–15	70–50	110–25	140–400
430	70–110,000	40–90,000	35–10	70–60	25–15	140–250
446	75–85,000	45–60,000	35–30	60–50	5–2	160–190

For high strength requirements[11] tensile strengths up to 200,000 psi and yield strengths up to 150,000 psi can be readily obtained. At the same time the material retains sufficient ductility and toughness to render it fully suitable for structural designs or other applications requiring a combination of high strength and toughness.

Working

Austenitic chromium-nickel steels respond readily to rolling, drawing, forming, bending and shaping. On the other hand they work-harden when severely cold-worked. In severe drawing work, this necessitates intermediate anneals when the material has work-hardened to such an extent that further drawing is impractical. A maximum reduction of about 50 per cent can be obtained before re-annealing.

In Figures 12, 13 and 13a are shown the effect of cold-working on the physical properties of various grades of stainless sheet and plate compositions.[11] In contrast to their high tensile strength, these steels have relatively low elastic properties when in the soft condition. In the initial deformation, therefore, the material yields with comparative ease. However, because of the rapid work-hardening of the material, the elastic properties also change materially. Hence, increasing degrees of cold deformation require the application of correspondingly greater forces for forming operations.

Although austenitic stainless steel is more ductile than ordinary steel, it is at the same time a stronger material, work-hardens more rapidly, and accordingly requires more power in forming operations. In general, slower speeds for drawing are advisable, especially in the case of equipment originally designed for softer materials. Experience has indicated that the slower the press speed, the greater the uniformity with which the deformation will spread over a large area, and therefore the deeper the draw that can be made in one operation. Clearance between the punch and die should be greater than for plain steel on account of these differences in behavior between austenitic and ordinary steels. Frequent practice is to make the clearance approximately 15 per cent over the blank thickness.

Forming and drawing operations demand effective lubricants such as the so-called water-soluble drawing compounds or linseed oil mixed with whiting and sulphur. The lubricant must be removed from the articles after the operation is completed.

Forming operations are best applied to annealed material. Severe draws are sometimes possible without intermediate annealing, and if annealing becomes necessary the lubricant must first be removed. If not cleansed the metal will become contaminated (particularly carburized) by the decomposing lubricant, and its final properties and surface appearance may be

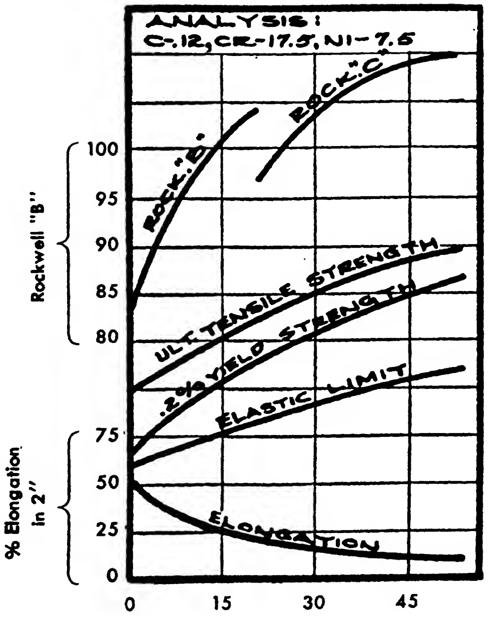


Figure 12

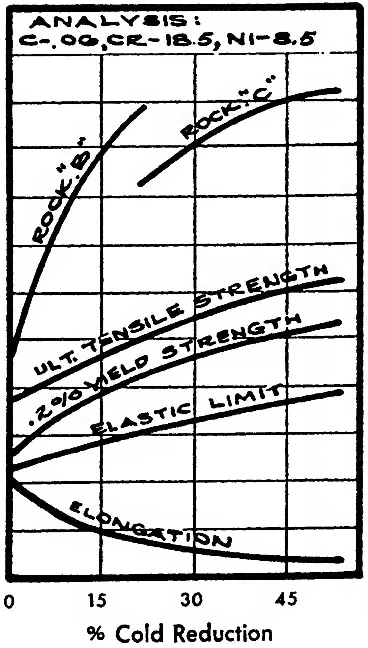


Figure 13

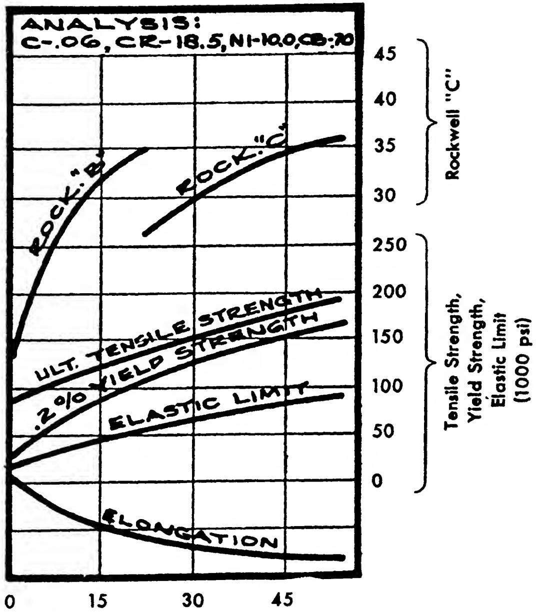


Figure 13a

Effect of cold working on physical properties of various stainless sheet and plate compositions.

impaired. After annealing, which should consist of heating to 1850–1900° F. or above, and quenching in water (or air-cooling in thin sections), the metal should be pickled before continuing with the forming operations. Pickling is performed at 150° F. by any one of the recommended methods. One bright pickling solution contains 10 per cent nitric acid and 3 per cent hydrochloric acid.

The grain structure of the stainless sheet should be of such a nature as to produce a smooth surface after drawing. A coarse-grained stainless steel tends to develop an "orange peel" surface when drawn. Generally, sheets with a clean, white pickled finish are used. This type of finish tends to give less die "pickup" and holds the lubricant better during drawing.

One characteristic of stainless steels that distinguishes them from plain steel is spring. This is due to their high elastic limit in the cold-worked condition. Frequently it can be overcome or corrected by providing a setting operation followed by a final anneal.

The amount of temper strength imparted to stainless steel depends upon the extent of cold reduction. The temper of cold-rolled stainless steel is described, like that of spring steel, copper, aluminum and magnesium, by the terms "annealed," "quarter-hard," "half-hard," "three-quarter-hard," and "full-hard." The harder tempers are used in members requiring high strength but less forming. When severe forming operations are necessary, the softer tempers are used. When both strength and workability are needed, the selection of the temper requires a compromise.

In materials such as austenitic stainless steel, there is seldom, if ever, a sharp yield point, and ordinarily the proportional limit is considerably below its yield strength. When such a steel is cold-reduced, the proportional limit, yield and tensile strengths increase. The yield strength is based on the stress of 0.2 per cent offset strain and is used as a measure of useful strength. Heat-treating austenitic stainless steels at 525 to 850° F. after cold-rolling produces a definite further improvement in yield strength without affecting ductility. This improvement is obtained in tension and in compression in both directions to rolling, and is of importance to engineers who are interested in working their designs to the utmost safe limit.

The directional properties make it unwise for the designer to depend on the simple strength values obtained from ordinary inspection testing in determining working stresses. Materials that have been cold-reduced do not exhibit the same compressive and tensile properties, nor are these properties equal in all directions of the material. Furthermore, the relation between stress and strain is not linear in the useful range of stress.

As has been pointed out by other investigators, the longitudinal compression strength of highly cold-worked materials is less than the corresponding tensile strength, and the transverse compression strength is greater than the corresponding tensile strength. Stress-relieving reduces these differences somewhat.

One of the most important characteristics of the cold-rolled stainless steels is their relatively high fatigue strength. A steel with a tensile yield strength of 115,000 psi has a fatigue strength in the cold-rolled condition of about 60,000 psi; after low-temperature heating, the fatigue strength increases to 65,000 psi.

Except when the nickel content is very high, the austenitic alloy begins to transform slowly as the metal is deformed in any of the various working operations. The transformation to ferrite makes the material slightly magnetic.

Heat Treatment: In heat-treating stainless steels, the general methods do not differ from those used with other steels. However, to take full advantage of the excellent corrosion-resisting and mechanical properties of stainless steels, proper attention must be paid to certain heat-treating variables.

Although all stainless steels[10] are highly resistant to oxidation, they may be expected to scale lightly at high heat-treating temperatures. They will show no evidence of oxidation until a temperature range of about 400 to 550° F. is reached. In this range a very thin oxide film is formed which increases in thickness as the temperature is raised. When completely scale-free heat treatment is essential, specially prepared atmospheres of dry cracked ammonia or dry hydrogen are used. Parts finished to a high luster can be heat-treated without visible trace of discoloration.

Austenitic stainless steels are annealed to obtain maximum softness and ductility by removal of cold-working stresses. In addition, annealing is desirable to dissolve any chromium carbides which may have been precipitated during forging or other hot-working operations; or when the material has been exposed to temperatures from about 800 to 1600° F., or slowly cooled through this range. Such carbides, when present in the grain boundaries, must be re-dissolved by reheating above the carbide precipitation range and rapid cooling to hold them in solution. Ranges of annealing temperatures are from 1750 to 2050° F. for 10 to 30 minutes, depending on alloy composition and thickness of section. The lower the carbon content the lower the annealing temperature within the specified range.

Rapid cooling from annealing temperatures is essential to keep the carbides in solid solution. Very thin sections can be air-cooled with satisfactory results, but heavier sections must be water-quenched. Air-cooling, of course, minimizes the distortion in thin sections.

If the austenitic alloys are cold-drawn or otherwise cold-worked to develop high strength, a low draw or stress-relief increases the elastic properties. This treatment consists of heating parts within the range of 525 to 850° F. for 30 minutes to two hours, and air-cooling.

Normally, austenitic stainless steels do not undergo critical transformations during either heating or cooling, and are therefore not hardenable by any process of heat treatment, as are carbon and low-alloy steels. However, the addition of 0.7 per cent of titanium and 0.2 per cent of aluminum to the 17 per cent chromium-7 per cent nickel grade of austenitic stainless steel has resulted in an age-hardening steel in which a hardness of 38 to 45 Rockwell C can be obtained.

Welding: The welding characteristics of the austenitic stainless steels[2] are dependent upon physical properties which differ considerably from those of mild steel in the following respects:

(1) Greatly reduced thermal conductivity and increased electrical resistance. The thermal conductivity is about 40 to 60 per cent less; the electrical resistance is about six times greater, in the annealed state, and 12 times greater in the extremely cold-worked condition, than that of mild steel.

(2) Thermal expansion is about 50 per cent greater than that of mild steel.

(3) Melting point is slightly lower than that of mild steel. To the experienced welder, the effect of the combination of greater expansion with less heat conductivity will be evident.

(4) There is a tendency toward carbide precipitation along the grain boundaries caused by the welding heat.

Because the heat is not rapidly conducted away, the higher temperatures will be reached in comparatively small areas near the weld joint; and since the coefficient of expansion is high, there will be a tendency toward greater distortion. The high electrical resistance of stainless steels is a property which makes them more suitable to methods employing electric current as a source of heat.

The straight-chromium steels[5] have about the same coefficient of expansion as plain steel, about 40 to 70 per cent of the thermal conductivity, and 4½ times the electrical resistance. Their melting points are only slightly less than that of mild steel. In general, they are more stable over all temperature ranges and therefore not subject to intercrystalline corrosion resulting from carbide precipitation, as are the chromium-nickel alloys.

The welds of the 11.5 to 14 per cent chromium steels harden because of rapid air-cooling from the welding heat, and therefore tend to be brittle. For most applications, however, sufficient ductility can be restored to the weld deposits by suitable annealing after fabrication.

While alloys containing over 20 per cent chromium do not harden at the weld joint during cooling, they may become brittle as a result of either grain growth when held for a long time above 1750° F., or slow cooling from above 1200° F. The grain growth cannot be remedied by heat treatment; but the brittleness due to slow cooling from 1200° F. can be removed by reheating to 1500° F. and rapidly cooling. While annealing restores a good measure of ductility, the weld deposit will not be as ductile as the original material.

It is apparent, therefore, that the technique and the results obtained in welding straight-chromium alloys are not the same as for chromium-nickel alloys.

The arc method and the gas method are generally used for welding austenitic stainless steels.[1] Flash or resistance welding can also be employed successfully. The choice of method depends upon two factors: (1) the thickness of the material to be welded and (2) the equipment available. Sheets heavier than 16 gauge are generally welded by the electric arc method. Gas welding lends itself better to light gauges, although there are several high-frequency electric arc welding machines on the market which are most adaptable to welding light gauge material. Spot welding and shot welding have been used with great success. Spot welding is particularly successful on hard-rolled 18–8 stainless steel of high tensile properties, as the time at heat is not sufficient to lower the high tensile induced by cold-working. Likewise, the time at heat is not sufficient to cause susceptibility to intergranular corrosion.

While sound, ductile welds may readily be made by either metal-arc or flame methods, the arc weld is preferable because it is more rapid and there is less diffusion of heat into the surrounding metal. Arc welding thus reduces buckling or warping, holds carbide precipitation to a minimum, and avoids carbon pickup. Light gauges, however, such as B. & S. No. 18 and No. 20 (0.0500 to 0.0375 inch) and lighter, are generally better welded with a gas torch, since more accurate control of temperature is possible. Where buckling has occurred it may be removed by hammering or peening the weld itself. This expands the weld metal and relieves the stress that has caused buckling.

In welding with a metal arc, direct current is used in preference to alternating current. Coated electrodes are necessary to deposit a solid, nonporous weld metal, to steady the arc, to protect the stream of molten metal from the atmosphere, and at the same time to form a fusible slag that will float on and protect the molten metal from oxidation. Welding is accomplished with as little disturbance or puddling of the molten metal as possible. Puddling is avoided because it increases the tendency toward oxidation and removal of valuable elements.

In joining long, tack-welded seams, it may be found helpful to use a modified "back-step" method to overcome buckling and distortion in the "unjigged" sheets. This practice involves welding a short section, after which the rod and flame are advanced a short distance along the unwelded joint; at this point, welding is begun again and carried back to meet the previous section of weld. The procedure is repeated along the entire seam.

The proper flame for gas welding is one that is strictly neutral, because a neutral flame protects the weld metal from reactive welding gases and from the atmosphere. A flame that is strongly oxidizing causes a porous weld. A strongly carburizing flame also is undesirable because it modifies the corrosion resistance and decreases the ductility of the metal.

One[2] of the effects of welding on the chrome-nickel steels is that the chromium is precipitated as chromium carbide at the grain boundaries, thereby permitting corrosion of the metal at and adjacent to the weld. To overcome this difficulty the shot-welding process utilizes an extremely high current for a short period of time, so that the chromium has no opportunity to precipitate carbide. Or if costs allow, the stabilized type of corrosion-resisting steels may be used. This type of steel contains a small amount of titanium or columbium, which fixes the carbides and prevents their precipitation during the spot-welding or arc-welding operation.

Welding produces a temperature gradient in the part being welded ranging from the melting temperature at the weld to room temperature at some distance from the weld. Therefore, some portion between these two extremes will have been subjected to the temperature range of 800 to 1600° F.

Depending on conditions, an annealing treatment at 1800° F. or above, followed by a rapid quench, as in water, will cause the precipitated carbides to be re-absorbed by the grains making the material homogeneous once more, and not subject to intergranular attack. However, it is not always possible or desirable to anneal after fabrication, in which case the stabilized grade of stainless steel containing columbium or titanium is used. Reducing the carbon content to 0.07 per cent maximum reduces the amount of carbide that can be precipitated, which is sufficient precaution against atmospheric conditions and rains. But where strong electrolytes are encountered, this is not enough and titanium, columbium, or some other element that will produce stable carbides is necessary.

It is possible to decrease the susceptibility of these alloys to intergranular corrosion by properly proportioning the carbon, chromium, and nickel contents so that short heating operations, such as in welding, can be carried out on sections up to ¼ inch in thickness without precipitation of harmful carbides.

Columbium- or titanium-bearing stainless steels require no heat treatment after welding, since they retain full corrosion resistance. Ordinarily stainless steels in the heavier gauges or for use under severe corrosive conditions require heat treatment for re-establishing the corrosion resistance in areas affected by the heat of welding.

The titanium and columbium types of austenitic stainless steel[2] are designed to resist intergranular corrosion after or during exposure to the range 800 to 1600° F. If either of these two grades is intended for service in this range, maximum corrosion resistance is obtained by heating to 1550 to 1650° F., and holding one hour per inch of section thickness, with a minimum holding time of two hours. This long-time period is essential to permit completion of the stabilizing reaction. For service below 800° F. these two grades of steel may be given the same heat treatment as that used for standard 18–8, or the 1550 to 1650° F. stabilizing heat treatment.

Remarks pertaining to the effect of carbide precipitation,[2] the use of stabilized steels and the desirability of annealing after welding, apply equally to all processes of fusion welding.

The extent to which carbide precipitation takes places depends upon a number of factors.[5] One of these is the ratio of the combined percentage of chromium and nickel to the percentage of carbon. The higher this ratio, the more stable the alloy. This discovery led to the development of the balanced alloys, or welding quality alloys for welding operations. Another factor of importance is the length of time the alloy is held within the carbon precipitation range. The shorter the time, the less harmful the carbide precipitation will be.

These two factors explain the importance of employing alloys of stable character for welding, and the general preference for those methods of welding which are faster and result in less heat absorption during the welding operation. Stabilization of the alloy for welding by adjustment of the carbon, chromium and nickel contents is considered effective only in thicknesses up to approximately 7/16 inch. Therefore, alloys stabilized with columbium or titanium are used for greater thicknesses.

It is evident that, in the case of multiple-bead welding on the chromium-nickel alloys, the material laid down in the initial beads may be subjected to carbide precipitation as a result of the heat incident to the following beads. This is a factor that should be given consideration when welding the heavier gauges. In such cases, it is desirable to install the last bead on that side of the joint which will be exposed to the medium being handled.

To maintain full corrosion resistance of the welds,[8] welding rods are used which contain slightly greater percentages of chromium, manganese, and silicon than does the base metal. The slight excess of these elements allows for the small oxidation losses that are likely to occur during welding, even when the molten metal is protected by a neutral flame.

Columbium-bearing 18–8 stainless steel welding rod is recommended for all stainless steel welding, regardless of whether or not the base metal contains columbium or titanium. Its melting point is about 2500° F. In arc welding there is a heavy loss of up to 85 per cent of the titanium in titanium-bearing welding rods.

Riveting

All low-carbon grades of stainless steel may be successfully riveted,[2] but certain differences from the procedure customary for ordinary mild steel are necessary. While riveting is possible, it is no longer practiced as extensively as when the stainless steels were first introduced. Welding technique has advanced so greatly that riveting is employed only in those cases where, because of structural requirements or the character of the metal, welding is not suitable.

Rivet stock must be carefully prepared. It should be processed to have a uniform fine-grained structure with maximum toughness and impact strength. Only smooth, centerless ground, or cold-drawn stock, which is free from seams, slivers, splits or other flaws, should be used. Finished rivet stock should be capable of withstanding without cracking a cold 180° bend around a mandrel whose diameter is equal to that of the rivet stock.

Rivet holes may be drilled or punched, the former being strongly recommended. If punched, the holes should be reamed true to remove strained or distorted metal, with an allowance of $\frac{1}{64}$ inch for clearance.

Small rivets, up to about $\frac{1}{4}$ inch diameter, may be driven cold, but heavy pressures are necessary, and the head should be finished in one or two blows. Larger rivets are hot-driven, the correct temperature being about 1950 to 2050° F. Driving must be completed as rapidly as possible in order to finish the head before the metal cools to the point where it becomes unworkable.

Machining

The successful machining of austenitic stainless steels depends largely on proper machining practice. Since stainless steels are generally stronger and tougher than many other metals, they naturally have different machining characteristics.

Machining these steels requires tools made of high-speed steel, ground with top rake or lip angle. Tools should always be kept sharp, and it is helpful to stone the top surface smooth. In general, it is practical to take fairly heavy cuts, at least heavy enough to prevent the tool from riding over the surface and "glazing" it. In practically all cases it is necessary to apply a cutting lubricant, preferably a sulphur-base oil, concentrated or diluted with paraffin oil.

All stainless steels machine more freely when their hardness is raised somewhat above that of the soft-annealed state by moderate cold-working, that is, when they are used in the moderately cold-drawn condition. Material that is heavily cold-worked will be found more difficult to machine.

Free-machining stainless steels contain 0.07 to 0.35 per cent of sulphur or selenium. About 0.40 per cent of molybdenum is generally added in combination with sulphur, and about 0.15 per cent of phosphorus with selenium. These steels have improved machining properties while retaining the corrosion resistance of the unmodified material.

In machining or forming operations, all high-chromium steels have a tendency to seize or stick to the tool when under pressure. Austenitic steels work-harden under pressure, which means that the next cut is rendered more difficult, especially in fine cuts. To counter work-hardening effects, only keen cutting tools are used, with slow speeds and heavy, steady cuts. This rule applies to machining, as well as sawing where a wavy, fine-tooth saw is used, and to drilling, where a short-twist, sharp-edge drill is necessary.

Chromium-nickel stainless steels do not break through when sheared; therefore the section must be completely cut. Shear blades must be very closely adjusted and kept in good sharp condition; otherwise, the metal, instead of shearing, will tend to drag or pull over the lower blade. The same is true in blanking, punching and perforating operations.

Cladding

In cladding,[6] a layer of stainless steel is bonded to a base metal, which is usually mild steel. The quality of the bond determines the usefulness of the clad material. Production methods include casting, sandwiching, arc welding, spot or resistance welding, intermelting and fusion melting. The corrosion resistance of clad steel is that of the stainless facing, and the physical properties are governed by those of the base metal, of the stainless facing and their relative amounts. Steels are available as 20, 10 or even 5 per cent clad, single- or double-faced with all the principal types of stainless steel. A good quality cladding will stand severe deformation without peeling or separating from the backing. It is claimed that clad steel is easier to fabricate than solid stainless steel; it can be flame-cut (solid stainless cannot be flame-cut without considerable trouble), welded, fabricated hot and cold, deep-drawn, and machined. Special techniques are employed in some of the various fabricating processes. The cost and weight factors determine the use of clad steel in preference to solid stock. In applications where both sides of a thin sheet are exposed to corrosive attack, solid stainless will frequently be found more economical than a double-clad grade.

Surface Condition

The most important factor affecting the service obtained from stainless steels is the condition of the surface. To obtain the best results and to allow the formation of a protective film, a clean, smooth surface free from foreign material and surface imperfections is necessary.

Oxide scale on stainless steel, whether formed during annealing, or by the heat of the welding operation, will almost certainly rust, and if not removed is likely to cause corrosive attack and pitting of the metal itself. Unless the fabricated piece is to be used in high-temperature service, the removal of scale is essential. Sandblasting is generally useful for this purpose, but clean flint rather than metal shot must be used to prevent contamination of the surface by foreign metal. Sandblasting is not recommended if surfaces are too polished. After the scale is removed the work should be passivated if possible by immersion in nitric acid.

Pickling practice for removing scale is to immerse the steel in a bath containing 15 per cent of sulphuric acid plus 10 per cent hydrochloric acid at 170 to 190° F. for 5 to 30 minutes, followed by an immersion in a bath containing 20 per cent of nitric acid and 1 per cent of hydrofluoric acid at 110 to 120° F. for 2 to 4 minutes. To obtain a white pickle the steel is immersed for 3 to 5 minutes in a bath containing 10 to 15 per cent of nitric acid and 1 to 3 per cent of hydrofluoric acid at 120 to 140° F. For passivation after fabrication the steel is immersed for 20 to 30 minutes in a 20 per cent nitric acid solution at 120 to 150° F.

It must be remembered that pickling causes "hydrogen embrittlement." If a hard and highly strained part is pickled, it is likely to crack right in the acid. If the part is merely hard, but not highly strained, it will seldom crack in the acid, but will be brittle and will easily break if subjected to stress after the pickling operation is complete. Hence, hardened parts should receive a thorough low-temperature strain-relieving draw before pickling and also a baking operation after pickling. Baking consists of heating the pickled steel to about 250 to 300° F. for an hour or two. This completely eliminates the hydrogen and all evidence of acid brittleness.

Corrosion Resistance

This is usually, but not always, the most important characteristic, and it should in general be given primary consideration. Corrosion resistance is directly proportional to alloy content and inversely proportional to carbon content: steels which best resist corrosion have the highest alloy and the lowest carbon content. Corrosion resistance of all types depends to a varying degree upon the heat treatment, and always to a great extent upon the surface preparation.

Austenitic stainless steels have remarkable corrosion resistance. They are entirely unaffected by nitric acid, cold acetic acid, citric acid, milk, food products, fruit juices, dyes, and many of the common corrosive agents encountered in industry. These steels retain their silvery surface under all atmospheric conditions.

All corrosion-resistant steels are such because their alloy content allows a tough, passive oxide film to be built up on the surface. This process can be hastened by an immersion in cold 20 per cent nitric acid for 30 minutes or in 20 per cent nitric acid at about 150° F. This is called *passivating*, and it does not affect the appearance of the polished surface. It should always be used after polishing, grinding, shearing, cutting or machining. It is good general practice to passivate after fabrication if possible.

(Courtesy Budd Manufacturing Co., Philadelphia, Pa.)

Figure 14. Side panel assembly of stainless steel railway car.

These alloys possess their maximum resistance to corrosion when they are free from carbides at the grain boundaries. The harmfulness of such precipitated carbides depends upon the use to which the welded material is to be put, and also upon the extent to which precipitation has proceeded.

The unique three-fold combination of high strength, light section, and high corrosion resistance available in austenitic steel makes it a successful material for fabrication into aircraft units, rail cars, buses and structural members.

References

1. Anon., "Working of Stainless Steels,"*American Machinist* (October 5, 1938).
2. Anon., "How to Weld 18-8 Stainless Steel," *Oxy-Acetylene Tips* (March and April, 1941).
3. Anon., "Table of Data on Chemical Composition, Physical Properties of Wrought Corrosion-Resisting and Heat-Resisting Chromium and Chromium-Nickel Steels," ASTM, December, 1942.
4. Anon., "Design Data on High Tensile Stainless Steel Sheets for Structural Purposes," American Rolling Mill Co. bulletin, 1944.
5. Anon., "Stainless Steels," *Product Engineering* (February, 1945).
6. Spencer, "The Stainless Steels," *Steel Processing* (August, 1947).
7. "Corrosion and Heat Resisting Steels," Crucible Steel Company of America bulletin.
8. "Fabrication of U.S.S. Stainless Steels," United States Steel Corporation bulletin.
9. "Stainless Steel," Allegheny-Ludlum Steel Co. bulletin.
10. "Heat Treatment of Stainless Steels," Rustless Iron and Steel Corporation bulletin.
11. Schaufus, H., and Braun, W., "Processing and Fabrication of Stainless Steel Sheet and Plate Products," *Steel Processing* (October, June, November and December, 1945); (January, May, June, and July, 1946).

Section II

Materials for Mechanical Products

Chapter VI

Gear Materials

A gear is a metal wheel bored to fit a shaft. Cut or generated in its rim are cogs or teeth, so shaped that they will engage, or mesh, with the teeth of another gear. Usual practice divides gearing into two distinct classes: gears and pinions, the latter term being applied specifically to the driving gear and the former to the driven gear.

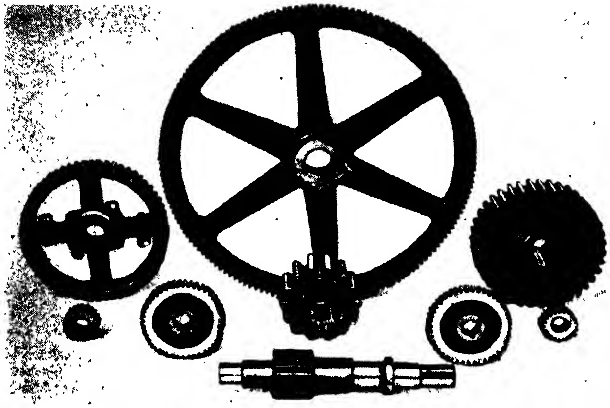
The primary purpose of gears is to transmit power or motion, or to change its rate of direction. The satisfactory performance of a gear drive[14] is fundamentally dependent upon the quality of its parts, which is determined by the kind of material used, by the heat treatment to which the gears have been subjected, and by accurate machining. Gears are designed with such dimensions and with such tooth form as to withstand the wear and tear of the particular type of service, and also to resist the applied loads, stresses and shocks. Therefore, the first requirements of a gear are that it must work in contact with another gear of the same or different material without undue wear, and must carry the load without crumbling of the teeth surfaces or fracture.

Since gearing provides the means of transmitting motion and power in a large percentage of existing mechanical appliances, its practical application must necessarily be based on a great variety of conditions. Because of these variations, gears differ greatly, not only as to type, design and size, but in regard to accuracy, methods of mounting, etc.

Types of Gears

There are many different types of gears, such as spur, helical, spiral, skew, bevel, miter, herringbone, worm and worm wheel, etc., all have different physical characteristics and applications. They are used to transmit power in many types of industrial gear drives and speed-reduction units. The loads vary from fractional horse-power to more than 30,000 horse-power per unit. The speeds may exceed 8000 rpm with pitch line velocities as high as 18,000 feet per minute. Lubrication may vary from the most refined automatic-pressure oiling system to haphazard swabs of a grease brush.

Spur gears are the most commonly used type. They have an average efficiency of about 78 per cent and are used to transmit power between parallel axles. The teeth are cut straight across parallel with the bore. However, they tend to be noisier than either helical or herringbone gears and are not equal to the others in tooth strength per inch of face (Figure 15).



(Courtesy Pittsburgh Gear & Machine Co., Pittsburgh, Pa.)

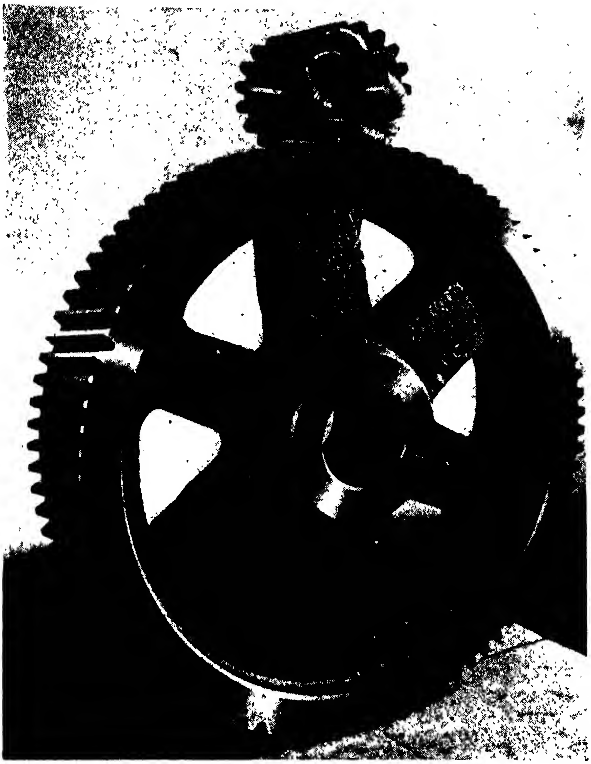
Figure 15. Assorted spur gears.

The motion[3] between the teeth of mating spur gears (gear and pinion) is a combination of rolling and sliding. While the rolling is always in the same direction, the sliding is toward the pitch line on the gear tooth and away from it on the pinion tooth. The action may be summarized as follows:

Tooth	Rolling	Sliding
Pinion tooth	Root to tip	Away from pitch line
Gear tooth	Tip to root	Toward pitch line

Helical gears have angled teeth cut as a helix angle and are preferred, since they minimize noise. They mesh progressively and drive a shaft with an even flow of power rather than with a series of blows or impacts, as is the case when spur gearing engages. Helical gears are stronger than spur gears of equal dimensions and have replaced them in many applications, especially for high-speed operation. End thrusts form the chief objection to the use of single helical gears. This end thrust is developed as a result of the angle drive, which imposes a heavy strain and bearing wear at the end which receives this thrust (Figure 16).

Herringbone gears are double helical gears; they operate very smoothly with a minimum of noise, backlash and vibration. They have relatively greater strength because of the double-angle tooth formation and distribution of load over the full width of the tooth. They are used at high speeds



(Courtesy Westinghouse Electric Corp., Pittsburgh, Pa.)

Figure 16. Helical gears.

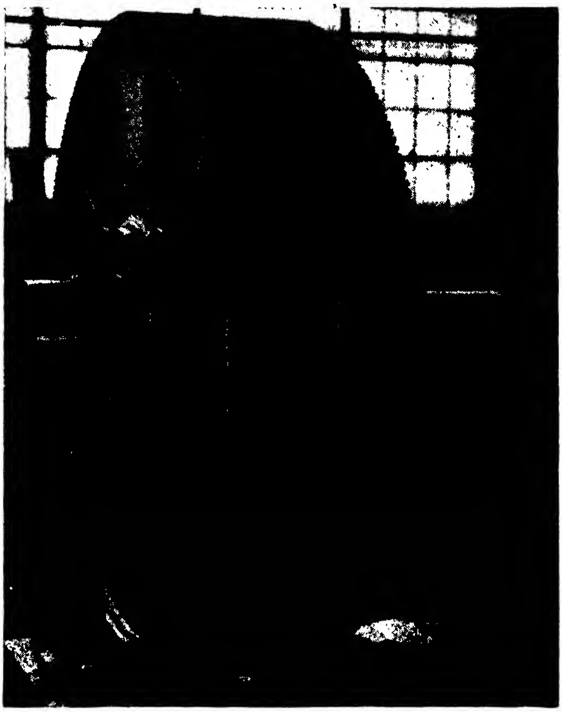
and high gear ratios like the single helical gears, that is, they are used for most heavy, high-speed drives. They eliminate shocks and end thrust, and also represent the most efficient type of geared drives for parallel shafts (Figure 17).

Bevel gears are used for transmitting power between shafts at an angle. For best operation it is recommended that bevel gears do not have a ratio of greater than 6 to 1 (Figure 18). Spiral gears, also called helical gears, differ from spurs only in that their teeth are helical. They may be used between parallel shafts, shafts at an angle or shafts askew, accomplished by varying the angle of the teeth (Figure 31).

Mitre gears are bevel gears of 1-to-1 ratio in which both units of a pair have the same diameter and number of teeth. Their purpose is to transmit power at right angles where no reduction of speed is required.

Skew bevel gears are those used in connecting shafts which are not parallel and do not intersect. They are little used.

Zerol gears are spiral gears cut on a Gleason spiral bevel gear-generating



(*Courtesy Westinghouse Electric Corp., Pittsburgh, Pa.*)

Figure 17. Large herringbone gears.

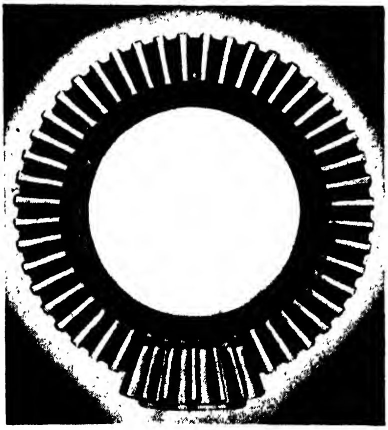
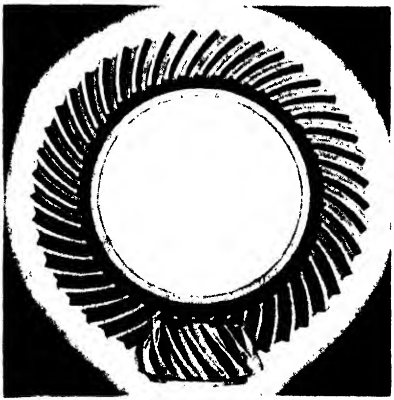


Figure 18. Straight bevel gears.



(*Courtesy Gleason Works, Rochester, N. Y.*)

Figure 19. Spiral bevel gears.

machine with zero spiral angle. They have the advantage over straight-bevel gears because they localize the tooth load and also permit more error in deflection of shaft and mounting.

Hypoid gears are spiral bevel gears with offset axis of pinion and gear. This offset axis permits the shafts to cross each other.

The elliptoid tooth form avoids end bearing as it is thinner at the ends and thicker at the center. This eliminates load concentration of gear teeth at one end or the other.

Internal or annular gears have their teeth extending inward toward the center of the pitch circle. As compared with gears having external teeth, internal gears offer a number of advantages, as follows: (1) large reductions may be secured in a comparatively small space; (2) greater strength, because there are more teeth always in mesh, and the load is more widely distributed; (3) better rolling action and more intimate contact of teeth, because the pitch circle of the inner gear follows the pitch circle of the pinion instead of receding, as in the case of two external gears in mesh; (4) shorter center distance between gears, allowing a more compact design and much more efficient drive; (5) quietness in operation because of greater length of tooth contact and reduction of sliding action; (6) longer life because of reduced friction and vibration, and more perfect rolling action. Internal gears are especially adapted for clutches used in the transmissions of automobiles, trucks and airplanes (Figure 20).

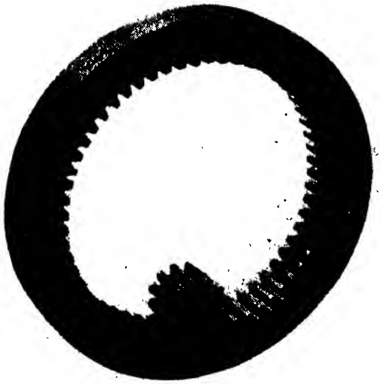


Figure 20. Internal gear and pinion.

(Courtesy Foote Bros. Gear & Machine Corp., Chicago, Ill.)

Worm gearing is employed for transmitting power between shafts at right angles; it consists of two essential parts, a worm and worm wheel. The worm is cylindrical in form and has one or more threads cut into it in the form of a screw or helix. The worm gear is designed to function with the worm, the teeth of the worm gear being cut to mesh with the worm which, when turning, drives the gear with a sliding action. Worm gearing gives great speed reduction and is the most powerful drive known. It is subject to considerable heating and abrasion at the point of contact area and to high tooth pressure (Figure 21). Worm gearing is largely used in places where a great velocity ratio is necessary with as few gears as possible. It is not well adapted to the transmission of heavy power, as its efficiency is necessarily low.

(Courtesy Westinghouse Electric Corp., Pittsburgh, Pa.)

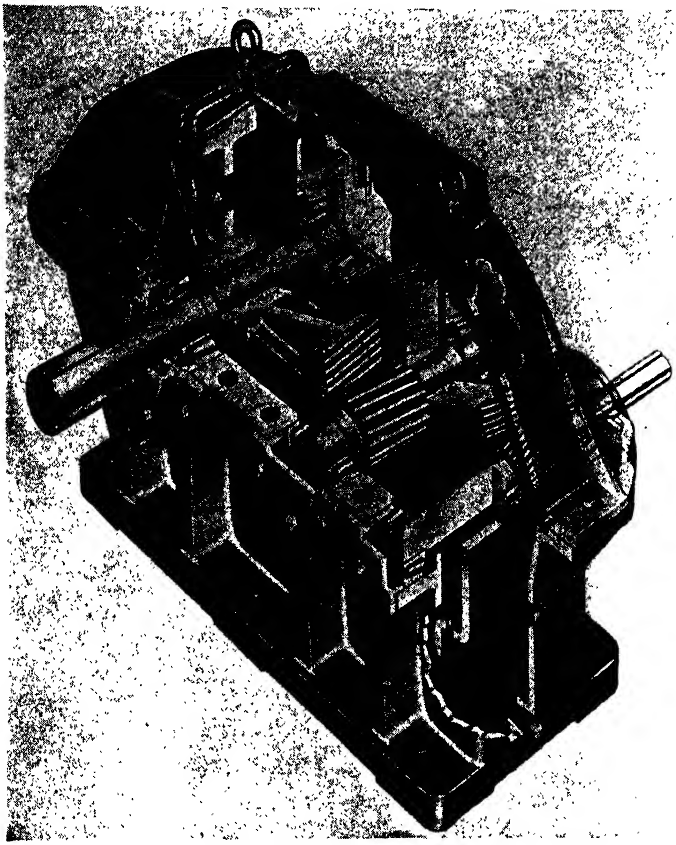
Figure 21. Worm gear set.

Figure 22 is a cut-away photograph of a gear reduction unit showing the assembly of driving and driven gears for increasing or decreasing speed of a power unit.

Gear Terminology

The actual physical characteristics and common dimensions of a gear include the following: number of teeth; pitch, either circular or diametral; pitch diameter; pitch circle; face; bore; outside diameter; diameter of hub; projection of hub; keyway; backlash; tooth form and materials (Figures 23a and 23b).

All gears have an imaginary circle called the "pitch circle." This is the circle which, if the tops of the teeth were cut off, would roll together with the same angular velocity as did the gears. That part of the tooth outside of the pitch circle is called the "addendum" and the portion inside is called the "land" or "dedendum." That part of the tooth outline outside the pitch circle is called the "face," and that part inside the pitch circle the "flank." The "pitch point" is where the "face" and "flank" join at the "pitch circle." The "root circle" passes through the bottoms of the teeth and the "addendum circle" passes through the tops of the teeth.



(Courtesy Westinghouse Electric Corp., Pittsburgh, Pa.)

Figure 22. Gear reduction unit.

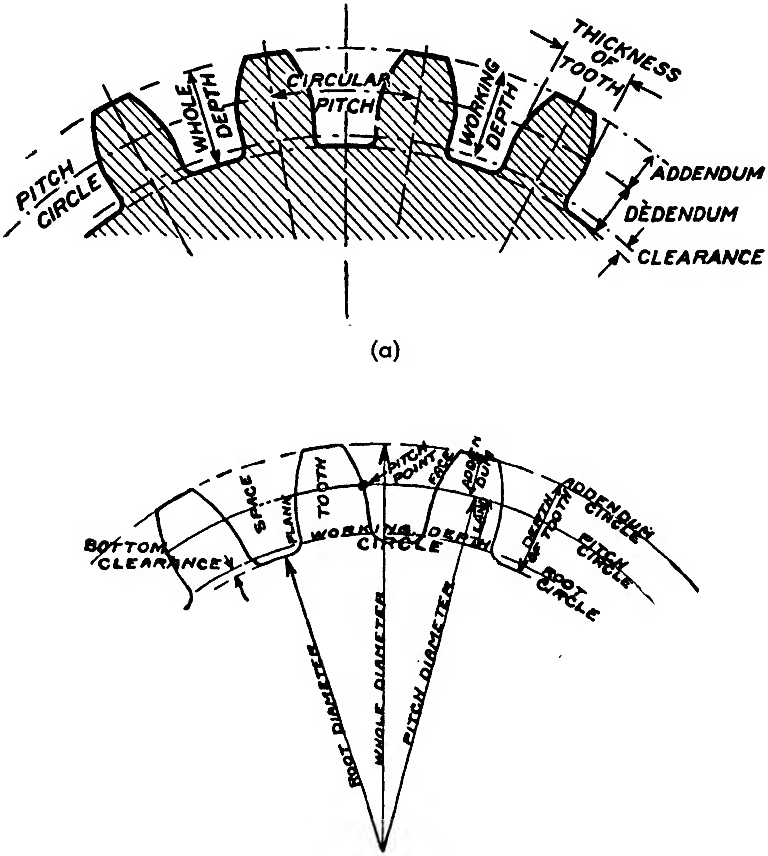
Backlash is the shortest distance between mating teeth whose opposite sides are in contact.

Gear ratio is the relation between the number of teeth in mating members.

Bore diameter is the diameter of the hole in the gear.

Circular thickness is the length of the chord subtended by the circular thickness arc.

Diametral pitch is the relation between the pitch diameters in inches and the number of teeth. It indicates the number of teeth in the gear for each inch of pitch diameter.



(a)

(b)

Figure 23. Gear terminology.

Circular pitch is the distance on the circumference of the pitch circle between corresponding points of adjacent teeth.

Addendum is the radial distance between the pitch circle and the top of the teeth.

Pressure angle is the acute angle between a line tangent to the base circles and a line tangent to the pitch circles intersecting at the pitch point.

Clearance is the radial distance between the top of a tooth and the bottom of the mating tooth space.

Pitch circle is the circle through the pitch point having its center at the axis of the gear.

Root circle is the circle containing the bottoms of the tooth spaces.

Pitch diameter is the diameter of the pitch circle.

Root diameter is the diameter of the root circle.

Tooth bearing is the area of the surface of the tooth which has theoretical contact with its mating tooth during its arc of action.

Tooth face is the surface between the pitch line element and the top of the tooth. It is often considered as the total area including the tooth face and tooth flank.

Tooth fillet is the curved line joining the tooth flank and the bottom of the tooth space.

Gear Requirements

Satisfactory gears must transmit power smoothly, with a minimum of vibration and noise, and must also have a reasonable length of useful life. To accomplish these ends, several essential requirements must be met; they are of a varying degree of importance, depending largely upon the service which the gears are to give. Some of them are requirements of the gears themselves, others have to do with their mounting and care in operation. The requirements for gears are often based on the following:

(1) Constant load:
    (a) Intermittent service
    (b) Continuous service
(2) Fluctuating load:
    (a) Intermittent service
    (b) Continuous service
(3) Shock load:
    (a) Intermittent service
    (b) Continuous service
(4) Severe shock load:
    (a) Intermittent service
    (b) Continuous service

It is rather difficult to specify a single material for each of these conditions, since there may be several other factors which should be considered in the choice of material for a given application. The size of the gear, for example, should be given serious consideration, since heavier gears require a greater degree of depth-hardening and therefore a higher alloy content. Other factors are such items as gear shape, machining practice, expected life, tooth pressures, cost, etc.

A satisfactory gear or pinion must have a hard bearing face to enable it to resist wear; it must be tough enough to resist fracture; and it must have cohesiveness to resist the tendency of particles of metal to tear out of the surface. The ideal material, then, for resisting energy loads in service, in which permanent distortion or plastic deformation must not occur, is one having a high elastic strength and a high modulus of resilience.

Selection of Material

The selection and treatment of gear materials call for a thorough knowledge of the stresses to which the gears are to be subjected in service, and also a proper appreciation of the limitations imposed by manufacturing methods. The latter influences to a large extent the selection of the most suitable material, since such factors as machinability, distortion in hardening, and practicability of grinding often govern the choice. In other words, there are two reasons underlying the choice of any material[10] for a specific gear application: (1) the mechanical properties must of necessity be such that the gear will satisfactorily meet its service requirements; (2) the fabricating characteristics must insure economical machining with adequate accuracy and response to simple heat treatment (if required) with a minimum distortion and freedom from cracking. Both of these considerations are heavily dependent upon the costs involved, and naturally the cheapest material which meets the desired requirements is the best.

Gears are made of various grades and compositions of steel, cast iron and bronze. They may be fabricated from bar stock, individual forgings or castings. Concurrently with a decision about physical properties of the material, the designer must decide on the type of material (forging, rolled shape, casting or bar stock), its chemical composition, and the heat treatment required.

Gears for silent drives are also made of rawhide, "Bakelite" and such plastic-impregnated fabric such as "Micarta," etc. This substitution of plastics for metals is often desirable in small pinions to protect larger and more expensive gears from breaking due to overload.

Assuming that the gear is to be made of steel, one has a choice between hot- or cold-rolled bars, forgings and castings. Rolled bar stock is limited to comparatively small sizes. The manufacturing process causes marked directional properties. Round bar stock or rolled flats formed and welded into circular rims have the minimum properties in the direction where maximum loading in bending and shear occurs. This is serious for heavily loaded pinions or gears.

Forgings include steel pieces shaped by a hammer, press, or upsetting devices. Forging can shape a piece more closely to dimension, can refine the grain structure, and can shape the metal to take advantage of the resulting directional properties. The most important portion of the forging is the rim, in which the teeth are cut; consequently the stock should first be upset to place the fiber in proper position, after which attention may be given to getting the exact shape desired. The proper arrangement of fiber or flow lines can be secured only by upsetting the material so that the forging fibers have a radial direction, thereby securing the maximum resistance to breakage.

Highly stressed gears are made from forgings with carefully controlled flow lines in order to secure maximum strength. It has been well established that steel gears are somewhat weaker under repeated loading and impact across the forging flow lines than in the direction of the flow lines; hence gears made of bar stock are not likely to be satisfactory in highly stressed applications. Some claim that a flat-forged gear is 30 per cent weaker transverse to the direction of working than in the longitudinal direction.

Since the tooth of a gear is loaded as a cantilever beam, the fiber or grain structure in the raw material should be partially radial, and not directional, to insure that the working stress at the root of each tooth falls transversely across the fiber flow of the structure, and not parallel to it. An upset gear blank is usually preferred because of the uniform grain flow. It is also believed that less distortion is encountered in an upset forging (Figures 24 and 25).

Furthermore, the resistance to fatigue and impact stresses is greater at right angles to the fiber than parallel to it. A gear machined from bar stock does not have the fatigue or impact resistance of an upset forged gear. Often the act of distributing the grain makes all the difference between success and failure. It is estimated that steel is 15 per cent stronger in shear across the fiber than parallel to it. Its resilience and toughness are also greater. The steel should be finish-forged at as low a temperature as possible to avoid grain growth.

Gear Steels

Steel is the most widely used gear material because it can be manufactured and processed to a great many different specifications, each of which has a definite use. In general, there are two types of steel, distinguished chiefly by their carbon content as "carburizing" or "through-hardening" grades. Nitriding steels ("Nitralloy") are an exception; these are surface-hardened by the nitriding process.

For carburized gears the carbon content of the steel usually is within the range of 0.15 to 0.25 per cent. The lower carbons are used to secure maximum toughness; the higher carbons give maximum core strength. The recent trend is toward the upper limits; the gears are then used with shallow cases obtained by gas carburizing or activated carburizing baths. This

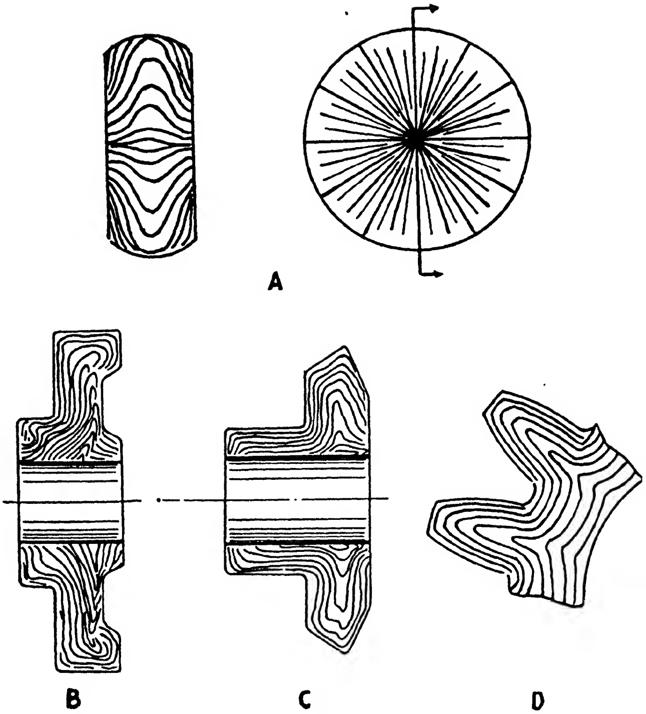


Figure 24. Proper positioning of stock to obtain radial flow in forging.

Figure 25. Upset forged crown gear.

trend exactly parallels that in automotive transmissions. Some carburized gears have been made of steels of approximately 0.30 to 0.35 per cent carbon.

A carbon content of 0.35 to 0.50 per cent is sufficient to satisfy the hardness requirements of most through-hardening gears and at the same time insure suitable shock resistance. Raising the carbon content of small gears is not desirable, because of the detrimental effect on the shock resistance of the gear teeth.

The ratio of carbon content to the mass of the gears is very important if the gears are to be used at high hardnesses, thus requiring the use of low drawing temperatures. Larger gears, heat-treated before machining, have 0.30 to 0.45 per cent carbon range if the steel is to be water-quenched, and 0.40 to 0.60 per cent if oil-quenched. Gears which are to be hardened after cutting usually have 0.45 to 0.55 per cent carbon. Carbon content should always approach the upper limit as the size of the section or desired core hardness increases. Alloy steels may have a lower carbon content, which is desirable to increase toughness or to promote their machinability, especially in gears that are cut after heat treatment.

Refinements in gear design and manufacture, in conjunction with better steel-making practice, have permitted the designer to increase the loadings on the gears, and thus have promoted the use of lower-alloyed steel, especially for smaller gears. On the other hand, the trend in steel mill units, large turbine drives, and crushers is toward the somewhat higher-alloyed steels. The main purpose of alloys is to facilitate the procedure by which the desired properties are obtained. Their particular importance in gear steels is to increase the penetration of hardening and reduce the distortions and internal stresses resulting from heat treatment. Alloys usually increase the ratio of yield point to ultimate strength, and also increase the overload capacity of gears rated on their endurance limit. Alloy gear steels also have better profile durability and strength, particularly against dynamic stresses. Durability depends on surface hardness, and some alloys are available which provide hardness or facilitate heat treatment for maximum hardness.

Of interest to the gear manufacturer is the fact that maximum hardness is dependent chiefly upon the carbon content, regardless of moderate amounts of alloy present. The value of alloying elements, such as chromium, molybdenum, manganese and others, lies in their ability to produce deep hardening with less drastic quench, while alloying elements such as nickel merely toughen the iron matrix.

In general case-hardened gears have been found to withstand higher loads than through-hardened gears, though the latter are less expensive because of the simplified heat treatment. Through-hardened gears have a higher tooth strength, but offer a lower unit resistance to pitting and less resistance to shock than case-hardened gears.

Metallurgically,[12] the choice of the grade of steel and the corresponding heat treatment for industrial gears is largely influenced by the application and by the production facilities available in the shop doing the work. For small gears of light applications, plain-carbon steel is satisfactory. Heavy loads, high speeds, and excessive shocks demand an alloy steel. Where minimum distortion during hardening is required, alloy steels are usually used. A carburized grade should be used for heavy duty involving high tooth pressure and shock stresses.

As the wear resistance of file-hard, carburized plain-carbon steel is just as good as that of the alloy steels, the purpose of using alloy steels is merely to supply strength to resist unusually high stresses arising in some instances from excessive loads and good design, and in others from low loads and poor design (which allows stress concentration).

Case-hardened steel is generally considered the best material for transmission gears. Usually the reason for substituting through-hardening steels is for the sake of economy or a desire to secure somewhat quieter operation. Such gears cannot be hardened to a degree sufficient to offer the highest wear resistance for heavy-duty service. A case-hardened gear, on the other hand, permits attainment of maximum hardness and wear resistance at the surface, while retaining great toughness in the interior to resist shock. If breakage does occur, the core strength can be increased sufficiently by raising the carbon content of the steel purchased. In addition, maximum core strength can be obtained in hardening by a single quench from just above the critical temperature for the core, instead of a double treatment.

Gear steels are usually specified as "fine-grained" because of the better dynamic properties and lower distortion during heat treatment. Coarse-grained steels are given special consideration where maximum hardenability or machinability is required.

Effect of Alloying Elements

The increasingly severe requirements demanded of modern engineering materials impose limitations on the apparent all around utility of the relatively low-cost carbon steels, especially since carbon steels suffer from mass effect in quenching, making uniformity unlikely throughout parts of a large mass. Obviously, one possibility of improving the properties of steel is by alloying it with other metallic elements. The mass effect of hardening can be overcome by a suitable selection of composition and heat treatment.

Alloying elements used in steels may for convenience be classed in three groups: (1) those which dissolve completely in the iron base or matrix; (2) those which combine with carbon to form a carbide; and (3) those which partly dissolve in the iron matrix and partly form a carbide. Elements of group (1) usually enhance the strength and toughness of steel; elements of group (2) increase the hardness and ultimate strength of the steel; while those of group (3) have the general tendency to enhance both the toughness and hardness as well as raise the ultimate strength.

The specific as well as the general effects of alloying elements in steel are as follows:

Carbon. Although the element carbon is not generally considered an alloying element, its effects in steel are quite marked. It hardens by forming iron carbide under heat treatment. Increased carbon content raises the ultimate strength but lowers the ductility and toughness. It reduces dynamic or shock resistance, increases abrasive or wear resistance, lowers the hardening or quenching temperature, and increases the depth of hardness.

Chromium. Chromium forms hard carbides, giving very deep hardening and great wear resistance. Small percentages toughen steel, increasing its strength, elastic limit and impact resistance. Chromium decreases hardening range unless balanced with nickel, but also raises the temperature for hardening or quenching. It also decreases machinability. In general it raises the ultimate strength, hardness and toughness by virtue of its partial carbide formation and solution in the iron matrix. It is usually used with nickel, molybdenum or vanadium.

Manganese. Manganese is a strong carbide-forming element and consequently raises the ultimate strength, toughness, and wear resistance. It lowers the quenching temperature and widens the hardening range. Small amounts increase depth of hardening and decrease tendency to distort under heat treatment. It partly dissolves in the ferrite and partly forms complex carbides.

Molybdenum. This element goes into solid solution, but when other elements are present it forms hard carbides. It gives deep hardening, widens the hardening range, raises the ultimate strength, hardness and toughness. It reduces susceptibility to temper brittleness and offers high resistance to shock impact and alternating stress. It is used to a limited extent as the single alloying element, but is generally associated with chromium or nickel or both.

Nickel. Nickel dissolves completely in the iron matrix and does not form carbides. It raises the ultimate strength without any sacrifice of ductility. It offers strength and shock or impact resistance in thin sections. By lowering the hardening temperature it allows simplified heat treatment, diminished quenching deformation or cracking, and less scaling. In general, nickel increases strength, hardness, ductility and impact resistance.

Vanadium. Vanadium forms hard carbides and also partly dissolves in the iron matrix. It refines the grain, thereby toughening and strengthening the steels. It increases fatigue resistance and shock resistance, but it does elevate the hardening or quenching temperature. Vanadium is usually associated with chromium.

Carbon and Alloy Steels

A review of the records shows that practically all SAE (AISI) analyses are being used or have been used in the past. This is due to the large number of gear sizes and gear applications.

Metallurgical practices[8] on gears with respect to the severity of service for which they are best suited may be classified as follows:

1. Very heavy duty: Carburized low-carbon alloy steel with case depth over 0.060 inch.
2. Heavy duty: Carburized low-carbon alloy steel with case depth 0.040 to 0.060 inch.
3. Heavy duty: Oil-hardened, medium-carbon alloy steel.
4. Medium duty: Carburized low-carbon alloy steel with case depth 0.020 to 0.040 inch.
5. Medium duty: Carburized 0.30 carbon alloy steel with case depth 0.010 to 0.015 inch.
6. Medium duty: Carburized 0.50 carbon alloy steel with case depth 0.005 to 0.010 inch.
7. Medium duty: Cyanide-treated medium-carbon alloy steel with case depth 0.003 to 0.010 inch.
8. Medium duty: Oil-hardened medium-carbon alloy steel.
9. Light duty: Cyanide-treated low-carbon plain-carbon steel with case depth 0.005 to 0.010 inch.
10. Light duty: Medium-carbon, plain-carbon steel, heat-treated to approximately 250 Brinell.
11. Extremely light duty: Free-machining type of steel from cold-finished bar stock.
12. Extremely light duty: Medium or low-carbon, plain-carbon steel, not heat-treated.

The steels[16] used for these various types of service are listed in the following tables. Table 29 shows the composition of those suitable for carburizing in order to obtain great wear resistance and load-carrying capacity. The hardenability rating of these steels is in the following order, beginning with the steel of the lowest hardenability and using the hardenability of the uncarburized core as an index: AISI A4620, A8620, A8720, A4820, A4320, A2512 and A3312.*

Although these are most commonly used, it is generally accepted that steels having carbon in the range of 0.10 to 0.25 and having sufficient alloy content to allow hardening in the section sizes in which they are used, are suitable for gears. Higher-carbon steels with shallower cases are sometimes used.

The steels shown in Table 30 are suitable for gears requiring medium wear resistance and load carrying capacity. These steels are the most com-

---

* See Appendix for composition of all A.I.S.I. and S.A.E. steels.

TABLE 29

S.A.E. steel no.	A.I.S.I. steel no.	C	Mn	Cr	Si	Ni	Mo	Al	P max.	S max.
3312	A3312	0.08–0.13	0.45–0.60	1.40–1.75	0.20–0.35	3.25–3.75	—	—	0.040	0.040
4027	A4027	0.25–0.30	0.70–0.90	—	0.20–0.35	—	0.20–0.30	—	0.040	0.040
4320	A4320	0.17–0.22	0.45–0.65	0.40–0.60	0.20–0.35	1.65–2.00	0.20–0.30	—	0.040	0.040
4620	A4620	0.17–0.22	0.45–0.65	—	0.20–0.35	1.65–2.00	0.20–0.30	—	0.040	0.040
4820	A4820	0.18–0.23	0.50–0.70	—	0.20–0.35	3.25–3.75	0.20–0.30	—	0.040	0.040
	A8620	0.18–0.23	0.70–0.90	0.40–0.60	0.20–0.35	0.40–0.70	0.15–0.25	—	0.040	0.040
	A8720	0.18–0.23	0.70–0.90	0.40–0.60	0.20–0.35	0.40–0.70	0.20–0.30	—	0.040	0.040
"Nitralloy"		0.38–0.43	0.40–0.70	1.40–1.80	0.20–0.40	—	0.30–0.45	0.90–1.35	0.040	0.040

TABLE 30

S.A.E. steel no.	A.I.S.I. steel no.	C	Mn	Cr	Si	Ni	Mo	V	P max.	S max.
	A1345	0.43–0.48	1.60–1.90	—	0.20–0.35	—	—	—	0.040	0.040
4145	A4145	0.43–0.48	0.75–1.00	0.80–1.10	0.20–0.35	—	0.15–0.25	—	0.040	0.040
4340	A4340	0.38–0.43	0.60–0.80	0.70–0.90	0.20–0.35	1.65–2.00	0.20–0.30	—	0.040	0.040
4640	A4640	0.38–0.43	0.60–0.80	—	0.20–0.35	1.65–2.00	0.20–0.30	—	0.040	0.040
	A5145	0.43–0.48	0.70–0.90	0.70–0.90	0.20–0.35	—	—	—	0.040	0.040
	A8645	0.43–0.48	0.75–1.00	0.40–0.60	0.20–0.35	0.40–0.70	0.15–0.25	—	0.040	0.040
	A8745	0.43–0.48	0.75–1.00	0.40–0.60	0.20–0.35	0.40–0.70	0.20–0.30	—	0.040	0.040
	A9845	0.43–0.48	0.70–0.90	0.70–0.90	0.20–0.35	0.85–1.15	0.20–0.30	—	0.040	0.040
2345	A2345	0.43–0.48	0.70–0.90	—	0.20–0.35	3.25–3.75	—	—	0.040	0.040
6145	A6145	0.43–0.48	0.70–0.90	0.80–1.10	0.20–0.35	—	—	0.15 min	0.040	0.040

monly used types for gears. However, any steel having the proper hardenability characteristics, with carbon content in the range of 0.35 to 0.50 per cent, is suitable for gears of this class. The hardenability rating of these steels is in the following order, beginning with the steel of lowest hardenability: AISI A1345, A4640, A3140, A5145, A8745, A4145, A9845, A4340, A3250, A6150, A4350.

The steels[16] listed in Table 31 are suitable for gears requiring only a moderate degree of strength.

TABLE 31. *Chemical Composition of Carbon Steel for Gears*

S.A.E. steel no.	A.I.S.I. steel no.	Carbon	Manganese
1035	C–1035	0.32–0.38	0.60–0.90
1040	C–1040	0.37–0.44	0.60–0.90
1045	C–1045	0.43–0.50	0.60–0.90
1050	C–1050	0.48–0.55	0.60–0.90
1141	C–1141	0.37–0.45	1.35–1.65

For certain highly stressed services, for example, the following might be recommended as typical alloy steels but they all would be subject to modification in the light of further details regarding service.

(a) Constant load, intermittent service: A.I.S.I. 4640, A.I.S.I. 3140, A.I.S.I. 8640, oil-quenched, at 1,500–1,550° F. and tempered at 400–450° F.
(b) Constant load, continuous service: A.I.S.I. 2350, A.I.S.I. 3250, A.I.S.I. 4350, A.I.S.I. 6150, oil-quenched at 1,475–1,575° F., and tempered at 400–450° F.
(c) Fluctuating load, intermittent service: A.I.S.I. 3150, A.I.S.I. 4150, oil-quenched at 1,425–1,475° F., and tempered at 400–450° F.
(d) Fluctuating load, continuous service: A.I.S.I. 2350, A.I.S.I. 3250, A.I.S.I. 4350, A.I.S.I. 6150, oil-quenched at 1,475–1,575° F., and tempered at 400–450° F.
(e) Shock load, intermittent or continuous service: S.A.E. 2315, A.I.S.I. 4320, A.I.S.I. 4620, carburized, oil-quenched and tempered at 275–300° F.
(f) Severe shock loads, intermittent or continuous service: A.I.S.I. 2512, A.I.S.I. 3312, carburized, oil-quenched and tempered at 275–300° F.

AISI 1141 is suitable for gears in which service is very light and which can be machined from cold-finished bar stock. This is a free-machining grade where high cutting speeds are employed.

AISI 1040 or 1050 can be used in the oil or water hardened conditions, depending on carbon content, for low-cost commercial gearing where speeds and loads are not too high.

AISI 3115 and 3120 are low-cost alloy steels of excellent properties after case-hardening for automobile and machine-tool gears. For greater hardness and penetration the chromium is increased, and for greater toughness the nickel is increased.

AISI 2512, 4320, 4820 and 3312 have highest resistance to fatigue and wear. They are used where subjected to continuous heavy duty and abuse. They have the highest core strength of all the carburizing grades.

AISI 2315 is used where the requirements are not as severe as for AISI 2512, but where excellent wear resistance, high fatigue resistance and good core strength are required. It is used extensively for ring gears and pinions.

AISI 4615 and 4620 are popular for automotive gears. The higher carbon is used for greater core strength.

AISI 5120 and 6120 are also used to give exceedingly high surface hardness when properly case-hardened.

AISI 4640 and 3150 are especially suited for cyaniding to provide skins of high hardness and improved wear resistance. AISI 3150 is valuable when a definite improvement over carbon steel is required at low cost, as in machine-tool gears of moderate section and for small gears of moderate service.

AISI 3250 and 3450 should be specified when the section is such that a higher degree of depth-hardening is required, as for gears of heavy sections or for moderate-size gears requiring better properties than those obtained with AISI 3150. For medium to large gears of heavy duty AISI 3250 is preferred, while for very large gears of heavy duty AISI 3450 is desirable.

AISI 2350 is recommended for applications requiring a high-quality gear of small or medium section, for heavy to moderate duty, and for highest resistance to shock, such as for automobile, bus and tractor transmission gears. It has an excellent combination of strength and toughness.

AISI 4640 and 4650 have a good combination of strength and toughness together with excellent machining characteristics for medium gears of moderate service. They are particularly useful where distortion must be held to the minimum.

AISI 4340 and 4345 have excellent depth-hardening properties for large gears of heavy duty, requiring high shock resistance.

AISI 6140 and 6150 have a broad quenching range and good resistance to shock.

Nitrided steels produce the hardest possible case. The process results in very low distortion, but requires long treating time and special steel composition.

Cast manganese steel gears have been used for driving rolling-mill tables and are still widely employed for their tough resistance to breaking stresses and abrasion. Gears made of 13 per cent manganese steel possess remarkable toughness and wear resistance. The teeth may bend under excessive loads but will not break; and the tooth face becomes work-hardened and polished from continuous usage. However, austenitic manganese steel tends to lose its temper under temperatures higher than 650° F. applied for any considerable period. This can be eliminated by adding about 4 per cent of nickel to the steel.

Nickel[15] alloy steels are popular for important gears, combining as they do dependability and uniformity, low hardening temperatures and response to mild quenching with resulting reduction in warping, distortion, internal stress, scaling, and resistance to grain growth.

It has been found from experience that direct oil-hardening gears in intermittent service (AISI 3150 steel) will give a satisfactory wear life if the maximum compression stress is not over 165,000 to 170,000 psi. In carburized gears the limiting stress is about 200,000 psi for AISI 2315 steel, or about 215,000 psi for 2515 steel. Other steels used in gears, depending upon their relative physical properties, will have limiting stresses falling slightly above or below those mentioned. These limiting loads apply to intermittent stresses only and are usually reduced by 25 per cent for constant-load jobs.

Carburized Gears

Carburized and case-hardened gears are best suited for heavy duty service, offering the maximum resistance to wear, pitting and to fatigue failures.

In modern practice almost all transmission gears[15] are case-hardened in one way or another. Gears of low-carbon alloy steel (AISI 2315, 2512, 3115, 4615, 4815, etc.) are pack or gas carburized, and higher carbon steel gears (AISI 2345, 3145, 4650, 3250, 4345, etc.) are given a superficial surface-hardening by cyanide or some similar activated bath. Low-carbon (carburized) gears are characterized by a heavy case and a soft core, and higher carbon (cyanided and heat-treated) gears by a light case and a hard core.

The case and core characteristics of low-carbon gears usually fall within the following ranges: case depths, 0.030 to 0.050 inch; case hardness, Rockwell C–55 to C–62; core hardness, Rockwell C–30 to C–40. A rule for depth of case, which has been found quite satisfactory for low-carbon transmission gears in a number of instances, specifies "twice as much core as case." Correctly interpreted, this means a case depth equal to one-sixth of the thickness of the tooth at its base. Thus a tooth 0.240 inch thick at the base would require a case depth of 0.040 inch.

With higher carbon gears,[15] the case and core characteristics usually range as follows: case depth, 0.001 to 0.010 inch; case hardness, Rockwell C–48 to C–58; core hardness, C–45 to C–55.

The tensile strength of the core of low-carbon alloy steel gears after final heat treatment varies from about 125,000 to 175,000 psi, while that of higher carbon alloy steel gears covers a range of approximately 200,000 to 325,000 psi. Fatigue strength is affected seriously by residual stresses from the quenching operation and has a much lower value than when higher tempering temperatures are used. A temper of 750° F. has been known to

TABLE 32. *Approximate Core Properties of Case-Hardened Carbon and Nickel Alloy Steels*

S.A.E. steel no.	Approx. crit. range, deg. F. of		Treatment after carburizing		Core properties					
	Core	Case	Heat, deg. F.	Quench, in.	Yield point, lb. per sq. in.	Tensile strength, lb. per sq. in.	Elong. in 2 in. per cent	Red. area, per cent	Brinell hardness	Izod impact ft. lb.
2315	1,435	1,305	1,375	Oil	57,000	90,000	32	60	190	75
			1,375	Water	60,000	95,000	28	55	200	60
			1,425	Oil	85,000	115,000	21	51	225	55
			1,425	Water	95,000	130,000	17	45	290	40
			1,475	Oil	135,000	160,000	11	47	345	35
			1,475	Water	150,000	180,000	9	45	390	30
			1,525 1,375	Oil Oil	60,000	95,000	35	65	195	85
			1,525 1,375	Oil Water	65,000	100,000	30	60	210	70
2515	1,400	1,285	1,350	Oil	65,000	105,000	28	60	210	65
			1,350	Water	70,000	115,000	26	55	230	50
			1,400	Oil	110,000	140,000	18	55	260	45
			1,400	Water	115,000	150,000	15	52	290	35
			1,460	Oil	160,000	195,000	14	50	385	30
			1,460	Water	165,000	200,000	13	50	390	30
			1,500 1,350	Oil Oil	70,000	110,000	30	65	220	75
			1,500 1,350	Oil Water	72,000	120,000	28	60	230	60
			1,525 1,400	Oil Oil	115,000	145,000	20	60	270	50
			1,525 1,400	Oil Water	120,000	155,000	17	55	295	40
3115	1,460	1,355	1,400	Water	85,000	130,000	16	45	260	35
			1,400	Oil	80,000	120,000	18	48	250	45
			1,475	Water	155,000	180,000	10	30	360	25
			1,475	Oil	125,000	155,000	13	43	335	30
			1,550 1,400	Oil Oil	85,000	125,000	25	55	255	55
4615	1,515	1,340	1,425	Oil	70,000	105,000	25	55	200	60
			1,425	Water	80,000	115,000	22	50	220	40
			1,525	Oil	105,000	145,000	17	52	300	35
			1,525	Water	110,000	150,000	17	50	300	30
			1,550 1,425	Oil Oil	75,000	110,000	28	57	215	75
			1,550 1,425	Oil Water	85,000	120,000	25	52	230	55
3312	1,430	1,320	1,400	Oil	165,000	195,000	12	40	390	35
			1,525 1,400	Oil Oil	170,000	200,000	13	42	400	40
4815	1,435	1,305	1,460	Oil	165,000	200,000	14	54	375	—

improve fatigue resistance greatly, but the lower hardness results in serious wear.

The nickel carburizing steels[3] are used chiefly where exceptional toughness in the underlying core combined with a high degree of wear-resistant surface is required. The most popular nickel alloy carburizing steels are shown in Table 32, together with the core properties developed by various commercial heat treatments. These properties serve to indicate in a general way the range of usefulness of each steel, insofar as strength and toughness developed in the gear teeth are concerned.

Current design practice is often more concerned with compressive stresses developed on the engaging tooth surfaces than in the actual strength of the teeth, particularly where high-speed gears are involved. In Table 33 are listed the relative compressive stresses of various nickel carburizing steels, together with a value commonly used for the direct-hardening types. It has been established that when compressive stresses, as calculated from the Hertz formula, do not exceed the figures given, the gear teeth are not overstressed in compression and hence not likely to fail by pitting in service.

TABLE 33. *Permissible Compressive Stresses for Nickel Alloy Gear Steels*

Type	S.A.E. classification	Permissible compressive stress, * (psi)
Direct Hardening	3150, 4640, 4650, etc.	170,000
Carburizing	3115, 3120	180,000
Carburizing	2315, 2320, 4615, 4620	200,000
Carburizing	3312, 4815, 4820, 2515	215,000

* These values are for intermittently loaded gears, and should be reduced by 20–25% for constant mesh loading.

Heavy-duty applications are served best by the more highly alloyed types, such as AISI 3312, 4815, 2515 and 4320. Intermediate types are represented by AISI 2315, 4615, and 3115, the latter being a rather inexpensive oil-hardening steel offering considerable advantage in properties over carbon steel. When better core properties are desired, it is customary to use these steels with an increased carbon content over 0.20 per cent, with sometimes the added advantage of better machinability in the annealed condition.

For carburized gears, wear resistance is primarily a matter of surface hardness, together with sufficient depth of case to prevent crushing. There is a relation between depth of case and resistance to compressive stress; however, it is such that the case depth required to prevent fatigue breakage is always adequate to prevent crushing.

A phenomenon which sometimes occurs when gears are carburized deeply is exhaustion of the carburizing gases and an unbalanced C, CO and CO_2

reaction toward the end of the operation, whereby the carburizing gases react with the carbon deposited in the steel and this decarburized surface ultimately reduces the wearing qualities. Slightly decarburized surfaces develop fatigue cracks very quickly under load.

Nitrided Gears

Nitrided gears give complete freedom from wear up to the load at which surface failure occurs, but at this load they become badly crushed and pitted, in a manner suggesting that they would not be suitable for duty where overloads might be encountered. One of the important advantages of "Nitralloy" steel is that it makes possible surface hardening of teeth of large gears of light section which may be utterly impractical to carburize and quench. The surface hardness does not drop off after continued service, as frequently happens with a carburized case.

Several grades of "Nitralloy" steels are used for surface hardening by the nitriding process. These steels are shown in Table 34.

TABLE 34

"Nitralloy" No.	C (%)	Cr (%)	Mo (%)	Al (%)	V (%)
115	0.11–0.19	1.3–1.5	0.15–0.25	0.85–1.2	—
125	0.20–0.29	0.9–1.4	0.15–0.25	0.85–1.2	—
135	0.30–0.40	0.9–1.4	0.15–0.25	1.0–1.4	—
225	0.20–0.30	—	0.60–1.0	1.0–1.4	—
230	0.25–0.35	—	0.60–1.0	1.0–1.15	—
630	0.25–0.35	1.4–1.6	—	—	0.45 min.
640	0.35–0.45	1.4–1.6	—	—	0.45 min.
135 Mod.	0.40	1.75	0.4	1.0	

A nickel nitriding steel containing 0.20–0.27 carbon, 0.40–0.70 manganese, 1.10–1.40 aluminum, 1.00–1.30 chromium, 0.20–0.30 molybdenum and 3.25–3.75 nickel, is a precipitation-hardening alloy, and can thus develop in its core as a result of exposure to the nitriding temperature, a strength and hardness considerably in excess of its original properties.

"Nitralloy" steel is nitrided in a cracked ammonia atmosphere at 950 to 980° F. for a sufficient time to give the desired case depth. To obtain greater diffusion of the case depth, "Nitralloy" gears are sometimes first heated for several hours at 950° F.; the temperature is then raised to 1200° F. for several more hours, and the steel is finally furnace-cooled.

Before nitriding, the steel must be in the sorbitic condition and free from surface decarburization. The customary practice is to quench the rough-machined gears in oil from 1700 to 1750° F. and to temper at 1100 to 1300° F. The gears are then finish-machined to remove any decarburized surfaces.

Often it is desired to nitride only the gear teeth and to leave the rest of the gear soft. Such selective hardening can be done by using tin plate as a stop-off. The gear is tin-plated to a thickness of 0.0003 to 0.0005 inch and the tin plate removed only from the gear teeth before nitriding. Other stop-offs have been used satisfactorily. Nitriding of "Nitralloy" steels can produce a depth of case to 0.030 inch after a 50-hour cycle with a developed surface hardness of 900 to 1000 Vickers-Brinell (equivalent to about 95 Rockwell–15N scale).

The core hardness limitations as they affect carbon content do not have any appreciable effect on the nitriding process, since no structural change takes place in the mass of the steel at the temperature employed. This is rather fortunate, since a relatively soft core is obtained to support the thin, hard case.

Since the hardness of nitrided surfaces does not alter up to temperatures in the neighborhood of 800° F., these steels are useful in cases where hardness must be maintained at temperatures which would speedily ruin a carburized surface.

Heat Treatment

In gearing, the term "heat treatment" usually refers to the operation of carburizing for case-hardened steels and hardening of all grades of steel by quenching, followed by tempering. Preannealing and/or normalizing of gear blanks, and also stress-relief annealing between rough and finish machining are also classed as heat-treating operations.

Fundamentally, there are but two methods of obtaining high mechanical properties for strength and high surface hardness for wear resistance: (a) surface hardening and (b) full hardening. Surface or profile hardness is obtained by means of (1) carburizing, (2) nitriding, (3) flame-hardening, and (4) induction-hardening.

Steel expands when heated and contracts when cooled.[7] On heating the steel expands up to the lower critical temperature, contracts slightly for a short period while passing through the critical range, and then continues to expand again up to the quenching temperature. The reverse occurs during cooling. In other words, steel goes through six volumetric changes during the hardening cycle.

The thin sections will cool first on quenching, thus producing strains which will cause warping. Everything in the hardening favors distortion. Because of the heat differential in various sections, some areas are expanding and others are contracting at the same time during heating and during cooling.

The oil-hardened gears almost invariably expand permanently in the hardening, and this of course increases the diameter of the pitch circle. This increase usually approximates 0.001 inch per inch of diameter, but it is not always uniform, depending on design and hardening temperature. Thus if the gear was a thin ring it might not expand, but actually shrink. The rule of 0.001 inch per inch is safely used in restricting backlash to the close requirements. Fine-grain steels do not change as much in dimension during heat treatment as coarse-grained.

When carburized gears are hardened the movement is toward the bore, hence there is shrinkage. Under good hardening practice the periphery changes very little. Hence it appears that there are greater possibilities for quiet gears from the case-hardened low-carbon steels than from the through-hardened higher-carbon steels.

Water-quenching produces more distortion than oil-quenching. The rate of quenching is one of the most important factors in gear distortion. Quenching conditions must be adjusted to the mass to be hardened. Many plants have solved the problem of distortion by use of press-quench fixtures.

Case-hardened gear teeth fail by fatigue, and the fatigue failure for the usual depth of carburization always originates at the surface of the case. The heat treatment therefore should consider the requirements of the carburized case only; the properties of the core are relatively unimportant. since in bending it serves mainly as a backing for the case.

Heat treatment of gear materials assumes special significance because the ability of gears to carry a given load is definitely related to the accuracy of the tooth dimensions. Quenched and tempered gears have frequently been unsatisfactory because of uncorrected warpage from heat treatment.

Distortion which occurs during hardening must be taken into special consideration in all parts that are used without finishing operation after heat treatment. Some of these parts of high hardness may be sized after hardening by grinding; but some gear designs do not lend themselves readily to grinding because of their shape, or because grinding removes a layer of metal of high surface hardness, expressly created by heat treatment. Distortion is particularly bad in these highly stressed gears, not only from the standpoint of imperfect functioning, which causes undeniable noise, but because it usually results in considerably increased stresses in the gear due to concentration of the loads on smaller areas.

Full-hardening steels[10] may be simply heat-treated to the usual hardening temperature and quenched in oil or water depending on the carbon content, the alloy content, the mass and the design. Quite frequently, however, steels are heated either in cyanide or in some special bath producing a light case, or in a gas carburizing furnace. This type of treatment produces a very hard case superimposed over a core having approximately the same properties as that produced by heating without cyanide or gas-carburizing.

Isothermal quenching has been used successfully to reduce quenching strains to a minimum, to decrease distortion and to increase the toughness of the gear teeth. In practice it involves (1) quenching into a liquid heated to a predetermined temperature, (2) holding in the liquid until the entire piece has attained the bath temperature, and (3) removing for cooling in air or some other medium.

Case-hardening heat treatment may restrict surface hardening to the work faces of the teeth. The case is localized during carburizing by a "stopping off" of copper plating. The gear blank is rough-machined, annealed to relieve all strains, copper-plated all over, finish-machined, heated in a carburizing mixture or atmosphere to about 1700° F. for several hours depending on the desired case depth, and furnace-cooled or quenched direct.

Before carburizing and after finish-machining and partial or rough tooth-cutting operations, the gear is completely copper-plated; it is then returned to the gear-cutting machine to receive a finish cut with the object of removing the copper plating entirely from the active faces of the teeth, leaving those surfaces only for reception of the carburizing. In this way there is no carburization of any part of the gear except the contact faces of the teeth that have been cleared of their copper plating in the finish operation of the gear cutter.

For hardening carburized gears it is generally recommended to use fine-grained steel and either single quench direct from carburizing heat, or cool in the box followed by reheating to nearly the carburizing temperature and quenching. This produces a structure containing more or less austenite, which can be broken down as desired in the subsequent tempering operation. The gears may also be double quenched, the first from a relatively high temperature for the core and the second from a temperature only slightly above the critical range of the case. This produces a fine martensitic structure in the case. It is believed that a higher resistance to bending fatigue is obtained by the double-quenched martensitic type of case, properly tempered.

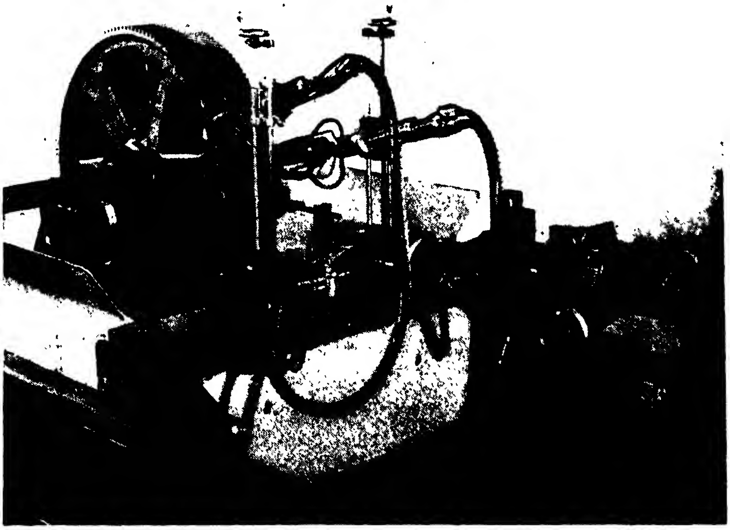
Double quenching after carburizing produces a soft core. Maximum core strength is obtained by a single quench from just above the critical temperature of the core.

An excellent gear is obtained by using a single quench. It gives good grain refinement and maximum strength in the core and good hardness in the case. With the double quench the core is harder and refined, but upon reheating to harden the case the core is tempered so high that its hardness and strength are decreased. A well refined core and case are produced, but the core is weaker than in a single quench. A low single quench merely hardens and refines the case; a gear so made would not be suitable for heavy loads because of the low strength of the core.

Teeth of gears may be locally hardened by rapid heating and quenching of the surface. Both electrical induction and flame-hardening methods are employed. In both methods, the application of heat is so rapid that the surface layers reach the desired hardening temperature before the center of the gear tooth becomes hot. The specified depth of hardening depends on the service loads and speeds. When bending stresses are low, only the bearing surfaces (contact surfaces) need be hardened; but if bending stresses are high, the fillets at the roots of the teeth should also be hardened. When crushing stresses near the pitch line are high, it is desirable to have either a relatively deep hardened area, or a fairly high core hardness, or both.

The intense heat of the oxyacetylene flame provides a ready solution to the problem of obtaining the hardness effect of a furnace heat treatment at the wearing surfaces and retaining the necessary shock-resistant properties of the body. Such selective hardening consists simply in heating the wearing surfaces, *i.e.*, the gear teeth, above the critical temperature with an oxyacetylene flame and cooling with a suitable quenching agent. The depth of flame hardness produced generally varies from $1/16$ to $1/4$ inch, corresponding in penetration to the case-hardening process, and it can be rigidly controlled. The hardness can be tempered by a second heating, as in furnace practice.

Flame-hardening can be accomplished either manually or mechanically. It is used to surface-harden gears larger than can be economically handled in carburizing equipment, or when the size or shape prevents a full quench, or when only the gear teeth contact surfaces need to be hardened (Figure 26).



(Courtesy Farrel-Birmingham Co., Inc., Buffalo, N. Y.)

Figure 26. The Sykes gear-hardening machine.

Flame-hardened gears have a lower strength and durability than full-hardened gears and decidedly lower capacities than case-hardened gears. Flame-hardening is therefore limited in its application to certain designs and service conditions.

In induction hardening, high-frequency current from 100,000 to 1,000,000 cycles is passed through a water-cooled inductor block or coil of pure copper which surrounds but does not touch the surface to be hardened. This high-frequency current produces a very strong magnetic field, which cuts the surface of the steel through the small air gap between the inductor block or coil and the part to be surface-hardened, inducing both hysteresis and eddy losses in the surface. The combined losses cause heat to be generated in the surface of the steel itself. The inductor block or coil remains cold.

The heating is dependent upon the strength of the magnetic field, the frequency of the current, the width of the air gap between the coil or block and the part, the steel analysis, the grain size of the steel, and also its electrical resistance and permeability. The higher the frequency, the greater the permeability and the shallower the penetration; the lower the frequency, the less the permeability and the deeper the penetration. High frequencies have skin effect and heat faster but to a shallower depth. The higher the electrical resistance of the material, the deeper the penetration. The area to be heated can be closely controlled by regulating the shape and size of the coil in relation to the part to be hardened; and by adjusting the power input and the time, the depth that is heated before quenching can be controlled. For a thin induction-hardened case, a high power input and a short time of one or two seconds is used, while for a deeper case, a lower power input and a longer time give best results (Figures 27 and 28).

Because of the inherent reaction of the steel as its temperature rises, *i.e.*, as the increase in electrical resistance with temperature increases, the heating effect decreases as the critical point of the steel is approached; consequently the surface of the steel is not overheated, since continued application of power would only cause the heat to be generated farther in toward the center of the part. Furthermore, when the steel is heated above the critical range, it becomes non-magnetic and further application of power heats it through eddy losses only, and not through hysteresis losses. In addition, even the eddy currents decrease because of the higher electrical resistance.

The short operating cycle in combination with almost instantaneous quench which follows reduces oxidation to a minimum. Decarburization is no problem because of this short cycle of heating. Depth of hardening can be varied from 0.015 to 0.125 inch or more.

Since the heating of a specific section is the main object of induction hardening, a magnetic field which follows the contour of the section is essen-

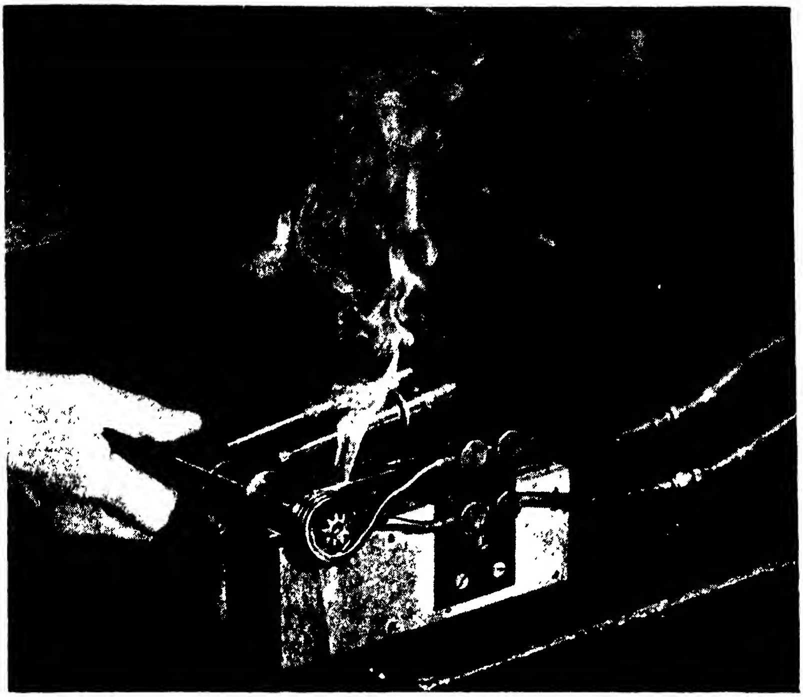


Figure 27. Induction hardening the armature shaft pinion teeth.

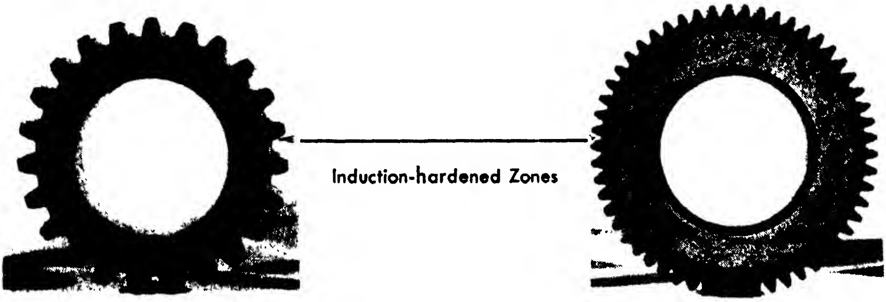


Figure 28. Induction-hardened spur pinion teeth.
(Ground and etched to show the induction-hardened zone darker than the core-hardened areas.)

tial. Hence, the conductor must be designed in suitable fashion to meet this requirement. The strength of the magnetic field depends upon the current in a single coil, and increasing the number of turns in a coil increases the number of conductors.

Cast Iron

As a material for gears gray cast iron of the ordinary type possesses certain disadvantages which have in many cases resulted in substitution of more expensive materials. Especially is this true in the case of gears of heavy section because of a tendency toward shrinkage and porosity in such castings. Often, after a considerable amount of machining has been done on a heavy gear, cavities will show up, which necessitate scrapping the entire casting. Its quality is dependent to a very large degree upon foundry practice. Most cast-iron gears are finished in the "as-cast" condition. In some instances the only heat treatment used is one to relieve casting stresses.

When heat treatment[15] is applicable, and improved wear with higher strength is desired, gears of simple shape, section and contour can be oil-quenched from 1550 to 1600° F. and drawn to 700 to 1000° F. The tensile strength is usually increased by 20 to 30 per cent and the hardness is approximately doubled, depending on the drawing temperature and the composition.

Alloy cast irons, such as nickel, nickel-chromium, nickel-molybdenum or nickel-chromium-molybdenum, are used where greater strength, hardness and wear resistance are required. These alloys give a more uniform hardness without chill. Dense, sound castings can be obtained; open grain and porous sections at the roots of the gear teeth where maximum stress may be imposed are eliminated.

Generally where gears are subjected to impact loading, the plain nickel and nickel-molybdenum high-test type irons have proved most satisfactory; and where constant loading and resistance to wear are primary factors, nickel-chromium iron or nickel-chromium-molybdenum iron is best.

For special applications, such as pump gears used in handling corrosive liquids, corrosion-resistant austenitic cast iron, such as "Ni-Resist," has been adopted quite generally. This alloy contains about 2 per cent of chromium, 6 per cent of copper, 13 per cent of nickel, 3 per cent carbon, the remainder being iron.

Cast irons vary in tensile and transverse strength depending on the alloy content and on the heat treatment. Ordinary gray cast iron has the following typical properties. Tensile strength, 25,000 to 40,000 psi, transverse strength, 2,200 to 3,000 pounds, transverse deflection, 0.30 to 0.35 inch, Brinell hardness 175 to 250. Alloy cast irons have higher properties, namely, over 50,000 psi tensile strength and over 4,500 pounds transverse strength, depending on the alloy content.

Table 35 shows the composition and properties of nickel-chromium-molybdenum cast-iron gear material.[17]

Table 35. *Cast-iron Gear Material*

Composition

Total carbon	3.10% max.
Silicon	2.10–2.40%
Manganese	0.80–0.90%
Nickel	0.75–1.25%
Chromium	0.15–0.30%
Molybdenum	0.40–0.60%

Typical Properties

Ultimate tensile strength (psi)	50,000
Ultimate strength in compression (psi)	150,000
Ultimate shear strength (psi)	58,000
Ultimate torsional strength (psi)	67,000
Modulus of elasticity (psi)	20,000,000
Torsional modulus of elasticity (psi)	7,500,000
Transverse strength (lbs) (1.2″ bar, 18″ span)	3,000
Transverse deflection (inches) (1.2″ bar, 18″ span)	0.4
Brinell hardness	220
Weight in pounds per cubic inch	0.26

Actual Properties on Test Bar Representative of Gear

Tensile strength (psi)	52,500
Rockwell "C" hardness	20
Brinell hardness	223

A type cast iron known commercially as "Meehanite" is supplied in various grades for gear applications. The typical properties of three different grades of this material are shown in Table 36.

Table 36. *Engineering Properties of "Meehanite"*

Meehanite type	Tensile strength (psi)	Modulus of elasticity (psi)	Modulus of rupture (psi)	Compressive strength (psi)	Fatigue strength (psi)	Shear strength (psi)	Damping capacity (%)	Brinell hardness as-cast
GM	60,480	23,000,000	93,000	200,000	25,000	55,000	21.0	217
GA	51,520	21,000,000	88,950	175,000	22,000	48,000	24.0	207
GC	41,440	17,500,000	82,000	150,000	17,500	40,000	25.0	192

Inherently, cast iron is relatively weak and brittle when compared with rolled, forged or cast steel. Cast iron has a low modulus of elasticity (10,000,000 to 20,000,000 psi) which should allow the development of a greater contact area, tooth to tooth, and hence improve lubrication and other factors controlling wear. The high damping capacity of cast iron has been cited as a desirable property.

Cast iron is usually used for gears of light unit loading, minimum shock and low speeds. Cast iron is preferable to steel castings for herringbone gears of large diameters and moderate power transmission. However, steel castings will be found more economical for high tooth pressures.

The recommended composition and the corresponding typical properties for alloy cast irons for particular services are as shown in Table 37.

TABLE 37. *Alloy Cast Irons*

Composition (%) and properties	Small gears	Small machinery	Large machinery	Diesel engine	Heavy duty	Corrosion resistance
Nickel	1.00	1.25	2.00	1.50	2.00	14.00
Chromium	0.30	—	0.30	0.50	—	2.00
Molybdenum	—	—	—	0.60	0.65	—
Total carbon	3.40	3.30	3.00	3.00	3.00	2.90
Silicon	2.20	1.50	1.00	2.00	1.50	1.50
Manganese	0.70	0.55	0.80	0.70	0.80	1.00
Copper	—	—	—	—	—	6.00
Tensile strength (psi)	30,000	38,000	42,000	48,000	50,000	25,000
Brinell hardness (as-cast)	200	200	220	220	230	180

Bronzes

In modern worm gear application the usual construction is a bronze worm wheel mating with a hardened steel worm. The worm wheel is properly the wearing or bearing member. Therefore, through-hardened alloy steel worms are recommended for low-speed applications, and case-hardened steel for high-speed applications. Nitrided steel worms are also recommended for high loads and high speeds.

Only point or line contact can exist between the gear and its worm, and this is essentially a sliding contact. Therefore, worm gear problems[2] are essentially bearing problems. Experience shows that for best results the bronze gear should be cast under chilling conditions, the object being to produce a material that is relatively fine-grained and yet has a liberal supply of hard bearing crystals.

Where the worm gear is subjected to high stresses and where the physical strength is of more importance than the properties of a bearing material, aluminum bronzes with varied heat treatments have given excellent results when used with a through-hardened steel worm (not case-hardened). The worm should have a high polish and finish; the harder the worm the more important is the finish.

In extreme cases the life of the bronze worm wheel may be shortened materially or even be completely destroyed by extreme oxidation of the lubricating oil. Oxidized oil becomes rancid and consequently corrosive in its effect.

The utility of bronze, particularly phosphor bronze, for gear duties necessitating low coefficient of friction and resistance to frictional wear has long been recognized.

The tin[1] content of commercial bronzes is usually limited to 12 per cent maximum, since there is a decreasing tensile strength, ductility and shock resistance with increasing tin content over 10 per cent. Phosphorus is restricted to that amount which will insure good fluidity and foundry practice. It is a powerful hardener by forming the compound Cu_3P, which is the hard, load-bearing constituent. But its intrinsic brittleness is reflected in the lower impact values obtained from bronzes of higher phosphorus content. Lead above 0.5 per cent lowers the yield point in compression, and therefore the tendency to pit under high compressive stresses is increased. Nickel raises the yield point in compression and thus resists pitting. It also increases the tensile strength and impact value. Its marked effect on the plasticity of the bronze necessitates careful control of the proportion of nickel, particularly in relation to tin content, as a certain degree of plasticity is essential in a gear bronze.

In a copper-tin alloy containing 10 to 12 per cent tin, approximately $\frac{1}{10}$ of the volume consists of hard crystals of alpha-delta eutectoid embedded in a matrix of relatively soft alpha solid solution. Phosphor bronze used for worm wheels, because of its high tin content, is unsuitable for forging and hot-working, and therefore castings have been used. The composition of a high-grade worm gear bronze is 10–12.5 tin, 0.5 max. lead, 0.2–0.4 phosphorus, 2 max. nickel and balance copper.

Bronzes containing zinc, manganese or aluminum are inferior to nickel-tin bronzes for frictional purposes. Experience has shown that the unheat-treated aluminum bronzes under high surface stresses are liable to failure through seizure or partial seizure, which leads to rapid wear. Particularly is this true if the mating worm shaft is slightly deficient in hardness or the lubrication in service is not ideal. Aluminum bronzes are satisfactory for slow-moving worm gears. Heat-treated aluminum bronzes containing iron are more satisfactory for heavier-duty services, as they have greater strength, hardness and wear resistance.

Gear wheel blanks and particularly rear-axle worm wheels for heavy-duty trucks and coaches have been made from phosphor bronze and also from aluminum bronze.

Some General Bronzes for Worm Wheels

1. *Naval Bronze*
   Composition: 88 Cu, 8 Sn, 4 Zn.
   Properties: 40,000 T.S., 20% elongation.
   Recommended for general purposes.
2. *Silicon Bronze*
   Composition: 93–95 Cu, 3–4.5 Si, 0.5–1.75 Fe.

Properties: 50,000 T.S., 20,000 Y.S., 15% elongation.
Recommended for worm wheels to mate with case-hardened worms for medium loads, medium to high speeds and severe service.

3 *Phosphor Bronze*
Composition: 88–90 Cu, 10–12 Sn, 0.3–0.6 Ni, 0.2–0.4 P.
Properties: 38,000 T.S., 23,000 Y.P., 10% elongation, 70 Brinell.
Recommended for worm wheels to mate with hardened worms (preferably case-hardened) of high hardness and fine accuracy, for severe service, medium loads and medium to high speeds.

4. *Leaded Bronze*
Composition: 78–81 Cu, 9–11 Sn, 9–11 Pb, 0.25 P, 0.5–1.0 Zn.
Properties: 25,000 T.S., 12,000 Y.S., 8% elongation.
Recommended for worm wheels to mate with soft steel worms for low loads and low to medium speeds.

5. *Aluminum Bronze*
Composition: 86–89 Cu, 7–9 Al, 2–4 Fe.
Properties (heat-treated): 75,000–140,000 T.S., 20–40% elongation, 6–18% R.A., 149–340 Brinell.
Recommended for worm wheels to mate with hardened steel worms for highly stressed applications.

Some General Bronzes for Spur and Bevel Gears

1. *Phosphor Bronze*
Composition: 86–89 Cu, 1–3 Zn, 9–11 Sn, 0.2 Pb, 0.02 P.
Properties: 40,000 T.S., 25,000 Y.P., 10% elongation, 80 Brinell.
Recommended for severe working conditions and heavy pressures.

2. *Manganese Bronze*
Composition: 55–58 Cu, 33–36 Zn, 3–4 Mn, 1–1.5 Fe, 2–4 Al.
Properties: 90,000 T.S., 45,000 Y.P., 20% elongation, 120 Brinell.
Recommended for severe service, high loads and high speeds. This alloy is highly wear-resistant.

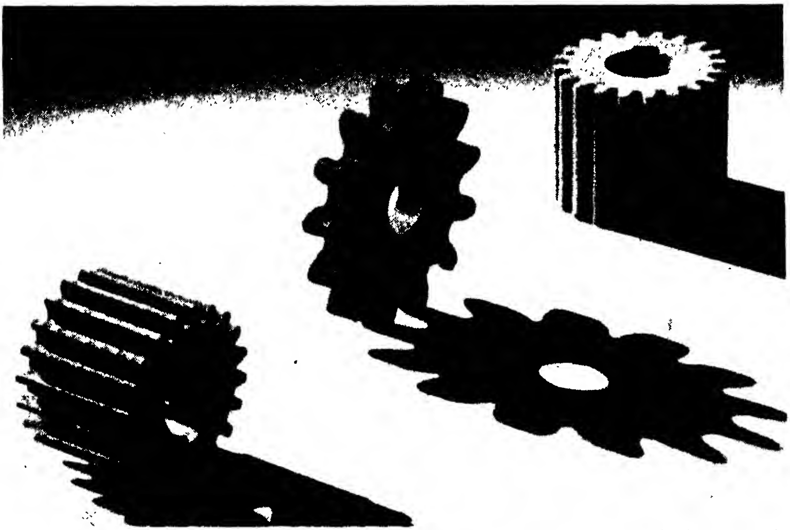
3. *Aluminum Bronze*
Composition: 86–89 Cu, 7–9 Al, 2–4 Fe.
Properties (heat-treated): 75,000–140,000 T.S., 20–40% elongation, 6–18% R.A., 149–340 Brinell.
Recommended for gears mating with hardened steel pinions for severe service and heavy loads. It has high fatigue and shock resistance. It is not recommended for worm wheel service where sliding and friction are great.

Non-Metallic Gears

The use of proper non-metallic gears makes for silence of operation. "Micarta," or a material of equal qualifications, assures strong and durable gears with silent operation. The base material in "Micarta" is a fabric, woven to a definite weight and thickness, and specially treated for impregnation with a binder. After the binder has been absorbed, the processes are carried to their final stage by applying heat and pressure. The characteristics of "Micarta" and similar materials are: (1) it is self-supporting, that is, no shrouds for the teeth are required and in most cases no end-plates whatever; (2) it is unaffected by extremes of temperature; (3) it is unaffected by running in hot or cold oil or water; (4) it is sufficiently elastic to absorb shocks that would wreck metal gears. Gears of the larger size have iron or steel hubs or webs.

"Lamicoid" gear stock has a specially prepared canvas or finely woven linen base impregnated with a thermosetting phenolic plastic. It provides maximum shock resistance. The canvas-base gear stock is used for large, heavy-duty gears, while the linen-base grade is used for small gears with fine teeth. In general it can be said that "Lamicoid" gear stock has a high degree of resiliency, a low modulus of elasticity (about 50,000 psi), a low coefficient of sliding friction on hardened steel, good dimensional stability, ready machinability, and a high degree of resistance to corrosive atmospheres and liquids.

Figure 29 shows several gears made from vulcanized hard, "bone" fiber. It is easy to machine, resistant to wear and abrasion, and is well suited to making noiseless gears.



(Courtesy National Vulcanizing Fibre Co., Wilmington, Del.)

Figure 29. Fiber gears.

Rawhide [18] has long been used as a material for the manufacture of gears and pinions, to mate with metallic gears where comparatively quiet operation is desired, and where teeth must withstand unusual shock. The efficiency of a rawhide pinion depends primarily upon the fibrous strength of the hide from which it is made.

To obtain a noiseless gear drive it is necessary to have only one of a pair of gears made of rawhide, and because of the relatively higher cost over metal it is usually the smaller of the two. For the other, a cast-iron gear is recommended, since it will transmit any load that a rawhide pinion of like pitch will deliver and because of its economical cost. Practical experience has indicated an approximate strength for rawhide pinions equal to 65 per cent that for cut cast-iron spur pinions of the same dimensions.

Rawhide is elastic and resilient and takes up shocks readily, but still produces gears of great durability and efficiency (Figure 30). The blanks from which rawhide gears are made are built up of layers of prepared steer hides. The laminations are coated with a special adhesive compound and subjected to hydraulic pressure until they adhere firmly. The rawhide blanks are then assembled with brass or steel flanges by means of steel rivets. These flanges provide protection and support to the rawhide. After assembly, blanks are turned to size on a lathe and then subjected to a milling operation for generation of the teeth.

(Courtesy Chicago Rawhide Mfg. Co., Chicago, Ill.)

Figure 30. Rawhide gear.

Rawhide gears should not be used on machinery where there is severe reciprocating or intermittent motion against them. They should not be allowed to become wet, as water will swell rawhide and destroy the cement, and in addition they shrink and lose their shape when dried out. Hard grease and graphite are the best lubricants, but mineral oil will soften the rawhide.

Powder Metal Gears

Gears may be made by pressing and sintering of powdered metals. They are limited in design and size and are not recommended for high stresses or shock resistance. They have good application in idler gears and gears of low speed and low load. Small spur gears can be made very economically by this method, when large quantities warrant the cost of the metal die.

Laminated Gears

Gears are also being made as laminations built up of steel stampings, copper-brazed together as shown in Figure 31. Such gears can be made very economically for certain applications.

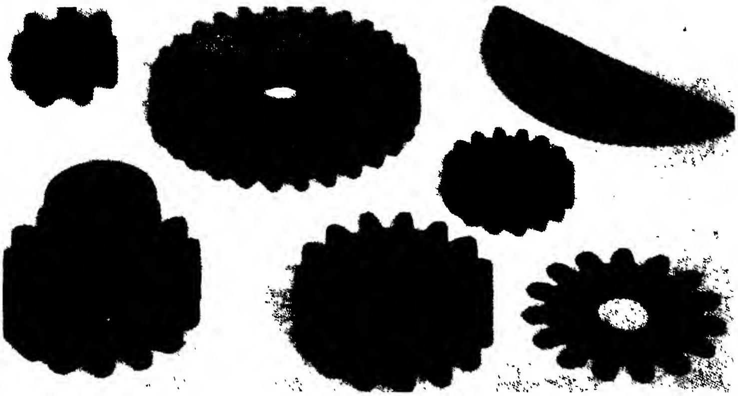


Figure 31. Gears formerly made of machined cast iron are replaced by these modern laminated gears built up of stampings, copper-brazed together.

Welded Steel Gears

For welded steel gears the rim of the gear blank is gas-cut to the required width from a rolled steel slab of the proper thickness. The rim is then rolled into a circle and welded to form a solid ring of pre-determined diameter. The indexing of the teeth for cutting is started at the weld so that the weld will not be in a tooth. The web can be a solid disk suitably stiffened. The stiffeners or spokes of U-shaped channels applied to each side of the thin web to form a double box section give additional strength, besides supporting the face of the gear. The hub is cut from a steel plate of proper thickness. A steel casting may be used for the hub (Figure 32).

The design freedom which is inherent in the use of welded steel gives a gear blank structure in which the metal has been placed in a theoretically ideal manner that has proved thoroughly practical. In particular, it enables the designer to choose a rim analysis which can be independent of the rest

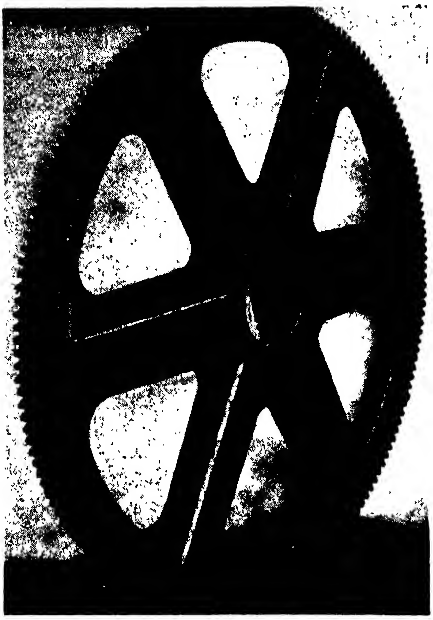


Figure 32. Welded gear.

(Courtesy Westinghouse Electric Corp. Pittsburgh, Pa.)

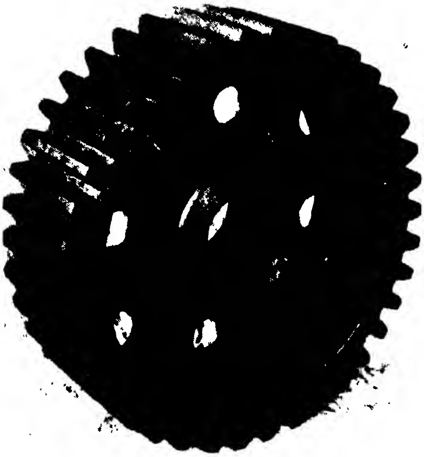


Figure 33. Welded gear.

(Courtesy Westinghouse Electric Corp., Pittsburgh, Pa.)

of the gear. Figure 33 is a built-up gear utilizing four quadrants of hot-rolled carbon steel plate for the web to take up welding stresses.

Durability of Gear Teeth

The strength of a gear tooth depends upon many factors. In designing a gear tooth the material and form of the tooth is of first importance. Some of the principal factors are: (1) material, (2) diametral pitch, (3) form and shape of tooth, (4) number of teeth and tooth ratio of gears in mesh, (5) backlash, as it affects the thickness of the tooth, (6) accuracy of machining and hardening, and (7) accuracy of and method of mounting.

It is self-evident that some materials will resist wear and deformation better than others. Consequently, material is an important factor and the method generally used for selecting the proper material is to determine a safe stress. The greater the number of teeth in contact, the greater the load-carrying capacity, and also the greater number of teeth in the gear the greater the beam strength. The strength of a gear tooth under static load, or at rest, is generally considered as being much greater than when it is operating under load at high speeds. The reason for this is that the impact is much greater, and stresses are introduced which do not exist when the gears are operating at comparatively low speeds.

Durability of gears is related to the toughness and hardness[4] of the material used. Gears of relatively soft steels have self-correcting properties, making them useful for applications where conditions of misalignment are possible. Gears that are heat-treated after cutting are subject to distortion, often resulting in highly concentrated and localized loading. This may lead to breakage of the teeth by fatigue in bending at loads satisfactorily carried by material heat-treated before cutting. Such distortion makes profile-grinding desirable on any gears where accurate and complete control of mass production is not available. Free-machining, high-sulfur steels allow high hardness before cutting and have proved satisfactory for small standard gears used where impact and dynamic loads are not excessive. The performance of a hardened gear under uniformly applied test loads cannot be taken as a criterion of its suitability for applications involving high external shock. Impact resistance decreases as hardness and surface durability increase.

When a static overload due to an accident or other cause is applied to a gear, resulting in stresses greater than the elastic strength of the material, the ultimate strength of the material determines whether the gear will successfully resist the load or will rupture. On the other hand, if a dynamic load, that is, an amount of rapidly applied energy in excess of the resilience of the material, is applied to the gear, thereby causing stresses in the teeth greater than the elastic strength of the material, the toughness determines whether the energy of the moving body will be absorbed by the member or will rupture it. In other words, toughness is a measure of ultimate energy strength, and it furnishes reserve strength for resisting excessive energy loads. Therefore, the toughness and resilience of a heat-treated steel will determine its resistance to overloads, shocks and impacts.

The property of a body by virtue of which work can be done on the body when stressed beyond its elastic limit is called toughness. A tough steel is needed, therefore, to resist energy loads when the gear in service is likely to be stressed beyond its yield point. Toughness is directly proportional to tensile strength and ductility, and is inversely proportional to yield strength. The lower the yield point and the higher the ductility, the greater the plasticity and therefore the greater the resistance to shock and the greater the ability to absorb the excess energy. Toughness is therefore the resistance to breaking after permanent change of form has occurred.

Inasmuch as wear resistance requires hardness, strength and plasticity, a simple formula can be stated for the wear resistance index; the wear resistance is equal to the product of the hardness and the toughness of the material. To wear well, a metal must resist the displacement of its particles and hence have hardness, but when they are displaced it must resist the removal of the particles from the body and hence have plasticity. In general, if two metals have the same tensile strength, the one having the greater ductility will possess the greater resistance to wear, although the resistance to wear of both metals would be increased by increasing the tensile strength and the fineness of crystalline structure, assuming the ductility to remain the same.

In calculating the strength of gear teeth, it is generally taken for granted that they will have full face width bearing. This condition is only realized when the gears are accurately cut, and when the shafts upon which they are mounted are in alignment.

Gear teeth must be hard enough to resist rolling and sliding friction, strong enough to resist the stresses imposed, and tough enough to withstand the shocks and pulsations which are frequently encountered.

Resistance to bending fatigue[8] is greatly influenced by the quality of finish on the surface of the fillets at the base of the teeth. Consequently, the machining practice employed in cutting a gear may have an important bearing on the suitability of a gear for a particular application. If the gear teeth are finished by lapping, shaving or grinding operations which do not include the fillet, it is essential for the initial machining of the fillet to leave a smooth surface.

Efforts to improve gears by improving surface finish sometimes have the opposite effect. Highly polished surfaces and fillets may lead to a false sense of security, if, as the result of machining or straightening operations, the parts have high internal stresses of the wrong kind. In ground surfaces the grinding operation may introduce high surface-tension stresses and thus promote fatigue failure. Surface-tension stresses from improper grinding often are so great as to produce visible or magnaflux surface cracks.

Whenever it is economically practicable, internal stresses that produce tension in any surface layer subjected to cyclic tension stress should be reduced or removed, or better still, converted to compressive stress by suitable treatment, because all fatigue failures are due to tension stresses. The surfaces of repeatedly stressed gear teeth, no matter how perfectly they are finished, are much more vulnerable to fatigue than the deeper layers. It has long been appreciated that vulnerability to fatigue increases with the surface roughness, particularly if the roughness consists of sharp notches, and more particularly if the notches are oriented at right angles to the principal stress.

The fatigue life of the most carefully prepared gear will be lengthened if a thin surface layer of the teeth is pre-stressed in compression by a peening operation. Tests show that the compression-stressed surface is effective whether applied to highly finished gears or to gears having rough surfaces. The most plausible explanation of the effectiveness of surface compression stress is that when a load is applied the tension stress in the surface layer is less by the amount of the compression pre-stress; and since fatigue failure starts only from tension stress, the fatigue durability of the surface layer is increased.

Breaking[8] of the tooth at the root is a bending-fatigue type of failure, in which the rupture originates at the surface. The properties of the surface or case are probably the most important as far as this type of failure is concerned. Soft spots in the fillet at the root of the tooth are conducive to very low fatigue strength.

Wear

Two distinct types of wear occur at the meshing faces of gear teeth: (1) a regular change in the shape of the tooth profile, and (2) the formation of a number of cavities or pits on the tooth face.

Wear may be due to (1) incorrect design or application, (2) defective workmanship or material, and (3) service or operating conditions. The latter may be subdivided into (a) overloading because of unpredictable conditions, such as shocks, vibrations, critical speeds and abuse; (b) lack of lubrication or inadequate lubrication; (c) presence of foreign matter such as abrasives, dirt or particles worn from the teeth in either the oil or the atmosphere; and (d) improper mounting, such as incorrect center distance, misalignment, excessive shaft deflection or defective related parts, such as bent shafts, worn bearings, or inadequate clearance.

Normal wear is a gradual polishing and smoothing of the working surfaces by removal of small particles of metal over a long period of time. Gear-tooth wear[6] is very similar to the wear on plain bearings. Contrast between gear-tooth profiles is similar to that between two cylinders, except that on gears the radius of curvature is constantly changing. In many cases wear on gear teeth first becomes apparent at or near the pitch line. When the stresses are below the elastic limit of the material, the wear on the gears is not appreciable. When the stresses exceed the elastic limit the rate of wear increases. Apparently, for any pair of gears there is a critical surface pressure, governed by the properties of the material, above which the life of the gears is short, and below which the gears will run indefinitely without appreciable wear.

Wear varies considerably over the tooth profile and is greater below the pitch line than above. Smooth abrasive wear is the normal type encountered with long-service gears, and this very slow removal of surface metal is not corrected by the use of extreme-pressure lubricants. High surface hardness is usually required to withstand this type of wear.

Actual wear is usually caused by abrasive particles getting into the gear box or fouling the lubricant, or chemical attack by lubricants or external agencies. Again, high surface hardness is required to withstand abrasive wear. Abrasion is generally distinguished by radial scratch marks on the teeth. In simple abrasion the worn surface usually becomes smooth in time.

Sometimes the property of hardness is made to include resistance to wear. However, resistance to wear depends upon ductility or plasticity of the material in addition to its strength hardness. In other words, to wear well, a steel must resist the displacement of its particles (and hence have hardness); but when they are displaced, it must resist the removal of the particles from the body (and hence have plasticity). Toughness requires both strength and plasticity. Wear resistance therefore requires hardness, strength and plasticity.

Pitting[5] is the most common variety of wear and is the major cause of tooth profile failure. Pitting is identified by the formation of concave pits ranging from very large ones common to heavily loaded, coarse pitch gears to very numerous small pits, fully or partially distributed over the profile of fine pitch gears. These pits actually impair tooth action and are not to be confused with the non-progressive initial pitting which sometimes occurs during running-in. Stresses causing such pits are due to sub-surface shear stresses which can be computed by the Hertz formula which determines mathematically the stresses to be expected when two elastic bodies are in contact under load.

Pitting is caused by the development of very high compressive stresses as a result of continual application of very high pressures per unit area. It is a form of fatigue that is induced by compression loads on the contacting tooth surfaces. The magnitude of the compressive stresses varies with the relative curvature of the contacting teeth, with the degree of load concentration at the ends of the teeth and with the applied load. The load that may be carried varies with the hardness and therefore with the strength of the material, with the temperature, and with the manner in which the lubricant is applied.

Repeated compressive stresses produce shear failure slightly below the surface, and eventually a small flake comes off. There is evidence indicating that oil contributes to pitting by entering surface fissures; if it is under hydrostatic pressure, the fissures are extended until pieces are lifted out of the surfaces of the teeth. This leaves numerous cavities, resulting in higher unit pressures on the surface, with a cumulative effect in developing further pitting.

Pitting[9] can be divided into two classes: (1) corrective, and (2) progressive and destructive. Failure by pitting occurs when the rate of pit formation is greater than that of normal wear, measured by increase in polished surface. Corrective or so-called incipient pitting occurs during the initial operation of the gears, and is caused by the concentration of stresses at localized areas or high spots. As soon as the high spots are eliminated in operation, pitting ceases, and subsequent normal wear often causes it to disappear.

If the pitting progresses to a point where the remainder of the surface is insufficient to carry the load, the contacting surfaces will be completely destroyed. The cause may be lack of material strength, extremely poor or rough surfaces, or high stresses of a repetitive nature caused by contact impacts. Compressive fatigue strength and resistance to pitting are approximately proportional to hardness. Therefore, case-hardened gears are better in resistance to pitting than through-hardened gears, since the hardness of the surface layers of the former is usually greater. In carburized gears, however, if the case is too thin, or the core is too low in hardness to support the case, the tendency toward failure on the surface is increased.

Spalling is a chipping, breaking or splintering of large fragments from the surface caused by yielding of the material under excessive loads or impacts. Spalling is very similar to pitting, except that the dislodged particles are much larger and extend over the entire tooth profile. Spalling is a common failure, frequently occurring in hardened gears where the residual quenching stresses have not been properly relieved by tempering.

Scuffing is caused by a combination of pressure and velocity resulting in a drawing action at the extremities of tooth contact. This produces vertical scratches above and below the pitch line.

Rolling is similar to scuffing except that a failure of the lubricant has allowed complete seizure of the mating profiles. The failure is identified by parallel scratches and concave grooves along the teeth perpendicular to the axis of rotation.[9] Materials ductile in compression sometimes exhibit considerable plastic flow of the surface layer without its being fractured, with consequent scoring or galling. Rolling may be said to have occurred when the surface spreads or flows at the tips or sides of the teeth.

Scoring and galling[9] have the appearance of severe abrasion. The surfaces are deformed either by plastic flow or the yielding of particles of metal. Seizing, or localized adhesion of the roughened surfaces or protuberances, may result in tearing out of portions of the mating surfaces which may have become welded. Scoring is defined as scratching, cutting, grooving, chafing or roughening of the surface. It may be characterized by scratches in the direction of sliding between the mating teeth, and appears to be caused by the welding of small areas of the contacting surfaces under the influence of high heat of friction and high unit pressure.

Galling describes surfaces when yielding, seizing, adhesion or tearing has occurred. These characteristics are similar to scoring and are the inevitable result of allowing scoring to continue.

Any of the following will cause scoring and galling: excessive unit pressure, excessive sliding velocities, rough surfaces, foreign matter passing through the mesh, incorrect tooth action, lack of or inadequate lubrication. Scoring is usually considered to be the result of failure of the oil film, rather than of the metallurgical properties of the gear material. The method of correction consists in changing the chemical properties of the surface of the gear by adding to the lubricant some substance such as sulfur or sulfur chloride, which will react chemically with the surface of the gear, making it non-welding. Under very severe conditions extreme-pressure lubricants are required.

Wear changes the location of tooth contacts; deflection separates the gear and pinion from normal positions and throws the point of load application nearer the top of the tooth; it thus increases bending stresses at the root and deflection of the teeth themselves, shifting the load from toe to heel along the tooth face. All these factors enter into gear life.

Causes of Failure

Under service conditions industrial gears can fail by tooth fracture due to bending, fatigue or impact, or by loss of metal from the working face. Surface or profile failure is caused by pitting, spalling, scuffing, scoring, rolling, plastic deformation or gradual wear. Profile failure has occurred, in a practical sense, when the load can no longer be transferred in a satisfactory manner because of either excessive noise, inadequate smoothness of operation, or too much heating (Figure 34).

Industrial gears seldom fail by breakage, and when they do break, the

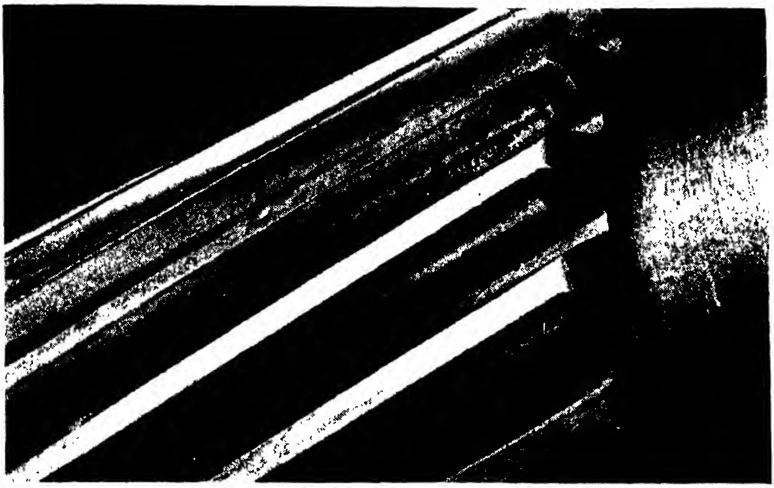


Figure 34. Pitting of gear teeth.

nature of their fracture or the attendant circumstances usually disclose the cause. The majority of the failures are caused by excessive wear of one sort or another, and vary with the type of gear and with the service they perform.

Tooth breakage is of two distinct types, one due to brittleness or low impact resistance, and the other to fatigue. Brittleness can be avoided by proper heat treatment. Fatigue failure may be due to incorrect design, low strength, overloading, or to notch effects caused by undercuts, tool marks, roughness, etc. Figure 35 shows a railway drive pinion which failed in fatigue (note broken tooth).

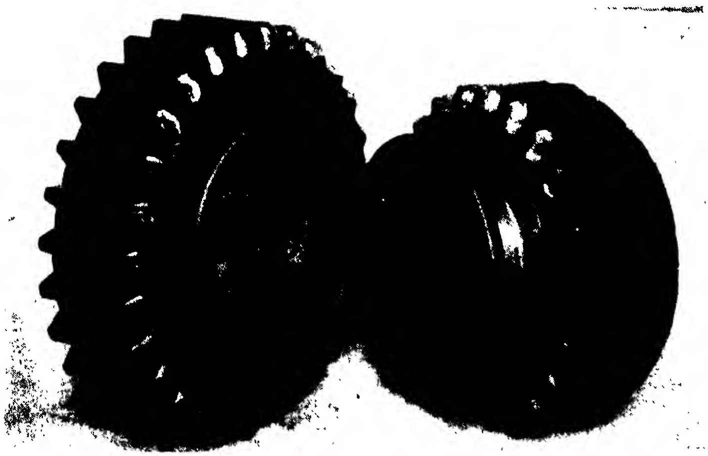


Figure 35. Failed bus transmission gears.

Fatigue failures are progressive and may result either from a few cycles of high stress or from many cycles of a lower stress. If the stress is below a certain critical value (endurance limit) for a given material and treatment, an infinite number of cycles can be applied without failure. Fatigue failure is caused by bending stresses which exceed the fatigue limit of the material. Since the stress decreases from the surface inward, the outer portions of the core are stressed to a degree depending upon the depth of the case of case-hardened gears. Therefore, a relation exists between depth of case and the resistance of case and core to fatigue. In medium-carbon, oil-hardened gears with a core hardness of Rockwell C–50 or more, this relation is usually ignored; but in low-carbon (case-hardened) gears with large differences in hardness between case and core, case depth becomes a factor of major importance. Fatigue may start in either case or core. The same may be true for the medium- and high-carbon steel gears, which are surface-hardened by the flame or induction method and therefore show a wide difference in core and case hardness.

Impact failures are caused by brittleness. Failures due to brittleness are not progressive and may result from a single application of stress above the elastic limit, which could be absorbed readily by a tough material without appreciable damage. While resistance to impact depends primarily upon material and heat treatment, it is also seriously affected by depth of case. The cores of low-carbon gears usually provide sufficient toughness to prevent impact failure, regardless of any depth of case likely to be used. High-carbon steel gears, however, are much more susceptible to this effect, and should not be cased too deeply if adequate toughness is to be maintained.

In addition to the tooth stresses at the contacting surfaces, the tooth can be considered as a cantilever beam; hence the tooth load tends to break the tooth at the root. To decrease failures it is often recommended to break the edges at the root of the teeth.

Fracturing at the root is a bending-fatigue type of failure, starting in the fillet at the root and proceeding approximately at right angles to the fillet at the point of origin.[10] With case-hardened gears this type of failure probably originates in the case. Considering the fact that in bending the stress varies from a maximum at the surface to zero at the center of the core, it seems probable that whether fracture originates at the surface of the case or between the case and the core depends upon the relative strength of the case and core and the depth of the case. In this connection the concentration of the stresses at the fillet must also be considered.

If the gear tooth were hardened all the way through to the same degree, it would undoubtedly be too brittle for many types of service and would fail readily by breakage. It is generally accepted that a softer core adds toughness to case-hardened gear teeth. It is also general knowledge that resistance to bending fatigue is inversely proportional to the sharpness of the fillet or the roughening of the surface. The larger the fillet and the more smoothly it is machined, the less will be the concentration of stresses or the greater will be the apparent resistance to bending fatigue at the root of the teeth.

Failure[5] by breakage and pitting can be partially controlled by increasing the strength—especially the combination of fatigue strength and wear-resisting hardness—and therefore by proper selection and heat treatment of the materials. The other types of failure are principally due to errors in design or manufacturing, or to operating factors; higher physical properties can aid in minimizing the latter destructive effects, but the only suitable solution lies in removing the fundamental causes.

As in all other cases, where corrosion is not a factor, failures in gears result from two main causes: wear and breakage. Avoidance of such failures is accomplished by proper attention to three important factors: (1) proper gear materials, (2) better gear design, and (3) controlled manufacturing processes. All three are interrelated: the design should not be altered without considering the advisability of a change in the steel composition to meet the requirements of a revised stress analysis, and an important change in fabricating methods should not be made without taking into account the machining qualities of the specified material and the nature of its response to heat treatment with respect to risk of distortion.

The physical properties essential to durability in service are those which provide adequate resistance to surface wear, fatigue breakage and impact breakage. Those factors tending to cause failure either increase stress or lower the ability of the material to withstand it. Stress concentrations, owing to deflections, warpage, runout, etc., promote pitting as well as reduce resistance to breakage.

In endurance runs of gears, failure generally ensues from fatigue cracks, which usually originate at the base of the teeth. Generally a deep acid etch will reveal that most of the teeth have fatigue cracks of varying depths, but none of them has actually failed. Wear almost invariably occurs first; the surfaces of the teeth show considerable wear near the pitch line before breakage occurs. It is therefore essential to make the surfaces hard enough to maintain the true involute.

With one or two exceptions, the cause of wear or breakage is excessive unit pressures, the magnitude and direction of which govern the kind and degree of wear or rupture. If a tool mark, scratch, or grinding check is present it becomes a fatigue point from which spalling may start. If there is a pin hole due to oxidation in heat-treating or other cause, tooth action will roll oil into it, generating great hydraulic pressure about the grain boundaries of the material, and pitting will ensue. If gear teeth are ground after hardening, care must be exercised to avoid (1) formation of grinding checks, (2) overheating due to grinding, which softens the surface of the teeth, and (3) removal of too much of the case, if the gear is carburized or nitrided.

Figures 36 and 37 show the result of abusive grinding on hardened gear teeth made from a 0.50 per cent carbon steel heat-treated to 455 Brinell hardness. Fine cracks appear, as shown in Fig. 36 and then flaking and spalling of the surface as shown in Fig. 37.

Figure 36. Grinding cracks.

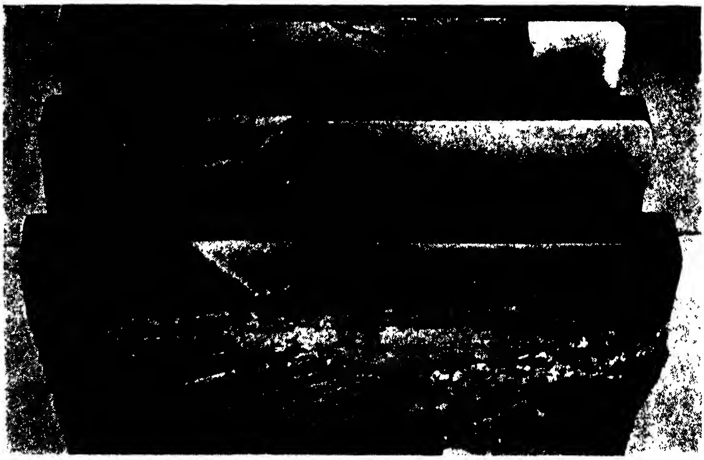


Figure 37. Grinding cracks and spalling.

Lubrication of Metallic Gears

Proper gear lubrication is one of the most important factors in machine operation. Neglect of lubrication results in noise and clatter, rapid wear of gears, loss of power and development of inaccuracy that often directly influences the quality of the product being made by the machine.

The lubrication of enclosed gear trains and speed reduction units is a comparatively simple matter as they are generally designed to operate in a bath of oil. On exposed gear trains, however, a heavier lubricant is necessary, to adhere tenaciously to the teeth at the speed the gear is designed for and to resist temperature changes. The essential requirements of a satisfactory gear lubricant are:

(1) Sufficient oiliness to insure a minimum of friction.

(2) Viscosity commensurate with method of lubrication, tooth pressures, temperature and speeds.

(3) Adhesiveness sufficient to remain on the teeth against the action of centrifugal force at the operating speed.

(4) Minimum tendency to congeal, harden, crack or become brittle at lower temperatures or to carbonize and chip at high temperatures.

Grease and so-called gear compounds are generally not satisfactory because of the talc, rosin, etc., used for thickening, generally at the expense of lubricating qualities.

In general the viscosity of a good gear lubricant should be relatively high, varying between 100 and 5,000 seconds Saybolt at 210° F. The specific requirements of each particular installation, and the type of gears used will determine the best type of lubricant.

Design

Design is the most important factor in producing a quality gear. The important points are (1) that the gears have rigidity, (2) that their internal supporting splines, if any, be so located as to substantially include the length of the tooth, and (3) that they have a harmoniously balanced mass so that they may be more uniformly heated and cooled, thus maintaining their shape during heat-treating.

Sharp edges at the end of gear teeth should be broken and polished to prevent fatigue failure from possible nicks in the sharp edges. Edges should be broken and blended along the entire tooth profile, as well as the tooth fillet for highly stressed spur gears. Sharp fillets reduce the load-carrying capacity under tension. The largest possible radii should be used at the roots of the teeth. All stress raising factors must be eliminated.

All gear teeth should be designed to afford a degree of tolerance for deflection, machining error and warpage, as has long been standard practice in spiral, bevel, hypoid and in some spur and helical gears. This is accomplished by so curving the teeth as to concentrate the load near the centerline of the gear width, and thus avoid load concentration at the weaker extreme ends of the teeth.

End-bearing load concentration of gear teeth at one end or the other has always been a source of gear noise and early failure. In conventional gear practice it can be avoided only by extremely close tolerances, which are difficult and costly to maintain and which retard production rate. Gear teeth having elliptoid teeth avoid end bearing. The elliptoid tooth is thinner at the ends and thicker at the center.

In designing[4] the conventional gear train, it is a question as to which type of gearing—spur, helical or herringbone—should be adopted. The answer depends entirely on the nature of the application and the requirements to be met: the power to be transmitted, the value attached to high efficiency, silence of operation, smooth running, compactness and inherent design qualities are the principal factors.

For rough-cast gears, such as are frequently used in construction and similar equipment, the straight spur-gear tooth is unquestionably the type to be used. The other extreme is turbine gearing, wherein great power must be transmitted at high pitchline speed. For such applications helical gears are used exclusively. Generally speaking, as speed and load increase, either herringbone or helical gears should be used. Also, when high efficiency, silence of operation and compactness are important considerations, these types are superior to straight spur gears.

In comparing[4] the different types of gears, ordinary commercial spur gears have a limited field of application with reference to load-carrying capacity and pitchline speed. This follows from the fact that spur gears do not have continuous tooth contact at the points of tangency of the pitch circle. Throughout the entire arc of action, the number of pairs of teeth in contact simultaneously rarely exceeds two. For this reason, the smoothness of action of spur gears depends entirely on the accuracy of the tooth profile over its total active portion. Inaccuracies at any point in the profile of the spur gear tooth are almost sure to result in vibration and noise, with decreased load-carrying capacity. Because of the inherently smoother running of herringbone and helical type gears, which is reflected in an absence of vibration, such gears can be run at higher pitch speeds and higher velocity ratios than straight-tooth spur gears.

One of the reasons for this smooth action is that slight inaccuracies in the tooth profile are not necessarily as detrimental as similar inaccuracies in the profile of straight spur gear teeth. Helical and herringbone gears always have one or more pairs of teeth in contact at the point of tangency of the pitch circle.

Considering the relative merits of the various tooth forms on the basis of strength, in both herringbone and helical teeth the line of contact across the face of the tooth is along diagonals. Also, because the teeth do not lie parallel to the axis of the gear, they are inherently stronger. Both these factors contribute to the possibility of designing herringbone or helical gears with a smaller diameter or a finer pitch than would be the case if straight spur gear teeth were used. This is further accentuated by the fact that with a greater number of teeth of finer pitch, a higher tooth strength factor can be applied.

With a finer pitch, smoother running is obtained, and the diameters of the gears can be made smaller. From this it follows that because the gears are smaller in diameter they can be run at a higher r.p.m. for the same velocity at the pitch circle.

Properties of the alloys[1] are often obscured by the much greater effects of stress concentrations, which in gears result from the tooth shape, machining scratches, deflection, shafts and bearings, eccentric assemblies, warping during heat treatment, etc. When considerable gain or loss is shown in the performance of a gear, it is often ascribed to the particular alloy used, when in fact it is probable that it resulted from a change of one or more of the stress-concentration factors. For this reason an alloy steel of any composition properly heat-treated to the specified hardness will often perform satisfactorily if all stress concentrations have been eliminated.

In attempting to obtain durability in a gear of almost any type, the materials engineer is at the mercy of the design engineer and the manufacturing department. Improperly shaped teeth with inadequate fillets will nullify his best efforts to supply a durable gear of long life. Sharp tool marks can shorten gear life and can nullify all the good efforts of engineering design.

It is customary to use a driving pinion which is somewhat harder than the driven gear depending upon the load stresses, speed and gear ratio. This gives a better-wearing combination. It is desirable to specify a heat-treated pinion regardless of the condition of the gear.

Design is important with respect not only to the form of the gear teeth, but also of the entire supporting assembly, in order to avoid excessive localized loading of the teeth as a result of shifting of the contact area under high service loads. In general, the better the design the smaller the gear required to do a satisfactory job. However, there are usual shop problems that nullify good design, *i.e.*, defective material, errors in machining, distortion in hardening, non-uniform hardening, quench cracks and grinding cracks.

In many industrial applications it is common practice to cut the gears after heat treatment. This practice, which is limited to gears that do not require a high degree of surface hardness, permits better control of the area of tooth contact, which is very important in the life of a gear.

In designing worm gearing, the factors governing load capacity are the heating effect and the abrasion, rather than the strength of the gear teeth. When gears are overloaded, the temperature often increases to such an extent that proper lubrication is difficult and excessive wear ensues.

For intermittent service, semi-steel worm gear and hardened steel worm are recommended; and for continuous duty, bronze worm gear and hardened steel worm. Where service is exceptionally severe a case-hardened and ground worm is desired to mate with the bronze worm gear. Semi-steel is usually not desired because of the comparatively high coefficient of friction, resulting in shorter life and hotter running under loads.

The efficiency of a worm drive depends on the low coefficient of friction between the mating parts.

Cast-tooth gears[18] have been displaced by machine-cut gears, which use less power and operate with less noise and greater efficiency. No matter how carefully a cast-tooth gear may be made, many uncertain elements are linked with the processes of manufacture which produce inaccuracies that affect the strength, life and operating efficiency of the teeth. Warping and shrinkage while in the sand mold, flaws in castings such as shrinks, blow holes, gas porosity, and roughness of finished surfaces, preclude the possibility of producing accurate cast-tooth gears. As a result, such gears may be noisy and highly inefficient, require a much greater factor of safety, and may be satisfactorily used only for low-speed service.

The demand for generated or cut-tooth gears has resulted from a recognition by industrial users of a definite superiority over the molded or cast-tooth type. Teeth cut on modern gear-cutting machines are correctly and evenly spaced and of uniform thickness; and the bore of the blank is always exactly concentric with the pitch circle.

References

1. Buckingham, E., "Relation of Load to Wear on Gear Teeth," *American Machinist* (May, 1926).
2. Davis, E., "The Heat Treatment of Gearing," A.G.M.A. (1933).
3. Rowe, F., "Centrifugal Bronze Gear Blanks," *Metal Progress* (June, 1933).
4. Day, P., "Gears," *Product Engineering* (Sept., 1933).
5. Woldman, N., "Tough-Hard Shock Resistant Gearing," *American Machinist* (Sept. 26, 1934).
6. Sands, J., "Nickel Alloy Gear Materials and Their Heat Treatments," *Product Engineering* (Oct., 1935).
7. McMullan, O., "Endurance of Case-Hardened Gears," *Trans. A.S.M.* (June, 1936).
8. Alman, J., "Durability of Automobile Gears," *Automotive Industries* (Sept. 25, 1937).
9. Bierbaum, C., "Materials for Worm Gear Drives," *Machinery* (June, 1939).
10. Rideaut, T., "Why Gear Teeth Wear," *American Machinist* (June, 1939).

11. Schwitter, C., "Modern Trends in Nickel Steel and Cast Iron Gear Materials," *Inco* (Oct., 1939).
12. Wellaner, E., "Industrial Gears," *Metal Progress* (Dec., 1939).
13. Wellaner, E., "Improving the Durability of Large Industrial Gears," *Metal Progress* (June, 1940).
14. Knowlton, H., "Selection of Steel and Heat Treatment of Spur Gears," *Trans. A.S.M.* (Sept., 1940).
15. Wickenden, T., "Evaluating Surface Desirability of Gears," *Machine Design* (July, 1946).
16. A.S.M. Handbook Committee Report, "Properties, Composition and Heat Treatment of Steel Gears" (1946).
17. Anon., "Durability Tests on Helical Gears," A.G.M.A.
18. International Nickel Company, publication.
19. Foote Brothers Gear Co., catalogue.

Chapter VII

Spring Materials

Selection of the proper spring material is a most important factor in the manufacture of devices and equipment whose operation is dependent upon spring action. Here reliability is most essential and the quality of the vital spring part must be beyond reproach.

There are cases where equipment requires that springs continue to operate and function properly despite temperature extremes, excessive vibration, and very corrosive conditions. Springs, therefore, call for greater care in design and selection of material than almost any other mechanical element. Not only must the limiting stresses be taken into account, but the elastic modulus must be considered also, so that the proper load-deflection rates will be obtained.

Spring design is generally approached from the viewpoint of the machinery field. Charts, tables, and design formulas usually are based on steel.[16] Instrument-spring design is different because a much larger range of materials is used. In usual machine-spring applications it is necessary only to make sure that a given spring is designed so it does not break or fail. The design of instrument springs, however, requires consideration of several other factors because of the required stability and permanence of calibration to be obtained under conditions of changing stress or changing temperature. In some instruments, these springs must function also as electrical conductors, or must be placed in a zone of elevated temperature or in a magnetic field. Since requirements for spring elements differ with each type of instrument, no one material can be considered as the best.

Instrument-spring design [12] is usually a compromise between best possible performance and such factors as available space, allowable working stresses, electrical resistance, frequency of vibration, resistance to drift, magnetic properties, ease of forming, and resistance to oxidation and corrosion.

Spring making and spring design are complex problems and call for extreme care in the selection, fabrication and design of materials. In general there are two types of springs, subdivided as follows:

Type I

Wire springs (coiled from wire and rod)

Helical and spiral springs
  (a) compression springs
  (b) extension springs
  (c) torsion springs

Type II

Flat springs (fabricated from strip or sheet)
  (a) flat springs
  (b) cantilever springs

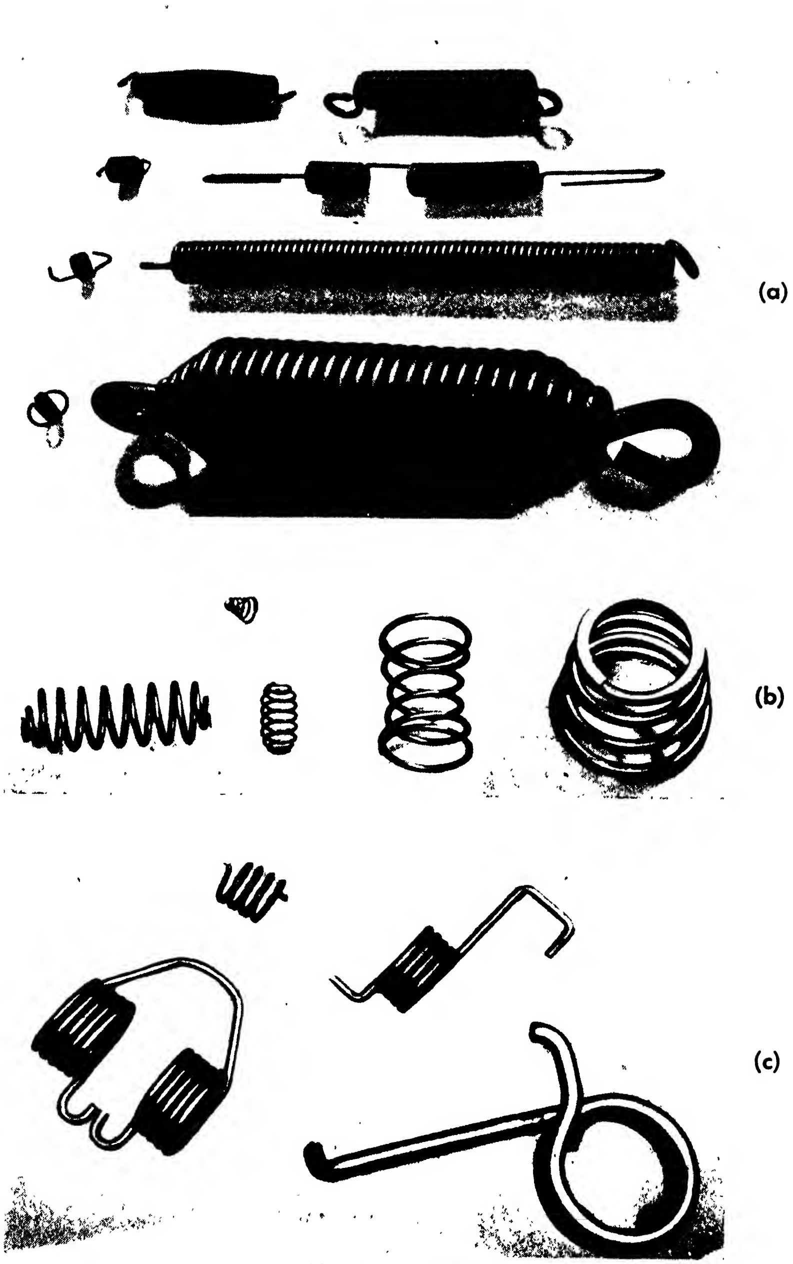
An extension spring is a close-coiled helical opening that resists a pulling force; a compression spring is an open-coil helical spring that resists a pushing (compressive) force. A torsion spring is a close-coiled helical opening that exerts pressure or tension in a circular or torsional direction. In compression and extension springs the material is actually in torsion, while in torsion springs it is in bending (Fig. 38a, b, c).

Flat springs include all springs made of flat or strip material—from straight pieces or pretempered spring material to intricate blanked and formed heat-treated parts. Most flat springs may be classified as beams, either clamped at one end and loaded with a concentrated load (commonly known as "cantilever springs"), or supported at each end with the concentrated load in the center (commonly known as "elliptical springs"). A combination of these conditions may exist. In the design calculations of flat springs the weight of the material of the spring itself and the shearing stresses may be disregarded, and only the direct result of ordinary bending due to the concentrated force and its moment arm is taken into account.

There are three considerations in the design of any extension or compression helical spring: (1) the load, deflection, and size conditions which the spring must satisfy in order to function most effectively; (2) the type or grade of material and of the maximum stress which may be allowable for the type of service; (3) selection of the proper wire diameter, outside coil diameter and number of coils to fit best into the space available and to give the desired stiffness rate in pounds per inch of deflection while withstanding the expected maximum deflection or maximum load.

Many different alloys, both ferrous and non-ferrous, are suitable as spring materials. Any metal or alloy which can be hard-drawn or rolled to a fairly high strength and retain sufficient ductility to form may be used for springs. Also any alloy which can be heat-treated to high strength and good ductility before or after forming may be used with satisfactory results. Many different materials are used for springs of special types, where such properties as superior fatigue life, non-magnetic characteristics, resistance to corrosion, elevated temperatures, and drift, etc., are desired.

The rod or wire from which springs are made must be carefully examined



(*Courtesy Wallace Barnes Co., Bridgeport, Conn.*)

Figure 38. (a) Extension springs. (b) Compression springs. (c) Torsion springs.

for the following faults, which are very important because of the high stresses and fatigue ranges undergone by springs: nicks from tools, die scratches, dirt inclusions, surface pits, surface roughness, surface decarburization (if steel), etc. Spring defects which ordinarily are considered negligible become a big factor when the spring is operating under highly stressed conditions, as in valve springs. When fatigue conditions are approached, surface defects become vital. Therefore, in order to obtain full fatigue resistance from springs it must be realized that all traces of surface imperfections, scale, surface pits and cracks, surface decarburization, etc., on the wire must be removed by grinding or polishing operations.

Studies[15] made in the spring and automotive industries indicate that practically all fatigue fractures of valve springs start at a surface or internal defect or irregularity. Surface seams cause the greatest damage because torsional fiber stress is reached at the surface of the wire. Slag and foreign inclusions, decarburized areas, and segregation also have been found to cause fatigue failure.

Stresses

For compression and extension springs[14] which are subject to shear loads and shear stresses, stress calculations are based on the torsional properties and torsional modulus of elasticity. Since the wire is stressed in torsion, the torsional strength is the factor limiting the maximum load which a spring will carry, and the torsional modulus is one factor determining the relation between load and deflection of a spring at any stress which is less than that required to cause permanent set. For torsion springs which are subjected to torque loads exerted in a radial direction and thus to bending, stress calculations are based on tensile properties and modulus of elasticity under tension. Flat and elliptical springs are subjected to bending and tensile stresses; for these also, tensile properties and tension modulus are the bases for stress calculations.

The factors governing the maximum safe stress for springs are the elastic limit or proportional limit in tension, and the torsional proportional limit; loading to greater stress values would result in permanent set and the spring would not return to its original position.

A spring fractured by fatigue shows a torsional type of fracture, which usually starts at the inside fiber adjacent to the axis of the spring, since at this point simple shear and torsional shear combine to produce a maximum intensity of stress.

The physical properties and chemical compositions[6] indicate the recommended safe working stress for each material. Values of this nature are variable and depend upon such qualifications as type of spring, atmosphere, temperature, ratio of outside diameter to wire diameter (in helical springs), rapidity and regularity of deflections, shock loads, wire size, and stress range. Safe working-stress tables are for compression and extension springs not subjected to high temperature, shock loads, etc. For suddenly applied loads, all stresses should be reduced 50 per cent for safe working stress.

In designing a spring one must consider not only the load per unit area, or stress in pounds per square inch at a given load, but more important, the range of stress and conditions through which the material in the spring travels in actual use.

In designing a helical spring for any given application or service, perhaps the most important consideration is the working or allowable stress, since this largely determines the size of spring required. To meet space requirements in many practical applications it is desirable to use as high a working stress as possible, consistent with safety.

For any material the allowable working stress will depend upon the magnitude of the following factors: (1) working stress, solid stress, and stress range, (2) frequency of deflections or oscillations, (3) temperature, stress and permissible relaxation.

$$\text{Fiber stress} = \frac{PD}{0.39d^3}$$

where

P = load in pounds
D = pitch diameter in inches
d = diameter of wire in inches

In general it must be remembered that the tensile properties of spring materials vary with the diameter: the smaller the diameter of the wire the higher the tensile properties, and conversely.

In the comparison of safe working stresses for compression and extension springs, certain practical considerations are involved. The weakest point in an extension spring is the point where the wire is bent to form the ends. In addition, extension springs wound with initial tension and having a high stress range per cycle are subjected to coil clash. These are sufficient reasons for reducing the allowable fiber stress below those permitted in compression springs.

Elastic Modulus

The one physical constant[12] that enters into the design of all spring elements is the elastic modulus or load-deflection ratio (Table 38). Metals differ widely in stiffness, the tension modulus ranging from 6,000,000 psi for magnesium to 75,000,000 psi for iridium. The spring materials most commonly used fall into three groups of stiffness values. Nickel and steels (carbon and alloy) have a tension modulus of 29,000,000 to 30,000,000 psi;

TABLE 38. *Value of Modulus of Commonly Used Spring Materials*

	Modulus of elasticity	
	In tension (E) (psi)	In torsion (G) (psi)
Flat spring steel	30,000,000	11,500,000
High-carbon steel wire	30,000,000	11,500,000
Oil-tempered steel wire	29,000,000	11,500,000
Music wire	30,000,000	11,500,000 * 12,000,000 *
Hard-drawn steel spring wire	29,000,000	11,500,000
Hot-rolled steel bars	28,500,000	10,500,000
Chrome vanadium	30,000,000	11,500,000
Silicon-manganese	29,000,000	10,750,000
Stainless steel	28,000,000	10,000,000
Brass (70–30)	15,000,000	5,500,000
Nickel silver	16,000,000	5,500,000
Phosphor bronze	15,000,000	6,500,000
"Monel"	26,000,000	9,500,000
"Inconel"	31,000,000	11,000,000
K Monel	26,000,000	9,500,000
Z Nickel	30,000,000	11,000,000
Nickel	30,000,000	11,000,000
Beryllium copper	16,000,000 † 18,500,000 †	6,000,000 † 7,000,000 †

* Depends on size.
† Depends on heat treatment.

It is of interest to note the wide difference in the modulus of elasticity in tension of some of the other metals compared to those commonly used for springs.

Magnesium	6,000,000
Aluminum	9,500,000
Silver	9,000,000
Gold	10,000,000
Platinum	22,000,000
Tantalum	28,000,000
Beryllium	42,000,000
Tungsten	56,000,000
Iridium	75,000,000

bronze and other copper alloys that are hardened by cold work have modulus values of 15,000,000 to 16,000,000 psi. Monel metal, aluminum bronze, and beryllium copper are among a group having a modulus between that of steel and phosphor bronze.

Second only to strength in importance for spring material is stiffness, the resistance to sagging and distortion under load. Materials with a high modulus have low deflection rates; that is, load deflections are small for a given design of spring made of high-modulus material. On the other hand, when large deflections are needed, materials with a low modulus are desirable.

A wide range of tensile strengths is obtainable among alloys having essentially the same modulus. Stability, permanence, and freedom from creep in most alloys is a function of the ultimate tensile strength rather than the elastic limit. Ductility is also an important factor in spring subjected to repeated stresses or possible overloads.

Springs that are required to be non-magnetic are restricted to alloys having a low modulus and in general a low tensile strength.

Drift, zero shift, or creep is also important for all calibrated springs. When working stresses can be kept low, phosphor bronze has been one of the most widely used materials. But precipitation-hardened beryllium copper offers a considerable improvement over phosphor bronze even at working stresses twice as high as are safe for bronze.

The modulus of elasticity is known to vary considerably because of different methods of manufacture of both the wire and spring. When a spring is operated at an elevated temperature, it cannot hold the same load as when tested at room temperature, because of the decrease in modulus of rigidity with increased temperature.

In general, deflection under a given load will depend upon the proportions of the spring and the modulus of elasticity of the material. Therefore, if the spring is not loaded beyond the elastic limit of the material, the hardness of the latter will have no effect on the deflection, and a softer material will have the same deflection as a harder one under these conditions. However, the elastic limit of the softer material will be exceeded by a much smaller load than will the elastic limit of the harder, so that the harder spring will have a greater load capacity through a correspondingly wider range of deflection.

Zimmerli[2] listed the effect of temperature upon the torsional modulus as follows (also see Table 39):

(1) There is a general downward trend in the moduli as temperature increases from 75 to 850° F.

(2) As temperature increases from -100 to $+75°$ F. the alloy steels and nonferrous metals show no regular change in their moduli.

(3) The modulus of 18–8 stainless steel is lower at all temperatures than that of other steels.

(4) "Monel" metal shows greater superiority at all temperatures to phosphor bronze and brass.

(5) The pressure of cold work causes an apparent increase in the modulus, this effect reaching a maximum around 180° F.

The literature indicates a decrease in the torsional modulus of steel amounting to 20 per cent as the temperature increases to 800° F. Phosphor bronze shows a decrease of 50 per cent, and brass 35 per cent over the same temperature range.

It is interesting to note[2] that the austenitic stainless steel has values consistently lower than the other steels and is about half-way between "monel"

TABLE 39. *Approximate Torsional Modulus Relation to Temperature*[2]

Material	Temperature (° F.) −100	0	200	600
Hard-drawn steel	11,550,000	11,200,000	11,240,000	10,700,000
Music wire	11,250,000	11,200,000	11,350,000	9,950,000
Si-Mn steel	11,450,000	11,200,000	10,600,000	10,000,000
Cr-V steel	11,400,000	11,250,000	10,600,000	9,950,000
Stainless (18/8)	10,100,000	10,300,000	9,750,000	9,100,000
"Monel" metal	9,100,000	9,100,000	9,050,000	8,700,000
Phosphor bronze	6,600,000	6,700,000	6,900,000	4,000,000
Brass	4,500,000	4,700,000	4,700,000	4,000,000

metal and the high-carbon steels. Probably the most striking phenomenon observed is the marked increase in torsional modulus through the range 100 to 200° F. Almost all the plotted curves show a maximum point in this range. This is probably due to the trapped stresses in the material caused by cold work. Below 200° F. the trapped stresses are neutralizing part of the applied stresses, so that the resultant stress is less than the calculated applied stress. The stress, therefore, is smaller and the modulus higher. This effect reaches a maximum in music wire, which is more severely cold-worked than the other metals. The modulus of annealed wire is lower through the whole temperature range than the modulus in severely cold-worked wire.

Relaxation

Relaxation[7] denotes load loss occurring at constant height in closely coiled helical compression springs. In this case elastic strain in the outer fibers of the wire, produced by the external load on the spring, is converted gradually to plastic strain, or permanent set. The amount of elastic or recoverable strain is thereby reduced and there is a proportionate reduction in the load supported by the spring. The percentage loss from the original load is expressed as "per cent load loss" or "per cent relaxation."

Since the elastic limit of the material governs the amount of set or loss of load, much of the set can be averted by preworking the spring beyond the elastic limit. In making compression springs, all the set is removed by pressing the coils tightly together or to the solid height.

Effect of Temperature

Design for operation at a low temperature usually does not involve trouble from a material standpoint. Most of the common spring materials will perform satisfactorily at moderately low temperatures. However, the decreased ability of materials to absorb dynamic forces at lowered temperatures may result in failure owing to impact or fatigue stresses. It is an inherent characteristic of most metals to become brittle at reduced temperatures. Carbon and alloy steels operating under certain conditions at subzero temperatures may become brittle, whereas the high-nickel alloys may be used without fear of such embrittlement. If it is necessary to design for operation at extremely low temperatures and severe impact and fatigue stresses, the spring is usually calculated for lower stresses than would be used at normal temperatures.

At high temperatures spring difficulties are associated with a static failure of the material resulting from decrease of the elastic limit as the temperature increases. Consequently, springs designed to operate satisfactorily at normal temperatures will undergo a slow plastic deformation known as *creep* resulting in a "permanent set to a greater or less degree, depending on whether the operating stresses are relativly high or low, and on the length of time during which the load is applied.

When springs are subjected to temperature in excess of atmospheric under pressure they often shorten in length, or "set," and lose load. The spring maker may be able to pre-set the springs with heat at temperatures and stresses above those to be encountered in operation and thus remove "set."

At elevated temperatures, particularly in excess of 400° F., carbon and alloy steel springs relax excessively and take a permanent set. Copper-base alloys, with the exception of beryllium-copper, behave similarly at temperatures above 200° F. The usual copper alloys in spring making will fail at low stresses above 250° F. The nickel-base alloys are more resistant to permanent set and some of them can be successfully used up to 650° F. The higher the permissible load loss, the higher the temperature at which any material can be used. Finally, for the usual carbon or alloy spring steels other than stainless steel, stress is the most important factor below 400° F. Above this temperature, these steels should not be used, since it is just a question of time until they lose practically all their load-carrying ability.

Recent researches on the effect of temperatures on compression steel springs have led to the following conclusions:

(1) Plain-carbon steel springs in sizes up to ⅝" diameter are reliable at temperatures up to 350° F. when they are stressed not in excess of 80,000 psi. If a small amount of set is permissible in operation, they may be used at temperatures up to 400° F. and at stresses not in excess of 120,000 psi. Satisfactory use of these steels is not possible over 400° F.

(2) Silico-manganese, chrome-silicon and chrome-vanadium steels in sizes up to ⅝" diameter are reliable at temperatures up to 400° F. when they are not stressed above 80,000 psi. If a small amount of set is permissible in operation, they may be used at temperatures up to 450° F. and at stresses not over 120,000 psi.

(3) Beyond 450° F., freedom from excessive creep and permanent set under load is possible only with such materials as chromium-nickel alloys and high-speed tool steels.

For all spring materials,[12] changes in temperature produce two effects that ordinarily must be taken into account, *i.e.*, change in elastic modulus and thermal expansion. Higher expansion rates are characteristic of copper alloys. Where negligible expansion changes are required, alloys of the "Invar" type (36 per cent nickel–64 per cent iron) have been used widely, but as spring materials such alloys present a difficult problem. To obtain the required low coefficient of expansion, the material must be annealed; and in the soft condition, the performance of "Invar" alloys leaves much to be desired for spring purposes. If such alloys could be hardened by heat treatment, much better spring properties undoubtedly would be obtainable.

Effect of Corrosion

In any spring application, the possibility of corrosion cannot be neglected. The successful working of any spring depends on its freedom from rust or corrosion effects. Where conditions are obviously severe from a corrosion standpoint, and pitting or loss of metal would take place at a rapid rate with plain-carbon steels, then nonferrous materials or stainless steels must be used for best results. Among the non-ferrous materials for good corrosion resistance are phosphor bronze, beryllium-copper, and high-nickel alloys. The selection of material, as in all other corrosion problems, should be based on the corrosive environment and operating conditions.

Corrosion fatigue is the simultaneous action of corrosion and fatigue, which may cause failure at a stress far below the ordinary endurance limit. Corrosion has a greater effect on hard spring material than on soft material. Even slight corrosion simultaneous with fatigue is very effective in causing failure at comparatively small stresses.

Before forming into springs the steel wire may be coated with tin or copper. Tin is deposited by running the strands of wire continuously through a bath of molten tin after final drafting to size; copper is usually plated on by dipping a coil of wire into a copper sulphate solution and immediately drawing the wire through a die, which results in a highly burnished surface. The copper coating is subsequently very thin and offers little resistance to corrosion.

Electroplating ordinary steels with cadmium, tin or other metals more than doubles the corrosion-fatigue limit. This brings them on a par with the corrosion-fatigue limit of corrosion-resistant steel, which is about twice that of plain carbon steel.

Spring steels subjected to stress while in contact with fresh water fail at a stress range only $\frac{1}{4}$ to $\frac{1}{9}$ the ordinary endurance limit. In contact with salt water the endurance range is even smaller. All this means that under corrosion fatigue the advantages of high physical properties are neutralized.

The large majority of springs[15] are made of steel with no protective coating other than paint or oil. After forming, steel springs may be enamelled, lacquered or coated with Japan, either by dipping or spraying. For mild corrosive service the spring may be plated with copper, zinc, cadmium, nickel, chromium, or silver. The procedure followed in plating steel springs and the danger of hydrogen embrittlement require that the process be carried out with extreme care. The chemicals used may cause a surface attack or embrittlement fully as destructive as the corrosive media in which the springs must operate. After plating, springs must be baked to prevent hydrogen embrittlement. The endurance or fatigue values of steel springs are reduced by plating.

Effect of Cold Work

Finished springs may be shot-peened by impelling steel balls against the surfaces. The material thus treated is work-hardened on the surface and retains residual compressive stresses. The net result in the spring is a much higher safe stress range and the use of higher maximum stresses for continuous service. Shot-peening can be applied to all materials, but the effect varies for each.

The desired results of peening are basically two: the first is to cold-work the surface and thus raise the physical properties where the stress is the highest. The second is more important but not so obvious. It consists in prestressing the surface layer under compression. Fatigue failures are due to tension stresses, and if a compression stress can be superimposed where the tension stress will come, the part will carry considerable load before it is actually stressed in tension. This surface treatment has done more to increase the fatigue life of springs than any other previous process used.

The results of peening, since it is a mechanical process, can be affected by heat. If springs are heated sufficiently after peening, the benefits will be lost and the endurance limit will revert to that of the wire as originally received.

STEEL SPRINGS

The great majority of steel springs are made of carbon steels ranging in analysis from 0.50 to 1.20 per cent carbon. These materials may be fabricated from any one of a number of conditions: hot-rolled, cold-rolled or drawn, annealed, hard-drawn, tempered or patented. Choice of material is governed by quality, cost, manufacturing technique and application in each case.

Spring temper [10] is given to materials by cold-working, by heat-treating, or by a combination of both methods. There are two general groups of materials: pretempered and untempered. In the pretempered class are oil-tempered wires and flat steel; hard-drawn wires, including music wire;

stainless steel; and certain nonferrous alloys. After being made into springs, most of these materials are usually given low-temperature heat treatment to relieve cold-working stresses. In the untempered class are annealed high-carbon steel and alloy steel bars, wires, and flats. After forming, springs of these materials are hardened by quenching in oil and tempered after quenching. In the use of pretempered material, the metal must be hard enough to produce an elastic limit sufficient to withstand the subsequent loads. The material must not be so hard as to fracture when being formed or to cause excessive wear or breakage of the tools.

In the manufacture of steel wire springs it is customary to have the steel in the pretempered condition, especially for valve springs of ⅜″ diameter. Alloy steels generally have a higher elastic limit and better fatigue-resisting properties than straight-carbon steels. Spring steels are somewhat similar to ordinary commercial steels, except that much greater care and more operations are required to produce them; also higher contents of carbon and manganese are used. Furthermore, oil-tempered wire of the same composition has a higher tensile strength and elastic limit than hard-drawn wire; moreover, there is a difference in ultimate strength of commercial spring wire with changes in size.

Steel has the highest endurance value of all spring materials. Cold-working the wire, especially by drawing it through dies or by shot-peening, considerably improves the properties desired on certain types of steels. Heat-treating spring steel produces the most effective elastic limit, in conjunction with the best fatigue properties.

Since the maximum stress occurs at the outside fibers of the steel, the surface condition of the material markedly affects the fatigue-resisting properties of the spring. The edge of strip of spring steel that is to be utilized as the finished edge of a spring is carefully worked until it is smooth and round, eliminating sharp corners or check marks that may cause a localized stress condition. Corrosion and decarburization of the steel surface are also detrimental to the fatigue properties of the spring. Removal of any surface decarburization, that is, the decarburized layer, increases the fatigue limit.

The alloy steels, heat-treated for high elastic properties and high fatigue values, are most susceptible to surface damage. Since the true fatigue resistance of a spring steel varies with the hardness, the fatigue limit of the surface is less than that of the inner portion if any decarburized layer is present. In addition, the surface may contain small irregularities, such as small pits, lines, or scratches, which would reduce fatigue limit, especially to alternating or repeated stresses. The bending moments on a steel plate cause the highest stresses to occur at the skin; accordingly, a decarburized surface layer containing small irregularities is very likely to induce fatigue cracks at stresses much below the real fatigue limit of the main body of the material. When a crack has been formed at the skin, the high stress concentration at the root of the crack would be sufficient to cause it to extend itself into the sound material of the middle portion, and so complete failure of the plate occurs.

Plain-carbon steels in sizes up to 5/8" diameter are reliable at temperatures up to 350° F. when they are stressed not in excess of 80,000 psi. If a small amount of set is permissible in operation, they may be used at temperatures up to 400° F. and at stresses not in excess of 120,000 psi. Satisfactory use of plain-carbon steels for compression springs is not possible over 400° F.

Hot-rolled Bars — Annealed High-carbon Steel

The fabrication of heavy-duty springs is usually accomplished by hot-coiling high-carbon or alloy steels. This is necessary owing to the large cross-section of the wire needed to carry the heavy loads involved. To develop the maximum physical properties after coiling, the springs are heat-treated and tempered.

For critical applications the surface condition of the hot-rolled bar is not such as to develop the maximum fatigue resistance of which the material is capable. The decarburized and rough surface is directly attributable to lowered fatigue resistance. If maximum fatigue resistance is to be developed, the decarburized surface is usually removed by centerless grinding the bars before coiling. In special spring applications the fatigue resistance can be further increased by shot-peening after coiling. The materials most commonly used for hot-wound springs are high-carbon steel (SAE 1095), chrome-vanadium steel (SAE 6150) and silico-manganese steel (SAE 9260).

Springs made from annealed wire must be hardened and tempered after forming. Almost invariably quenching is done in oil for both continuous tempering of wire and finished springs. Relatively high tempering temperatures of either wire or coiled springs produce wire with relatively low tensile strength and hardness. In general, it has been found within certain limits that the softer the wire in a spring, the longer will be the fatigue life when the spring is subjected to rapid and continued deflection. This is the reverse of a conclusion commonly accepted that the life is longer with material of higher tensile strength. However, a great deal depends on the character of the surface decarburization. Most springs are operated well above the endurance limit, and data applying to endurance limit may not necessarily lead to the same conclusions for relatively high stresses. Furthermore, a great many springs set slightly in operation before final fracture occurs, and thus operate at lower stress. In softer wire, the set of a spring and the subsequent decrease of working stress occur more readily than in harder wire.

The allowable stresses for high-carbon steel compression springs are: 82,000 psi for light service, 70,000 psi for average service, and 57,000 psi for severe service. However, the exact values will depend on the wire used.

"Tempered" Spring Wire

Oil-tempered or "tempered" spring wire is a high-carbon steel wire to which the proper qualities of hardness, stiffness and ductility have been imparted by a final heat treatment before coiling the wire into finished springs. Table 40 shows the chemical composition and typical mechanical properties for this material.

Table 40. *Oil-Tempered Steel Wire*

Composition

Carbon	0.60–0.70
Manganese	0.60–1.20
Phosphorus	0.04 max.
Sulphur	0.04 max.
Silicon	0.10–0.20

Mechanical Properties

Tensile strength (psi)	155,000–300,000
Elastic limit in tension (psi)	120,000–250,000
Torsional strength (psi)	115,000–200,000
Elastic limit in torsion (psi)	100,000–120,000
% Elongation in 2″	5–2
Modulus of elasticity (psi)	
In tension	29,000,000
In torsion	11,500,000
Hardness, Rockwell C	40–50

Note: Properties vary with size, the smaller the diameter of the wire the higher the properties.

The wire is hardened by quenching in oil and tempering in a lead bath. Tempered wire is used largely for springs up to ½″ diameter wire. The wire should wind around itself as an arbor without fracture up to 0.162″ diameter; from 0.162″ to $\frac{5}{16}$″ diameter it should wind around an arbor twice the diameter of the wire without fracture.

With uniform toughness, the tensile strength varies, being high for small sizes and low for large sizes. The elastic limit is between 75 and 80 per cent of the tensile strength. When tempered wire is used in making springs, stresses are placed in the material by winding (coiling). The recommended working stress for springs made from "tempered" wire are: light stresses, 80,000 psi; average stresses, 65,000 psi; severe stresses, 55,000 psi, when the hardness of the material is around 42 to 46 Rockwell C.

Oil-tempered spring-steel[6] wire is a general-purpose steel, commonly used for all types of coil springs where the stress range is not too high and where the springs are not subjected to continuous shock or impact loadings.

The use of tempered wire permits the design of springs for considerably higher stresses, without danger of deformation, than is possible with hard-drawn or rolled material of the same tensile strength.

Hard-drawn Wire

Hard-drawn spring wire is made from stock having an analysis similar to tempered wire, but is usually drawn to a lower tensile strength and has a considerably lower elastic limit. This is the least expensive grade of spring wire and is used in sizes similar to "tempered" wire. Better springs can be made from "tempered" than from hard-drawn spring wire, because of its higher elastic limit for the equivalent tensile strength. The ultimate strength of hard-drawn wire is the tensile strength after "patenting," to which is added the strength induced by the cold work of drawing. (Spring steels are annealed for subsequent work by a continuous process known as "patenting.") Wire 0.162″ and smaller in diameter should wind on itself as an

TABLE 41. *Hard-Drawn Wire*

Composition

Carbon	0.45–0.75
Manganese	0.90–1.20
Phosphorus	0.045 max.
Sulphur	0.045 max.
Silicon	0.10–0.20

Properties

Tensile strength (psi)	150,000–300,000
Elastic limit in tension (psi)	100,000–200,000
Torsional strength (psi)	120,000–220,000
Elastic limit in torsion (psi)	110,000–140,000
% Elongation in 10″	3–2
Modulus of elasticity (psi)	
In tension	29,000,000
In torsion	11,500,000
Hardness, Rockwell C	40–48

The tensile strength varies with the wire diameter as follows:

Diameter (inches)	Tensile strength (psi)
0.025	280,000–300,000
0.075	225,000–250,000
0.125	190,000–215,000
0.250	160,000–185,000
0.375	140,000–165,000
0.500	130,000–155,000

Mechanical Properties at Elevated Temperatures

	250° F.	350° F.
Stress to produce 2% loss of load (psi)	45,000	——
Stress to produce 4% loss of load (psi)	92,000	50,000
Stress to produce 6% loss of load (psi)	106,000	80,000
Stress to produce 8% loss of load (psi)	115,000	92,000

arbor without breakage; up to $\frac{5}{16}''$ diameter should wind on an arbor twice the wire diameter without breakage.

Hard-drawn spring wire is generally a basic open-hearth steel of the SAE 1060 type. Table 41 shows the chemical composition and typical properties of this material. The tensile strength varies with the diameter; the elastic limit in tension is 60 to 70 per cent of the tensile strength, and the elastic limit in torsion is 45 to 55 per cent of the tensile strength. The recommended working stresses for springs made from hard-drawn wire are: light stresses, 60,000 psi; average stresses, 50,000 psi; severe stresses, 40,000 psi. This material is used for helical springs subjected to steady loads or infrequent stress repetitions.

Music Wire

Music wire is nearly always used in fine sizes. It has a very high tensile strength, fairly high elastic limit and a bright surface finish. Music wire is essentially the same as hard-drawn spring wire except that it is made from the best quality cold-drawn high-carbon spring steel obtainable, employing corresponding refinements in drafting practice in order to finish a tougher wire with greater strength and more uniform size. It is obtained in small sizes varying from 0.005 to 0.125″ diameter. Table 42 shows the chemical composition and typical properties of this material.

TABLE 42. *Music Wire*

Composition

Carbon	0.75–1.00
Manganese	0.25–0.50
Phosphorus	0.030 max.
Sulphur	0.035 max.
Silicon	0.10–0.25

Properties

Tensile strength (psi)	250,000–400,000
Elastic limit in tension (psi)	150,000–300,000
Torsional strength (psi)	150,000–300,000
Elastic limit in torsion (psi)	130,000–200,000
% Elongation in 10″	Approx. 8.0
Modulus of elasticity (psi)	
In tension	30,000,000
In torsion	11,500,000
Hardness, Rockwell C	42–46

Mechanical Properties at Elevated Temperatures

	250° F.	350° F.
Stress to produce 2% loss of load (psi)	50,000	——
Stress to produce 4% loss of load (psi)	95,000	——
Stress to produce 6% loss of load (psi)	107,000	45,000
Stress to produce 8% loss of load (psi)	120,000	87,000
Stress to produce 10% loss of load (psi)	——	100,000
Stress to produce 12% loss of load (psi)	——	116,000

This type of wire is frequently called "piano wire," but the name "music wire" is more generally accepted. Music wire is "patented" and cold-drawn to size, thereby receiving its high physical properties from cold work. It is one of the highest grades of spring steels and is recommended for small helical and torsion springs which must meet exacting physical requirements or maximum load deflections. It can also be subjected to high stress, frequent deflections, and suddenly applied loads.

This steel usually analyzes 0.75 to 1.0 per cent carbon, and the wire after cold-drawing has a hardness of about 42 to 46 Rockwell C. The material should withstand coiling around an arbor 3 to 3½ times its own diameter without fracture. The recommended working stresses are: light stresses, 100,000 psi; average stresses, 85,000 psi; severe stresses, 75,000 psi.

Low-temperature heat treatment (500 to 550° F.) of music wire and hard-drawn wire after coiling relieves stresses within the wire itself due to cold work performed in coiling. This treatment increases both the elastic limit of the wire in the spring and its resistance to deformation when in operation. In the case of extension springs, the initial tension is decreased by this anneal. Therefore, extension springs are baked at a lower temperature and purposely wound with excess initial tension, because it will be decreased by the correct amount during the baking operation. A spring with set completely removed at normal temperatures will show a marked decrease in strength with increase in temperature if loaded and subjected to heat at the same time. At 500 to 550° F., for example, an ordinary carbon-steel spring will lose a major part of its strength when fully compressed. Tempered wire springs that have been finished at 800° F. (quenched in oil and tempered at 800° F.) will set under the above conditions in almost exactly the same manner as hard-drawn wire springs.

Low-temperature anneal or stress-relief anneal is applied to springs wound from tempered wire as well as from hard-drawn wire. However, its effect is more marked on hard-drawn wire and music wire.

In general it may be said[6] that music-wire spring steel is about the best, toughest, and most widely used material for all types of small springs subjected to high stresses, frequent deflections and suddenly applied loads. However, music wire springs should not be exposed to temperatures exceeding 250° F. At that temperature, they will suffer a load loss of approximately 5 per cent when stressed to 100,000 psi, and this loss increases rapidly at higher temperatures, unless they have been heated to remove coiling stresses at 750° F., in which case they are about equal to tempered wire.

Clock and Watch Spring Wire

Clock-spring or watch-spring steel is a cold-rolled steel of 0.90 to 1.20 per cent carbon and is heat-treated to a high hardness before coiling or forming. It has very high tensile strength, with an elastic limit almost 90 per cent of the tensile strength and a hardness of about 48 to 52 Rockwell C. The recommended allowable stresses for compression springs are 80,000 psi for light service, 70,000 psi for average service, and 60,000 psi for severe service.

Clock-spring wire is used for brush holders, clock and motor springs and miscellaneous flat springs for high stresses. Watch springs are used for the mainsprings of watches and similar devices.

Table 43 shows the chemical composition and properties of these two materials.

TABLE 43. *Clock and Watch Spring Wire*

	Composition	
	Clock	Watch
Carbon	0.90–1.05	1.10–1.19
Manganese	0.30–0.50	0.15–0.25
Phosphorus	0.03 max.	0.03 max.
Sulphur	0.025 max.	0.025 max.
Silicon	0.15–0.25	0.15-0.25
	Properties	
Tensile strength (psi)	200,000–325,000	325,000–340,000
Elastic limit (psi)	180,000–310,000	310,000–330,000
% Elongation in 8″	Approx. 4.0	——
Hardness, Rockwell C	48–52	52–55

Chromium-Vanadium Steel

Chromium-vanadium spring steel is best for use in high stress applications calling for high tensile strength, high yield strength and high fatigue limit, particularly at elevated temperatures. This grade of steel is noted for its retention of a high percentage of its room-temperature properties at temperatures of 300° F. and higher.

The steel is of the SAE 6150 grade, and is oil-hardened to about 42 to 48 Rockwell C. The recommended working stresses for compression springs are: light service, 85,000 psi; average service, 75,000 psi; severe service, 60,000 psi.

In chrome-vanadium alloy steel the chromium (0.8 to 1.1%) increases the tensile strength, hardness, and toughness, reduces the necessity of having high carbon content, and improves corrosion and heat resistance. It increases the ability of the steel to withstand elevated temperatures. Besides increasing tensile strength, elastic limit and toughness, vanadium enables the material to resist higher impact shock and alternating stresses.

Table 44 shows the chemical composition and properties of this material.

TABLE 44. *Chromium-Vanadium Spring Steel (S.A.E. 6150)*

Composition

Carbon	0.48–0.53
Manganese	0.70–0.90
Chromium	0.80–1.10
Vanadium	0.15–0.20
Phosphorus	0.025 max.
Sulphur	0.025 max.

Properties

Tensile strength (psi)	200,000–250,000
Elastic limit in tension (psi)	180,000–320,000
Torsional strength (psi)	160,000–195,000
Elastic limit in torsion (psi)	150,000–180,000
% Elongation in 8″	8–5
Modulus of elasticity (psi)	
In tension	30,000,000
In torsion	11,500,000
Hardness, Rockwell C	42–48

Mechanical Properties at Elevated Temperatures

	250° F.	350° F.
Stress to produce 2% loss of load (psi)	81,000	——
Stress to produce 4% loss of load (psi)	96,000	81,000
Stress to produce 6% loss of load (psi)	108,000	95,000
Stress to produce 8% loss of load (psi)	120,000	104,000

Silico-Manganese Steel

This steel is of the SAE 9260 grade and is oil-hardened to about 42 to 48 Rockwell C. It requires a high hardening temperature to develop the best mechanical properties. Table 45 shows the chemical composition and physical properties of this material.

TABLE 45. *Silico-Manganese Steel (S.A.E.-9260)*

Composition

Carbon	0.55–0.65
Manganese	0.70–1.00
Silicon	1.80–2.20
Phosphorus	0.40 max.
Sulphur	0.50 max.

Properties

Tensile strength (psi)	200,000–250,000
Elastic limit in tension (psi)	180,000–230,000
Torsional strength (psi)	140,000–195,000
Elastic limit in torsion (psi)	120,000–180,000
% Elongation in 2″	12–9
Modulus of elasticity (psi)	
In tension	30,000,000
In torsion	11,500,000
Hardness, Rockwell C	42–48

Silicon-manganese steels in sizes up to 5/8" diameter are reliable at temperatures up to 400° F., when they are stressed not in excess of 80,000 psi. If a small amount of set is permissible in operation, they may be used at temperatures up to 450° F. and at stresses not in excess of 120,000 psi (for compression springs). In general they exceed the chromium-vanadium steels in heat resistance. The recommended working stresses at room temperatures are: light stresses, 80,000 psi; average stresses, 70,000 psi; severe stresses, 55,000 psi.

The silicon combined with the manganese in silicon-manganese steel raises the tensile strength without sacrificing ductility or toughness.

Stainless Steel Springs

Certain qualities of corrosion and heat-resisting alloys can be hard-drawn to spring strength and do compare favorably with hard-drawn carbon steel wire. Because of their high alloy content, stainless steel springs subjected to loading under elevated temperatures have considerably higher resistance to loss of strength and to surface oxidation than do ordinary steels.

Stainless steel has come to the fore for springs working at high temperature and under corrosive conditions; the non-hardenable alloy containing about 12 per cent chromium and less than 0.10 per cent carbon, and the hardenable alloy (cutlery type) containing 12 to 14 per cent chromium and about 0.35 per cent carbon are good. The former alloy is used in the hard-drawn state, ranging from 200,000 to 250,000 psi, and is corrosion-resistant or rustless without further surface finishing. The latter alloy, however, is formed into springs in the annealed state, then hardened at 1825 to 1850° F., and drawn at 1000° F. Finally the springs must be ground or sandblasted to remove every trace of surface scale if the rust-resistant qualities of the steel are to be preserved. This is a difficult operation, especially on coiled wire springs.

Stainless steel of the cutlery type has a torsional modulus of elasticity of 11,750,000 psi when hardened and tempered. It is primarily stainless only in the hardened condition and is tough when hardened and tempered at about 600° F. It is likely to be brittle if tempered somewhat above 600° F. but below 900° F., and is again apparently quite tough when drawn at temperatures above 900° F. Springs made from this alloy are used where resistance to effects of heat while under stress is required.

A steel containing approximately 13 per cent chromium, 2 per cent nickel and 0.12 maximum per cent carbon is used for springs which must resist corrosion. When it is cold-rolled or drawn from annealed bars or strips, various degrees of hardness, depending upon requirements, can be obtained up to 220,000 psi in maximum tensile strength. It is used principally for stiff, resilient flat springs, but can be produced in wire form if necessary.

The 18–8 type stainless steel does not respond to hardening heat treatment, but it can be hardened and strengthened by cold-working or cold-drawing into wire. It has better corrosion-resisting properties than the other grades, but much lower elastic limit, proportional limit and endurance limit at the lower hardnesses. The low elastic properties of 18–8 stainless steel at the low hardnesses are a distinct drawback in springs. However, the chief advantage of this alloy, in addition to its corrosion- and rust-resisting qualities, is that the metal retains its elastic limit at high temperatures. This type alloy (Type 302) is most used for stainless springs.

Tables 46 and 47 respectively show the chemical composition and properties of the cutlery type and of the 18–8 type of stainless steel.

Allowable Working Stresses

Stress values[8] used in the design of springs of a given material depend upon such qualifications as type of spring, temperature, ratio of spring diameter to wire diameter, rapidity and regularity of deflections, shock loads, wire size and stress range (see Table 48).

When designing springs that will be required to give dependable service, the stresses should be calculated by the conventional formula that includes the curvature correction (Wahl) factor based upon the spring index. The maximum stress thus calculated should not exceed the allowable stress as listed above for the given type of service.

COPPER ALLOY SPRINGS

Several copper-base[3] alloys have been developed in which desirable spring properties are obtained by precipitation-hardening heat treatment. These alloys combine the physical properties of steel with the corrosion resistance and conductivity of bronze, and since they can be given the desired spring properties after forming, entirely new possibilities in design are available. The copper alloys, in general, are characterized by low values of elastic modulus, low tensile strength, and relatively poor spring performance under high working stresses.

Phosphor Bronze. Phosphor bronze springs are usually made from two different copper-base alloys: one containing about 5 per cent tin and the other about 8 per cent tin, with a phosphorus content between 0.1 to 0.15 per cent. They are characterized by high fatigue value and excellent resistance to wear and corrosion. In addition, excellent spring properties are retained under repeated flexing, as they are stiff and resilient. The alloy containing 8 per cent tin is used for more severe service, as it has somewhat higher mechanical properties. Both alloys may be used in corrosive surroundings at normal temperatures, but their properties are rapidly de-

TABLE 46. *Corrosion Resistant Steel (Type 420) (Cutlery Type)*

Composition

Carbon	0.30– 0.40
Chromium	12.0 –14.5
Manganese	0.50 max.
Silicon	0.50 max.
Sulphur	0.030 max.
Phosphorus	0.030 max.

Properties

Tensile strength (psi)	170,000–250,000
Elastic limit in tension (psi)	130,000–200,000
Torsional strength (psi)	120,000–180,000
% Elongation in 2″	13–7
Modulus of elasticity (psi)	
In tension	28,000,000
In torsion	11,000,000
Hardness, Rockwell C	42–48

TABLE 47. *Stainless Steel (Type 302) (18–8)*

Composition

Carbon	0.08– 0.20
Chromium	17.50–20.00
Nickel	8.00–10.00
Manganese	1.25 max.

Properties

Tensile strength (psi)	160,000–330,000
Elastic limit (psi)	60,000–250,000
Torsional strength (psi)	120,000–240,000
% Elongation in 2″	20– 5
Hardness, Rockwell C	35–48

Mechanical Properties at Elevated Temperatures

	350° F.	450° F.	550° F.
Stress to produce 2% loss of load (psi)	45,000	40,000	——
Stress to produce 4% loss of load (psi)	112,000	67,000	——
Stress to produce 6% loss of load (psi)	——	88,000	43,000
Stress to produce 8% loss of load (psi)	——	105,000	67,000
Stress to produce 10% loss of load (psi)	——	120,000	87,000
Stress to produce 12% loss of load (psi)	——	——	103,000
Stress to produce 14% loss of load (psi)	——	——	118,000

TABLE 48. *Moduli of Elasticity and Allowable Working Stresses*

Type of stainless steel	Modulus of Elasticity E = tension G = torsion	Type of service	Allowable Stresses (psi)		
			For compression springs	For extension springs	For flat, torsion, cantilever and clock type
302, 304	E = 26,500,000	Light	70,000	65,000	125,000
316	G = 10,000,000	Average	60,000	55,000	110,000
		Severe	50,000	45,000	90,000
414, 420	E = 28,500,000	Light	67,000	60,000	120,000
	G = 10,500,000	Average	57,000	50,000	105,000
		Severe	45,000	40,000	85,000

stroyed at elevated temperatures. Table 49 shows the typical mechanical properties of these two grades of phosphor bronze.

TABLE 49. *Properties of Phosphor Bronze*

	95–5 alloy	92–8 alloy
Tensile strength (psi)	103,000	112,000
Elastic limit (psi)	51,000	55,000
% Elongation in 2″	4	3
Rockwell Hardness	B93	B100

The material for fabrication into springs is cold-rolled or drawn to about 60 per cent reduction to spring temper from annealed bars or strips. The allowable stresses for compression springs are: 50,000 psi for light service, 40,000 psi for average service, and 30,000 psi for severe service.

Table 50 shows the chemical composition and properties of phosphor bronze spring wire when the specification calls for a minimum of 3.5 per cent tin and a phosphorus range of 0.05 to 0.50 per cent.

TABLE 50. *Phosphor Bronze*

Chemical Composition

Tin	3.50 min.
Phosphorus	0.05–0.50
Lead	0.20 max.
Zinc	0.30 max.
Iron	0.10 max.
Copper	94.0 min.
Cu + Sn + P Total	99.0 min.

Properties

Tensile strength (psi)	100,000–150,000
Elastic limit in tension (psi)	60,000–110,000
Torsional strength (psi)	80,000–105,000
Elastic limit in torsion (psi)	45,000– 75,000
% Elongation in 2″	2
Modulus of elasticity (psi)	
In tension	15,000,000
In torsion	6,500,000
Hardness, Rockwell B	90–100

Nickel Silver (German Silver). Nickel Silver (18% grade) has good spring properties and high electrical resistance. The average properties in strip form are 115,000 psi tensile strength, 60,000 psi elastic limit, 45,000 psi proportional limit, 2.5 per cent elongation and B–99 Rockwell hardness (see Table 51). The alloy is cold-rolled or drawn from annealed stock to 60 per cent reduction to spring temper, and is used for high-grade springs where white color is desired.

Clock Brass. The average composition of clock brass is 62.5 per cent copper, 36 per cent zinc and 1.5 per cent lead. Its average properties in

TABLE 51. *Nickel Silver*

Composition	
Copper	55.0–67.0
Nickel	16.0–19.0
Iron	0.50 max.
Sulphur	0.03 max.
Manganese	0.50 max.
Lead	0.80–1.20
Other impurities including Al	0.25 max.
Zinc	Balance
Properties	
Tensile strength (psi)	135,000–150,000
Elastic limit in tension (psi)	80,000–110,000
Torsional strength (psi)	85,000–100,000
% Elongation in 2″	2.5
Modulus of elasticity (psi)	
In tension	16,000,000
In torsion	5,500,000
Hardness, Rockwell B	95–100

strip form for springs are: 73,000 psi tensile strength, 31,000 psi elastic limit, 30,000 psi proportional limit, 9.5 per cent elongation and B–80 Rockwell hardness. The brass is cold-rolled or drawn from annealed bars or strip to 35 per cent reduction to hard temper for springs, and is generally used for flat springs with sharp bends.

Spring Brass. This alloy, containing about 64 to 68 per cent copper and 32 to 36 per cent zinc, is stiff and springy. It is used for making light-duty, moderately stressed flat or coiled springs, but it is not recommended for outdoor use or for conditions requiring repeated flexing. It is generally cold-rolled or drawn from annealed bars or strip to 60 per cent reduction to spring temper (see Table 52).

TABLE 52. *Spring Brass*

Composition	
Copper	64.00–68.00
Lead	0.30 max.
Iron	0.05 max.
Zinc	Balance

Properties	
Tensile strength (psi)	90,000–130,000
Elastic limit in tension (psi)	40,000– 60,000
Torsional strength (psi)	40,000– 80,000
Elastic limit in torsion (psi)	30,000– 55,000
% Elongation in 2″	2.0
Modulus of elasticity (psi)	
In tension	15,500,000
In torsion	5,500,000
Hardness, Rockwell B	90

Silicon Bronze. Silicon-copper alloys containing about 3 per cent silicon are sometimes used for springs. They have a tensile strength of 85,000 psi, an elongation of 3 per cent and a Rockwell hardness of B–86.

Beryllium-Copper. Of the various heat-treatable copper alloys, the best combination of strength, corrosion resistance and electrical conductivity is found in beryllium-copper. This alloy, containing about 2 per cent beryllium, can be heat-treated to a tensile strength of 200,000 psi or higher and has an endurance strength of 40,000 psi when heat-treated for high fatigue strength. Other elements are added up to 0.5 per cent by some alloy manufacturers (see Table 53).

TABLE 53. *Beryllium-Copper Alloys*

Composition

Beryllium	1.85–2.10
Cobalt	0.25 max.
or	
Nickel	0.2–0.5 max.
Copper	Balance

Properties (Heat-treated)

Tensile strength (psi)	160,000–200,000
Elastic limit in tension (psi)	100,000–150,000
Torsional strength (psi)	100,000–130,000
% Elongation in 2″	Approx. 2.0
Modulus of elasticity (psi)	
In tension	16,000,000
In torsion	6,000,000
Hardness, Rockwell C	32–42

Any type of spring[3] made from wire, strip or sheet beryllium-copper usually is completely formed in the soft condition before hardening heat treatment. Adjustments can be made thereafter, if necessary. Springs can be quenched in water or cooled in air from the hardening temperature without affecting their properties or dimensions in any way. Heat-treated springs are free from some of the setting or creep effects found in other spring materials, as the internal stresses and strains set up in forming are automatically relieved during heating for hardening. To obtain the maximum strength the spring material should be given the maximum amount of cold work or spring temper permitted by the forming operation. In general, material is always fabricated in the prequenched condition and then simply heated to 500–700° F. for age-hardening.

The increase in elastic modulus of beryllium-copper during the hardening heat treatment makes helical springs stiffer, resulting in a decrease in measured spring deflections under the same load.

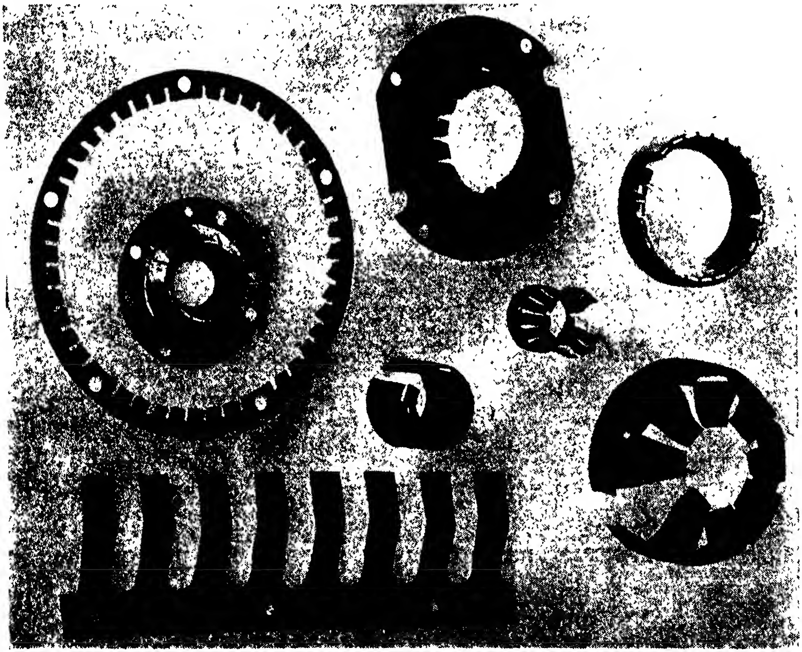
It cannot be too strongly emphasized that the advantages of beryllium-copper are the result of a heat treatment of the finished spring, and that this heat treatment must be carefully controlled to get optimum results. General recommendations on this heat treatment cannot be made, as each job must be considered in the light of (1) the amount of cold work in the material, (2) the job the spring must do, and (3) the size and shape of the piece. For most spring applications the alloy is prepared with the maximum amount of cold work that it can stand during the forming or coiling process.

Beryllium-copper has the highest endurance value of all the corrosion-resistant materials. Its electrical conductivity is twice that of phosphor bronze. In addition, the higher heat resistance of beryllium-copper permits its use at temperatures 100° F. higher than bronze will stand.

In processing the spring material, beryllium-copper is made susceptible to hardening by a solution heat treatment at about 1425° F., followed by a rapid quench. This treatment is usually performed by the alloy manufacturer. Generally the material is given additional cold work or reduction to introduce some spring temper, since physical properties are thus improved.

The allowable service stresses for compression springs are: 60,000 psi for light service, 50,000 psi for average service, and 40,000 psi for severe service.

Figure 39 shows a group of typical springs used in radar equipment by various manufacturers. Beryllium-copper was used because it is non-mag-



(Courtesy Instrument Specialties Co., Little Falls, N. J.)

Figure 39. Beryllium-copper springs.

netic and has better electrical conductivity than all other spring material of similar hardness. These parts must conform to close dimensional tolerances and maintain constant spring pressure under severe operating conditions.

NICKEL ALLOY SPRINGS *

The oxidation and corrosion resistance of nickel and nickel alloys, combined with their ability to retain strength to a considerable degree at elevated temperatures, have made them useful in many elevated temperature spring applications. The spring materials are nickel, "Monel" metal, "K-Monel," "Inconel," "Inconel-X," "Duranickel" (formerly "Z" Nickel) and "Permanickel (formerly "Z" Nickel Type B).

These seven high-nickel materials are admirably suited for springs operating under special conditions. Being of the same family, they resemble each other in their excellent resistance to corrosion, their high mechanical properties, and their white, silvery color. They are all rustless materials. Yet each has its own distinguishing features.

Springs made from these materials are more resistant to corrosion than steel springs of equivalent strength. Under corrosive conditions their endurance values are likely to surpass even those of steels which may have shown higher fatigue values when tested in air. In comparison with springs of most other non-ferrous materials, they are stronger and stiffer and retain their properties to higher temperature levels. There is no danger of failures from embrittlement in subzero service. With decreasing temperatures their strength properties, hardness, and rigidity increase, with no appreciable change in ductility or impact values.

Nickel. Nickel of 99.4 per cent purity may be used for springs operating at temperatures up to 400° F. It is moderately magnetic at ordinary temperatures, and has the highest electrical conductivity of the high-nickel alloys. Since it does not work-harden as much as the other nickel alloys, design stresses must be kept to a fairly low level.

"Monel" Metal. "Monel" metal, containing about 67 per cent nickel and 29 per cent copper, is widely used for rust-proof, corrosion-resisting springs that are moderately stressed. It is slightly magnetic and may be used at temperatures up to 400° F. at moderate stress levels. Monel metal springs should be stress-equalized for one hour at 650° F. after coiling to equalize internal stress and moderately increase the proportional limit. "Monel" metal is cold-drawn from annealed rod and the wire is reduced 65 to 75 per cent to spring temper (see Table 54).

---

* All data on nickel alloy springs were obtained from the publications of the International Nickel Co., and from private communications with the company's engineers.

TABLE 54. *"Monel" Metal*

(For properties of spring wire, see Table 60.)

Composition

Nickel	63.0–70.0
Iron	2.5 max.
Aluminum	0.5 max.
Manganese	2.0 max.
Carbon	0.3 max.
Silicon	0.5 max.
Sulphur	0.02 max.
Copper	Balance

Properties (Cold-rolled strip, spring temper)

Tensile strength (psi)	100,000–140,000
Yield strength (0.2% offset) (psi)	90,000–130,000
Torsional proportional limit (psi)	Approximately 40% of T.S.
% Elongation in 2″	15–2
Modulus of elasticity (psi)	
In tension	26,000,000
In torsion	9,500,000
Hardness, Rockwell C	20–28

Properties at elevated temperatures (typical)

	Room temp.	250° F.	500° F.	750° F.
Modulus in torsion (10^6 psi)	9.5	9.2	8.7	8.1

Relaxation (% load loss) of helical springs	400° F.	500° F.
Stress * to produce 2% relaxation in 7 days (psi)	43,000	3,000
Stress * to produce 4% relaxation in 7 days (psi)	57,000	7,000
Stress * to produce 6% relaxation in 7 days (psi)	60,000	10,000

* Includes Wahl curvature correction factor.

"K-Monel." "K-Monel" contains approximately 68 per cent nickel, 29 per cent copper and 2.75 per cent aluminum. It is a non-magnetic alloy with high spring properties and excellent corrosion resistance. It responds to heat treatment and may be used at temperatures up to 450° F. in springs under fairly high stresses. Its relaxation at elevated temperatures is moderately progressive with increased time at stress and temperature, but it is inferior to "Inconel" and "Duranickel" in this respect (see Table 55).

"K-Monel" springs, when coiled from cold-drawn spring temper wire, are given a heat treatment of 980° F. for 6 hours after cold-coiling. Springs that are hot-coiled are aged after coiling for 8 to 16 hours at 1080° F. Springs of 1⅜″ and 1¾″ diameter have been successfully hot-coiled with stresses at solid height of 60,000 to 65,000 psi.

"Inconel." "Inconel," containing about 80 per cent nickel, 14 per cent chromium and 6 per cent iron, is a heat-resisting alloy recommended for springs operating at temperatures up to 650 to 700° F. It also resists corrosion of a wide variety of chemicals. "Inconel" resists relaxation up to high

Table 55. "*K-Monel*"

(For properties of spring wire, see Table 60.)

Composition

Nickel	63.0–70.0
Aluminum	2.0–4.0
Iron	2.0 max.
Manganese	1.0 max.
Silicon	0.50 max.
Carbon	0.25 max.
Titanium	0.50 nominal
Other impurities, total	1.00 max.
Copper	Balance

Properties of cold-rolled strip, spring temper

	As-rolled	Age-hardened
Tensile strength (psi)	145,000–160,000	170,000–200,000
Yield strength (0.2% offset) (psi)	105,000–120,000	125,000–145,000
Torsional proportional limit (psi)	Approximately 40% of T.S.	
Modulus of elasticity (psi)		
In tension	26,000,000	
In torsion	9,000,000	
Hardness, Rockwell C	33–40	
% Elongation in 2"	8–2	10–2

Properties at elevated temperatures (typical)

	Room temp.	250° F.	500° F.	750° F.
Modulus in torsion (10^6 psi)	9.5	9.2	8.7	8.1

Relaxation (% load loss) of helical springs	450° F.	500° F.	600° F.
Stress * to produce 2% relaxation in 7 days (psi)	50,000	22,000	4,000
Stress * to produce 4% relaxation in 7 days (psi)	——	42,000	8,000
Stress * to produce 6% relaxation in 7 days (psi)	——	——	11,000

* Includes Wahl curvature correction factor.

temperatures and may be used at fairly high stresses up to 650° F. Above this temperature, the stress must be lowered considerably and a greater degree of relaxation must be tolerated. Inconel springs should be stress-equalized after coiling for one hour at 850 to 900° F. for all service conditions. This thermal treatment raises the tensile strength and proportional limit by 15,000 to 25,000 psi and increases the hardness by 2 to 5 points on the Rockwell C scale. Inconel is non-magnetic down to −40° F. (see Table 56).

Inconel springs have been used widely at temperatures up to 650° F. for applications such as relief valve springs operating in steam and oil refinery service and for thermostat flat springs and helical compression springs. Where used for helical extension springs at elevated temperatures, such as piston packing springs, the springs should be stress-relieved after coiling. This thermal treatment will wipe out all or most of the initial stress wound into extension springs, and design should be based on extension springs having no initial tension.

TABLE 56. *"Inconel"*

(For properties of spring wire, see Table 60.)

Composition

Nickel	75.0 min.
Chromium	13.0–16.0
Iron	9.0 max.
Manganese	1.0 max.
Copper	0.50 max.
Carbon	0.15 max.
Silicon	0.30 max.

Properties of cold-rolled strip, spring temper

Tensile strength (psi)	145,000–170,000
Yield strength (0.2% offset) (psi)	110,000–160,000
Torsional proportional limit (psi)	Approximately 40% of T.S.
% Elongation in 2″	10–2
Modulus of elasticity (psi)	
In tension	31,000,000
In torsion	11,000,000
Hardness, Rockwell C	28–38

Mechanical properties at elevated temperatures

Endurance limit of cold-drawn Inconel rod:

	Room temp.	800° F.	1,000° F.	1,200° F.	1,400° F.	1,600° F.
Endurance limit (psi)	51,500	47,500	32,500	26,000	15,000	9,000

Properties at elevated temperatures (typical)

	Room temp.	450° F.	550° F.	650° F.
Modulus in torsion (10^6 psi)	11	10.3	10.1	9.8

Relaxation (% load loss) of helical springs	450° F.	550° F.	650° F.
Stress * to produce 2% relaxation in 7 days (psi)	67,000	55,000	30,000
Stress * to produce 4% relaxation in 7 days (psi)	75,000+	75,000	55,000
Stress * to produce 6% relaxation in 7 days (psi)	75,000+	75,000+	75,000

* Includes Wahl curvature correction factor.

A modified composition of "Inconel" is "Inconel-X," an alloy which responds to age-hardening heat treatment. It has higher hardness and other properties than standard "Inconel," and can also be used safely at higher operating temperatures (see Table 57).

"Duranickel." "Duranickel" is a heat-treatable nickel alloy with excellent spring properties, plus the corrosion resistance of pure nickel. It contains about 94 per cent nickel. It is moderately magnetic, and temperatures up to 400° F. have little effect on its spring properties. It may be used with fairly high stresses at temperatures up to 550° F. and with reduced stresses up to 600° F. All "Duranickel" springs should be aged at 980° F. for 4 to 6 hours after coiling.

TABLE 57. "*Inconel-X*"

(For properties of spring wire, see Table 60.)

Composition

Carbon	0.08 max.	Columbium	0.70–1.20
Manganese	0.4–1.0	Titanium	2.25–2.75
Silicon	0.50 max.	Aluminum	0.40–1.00
Sulphur	0.01 max.	Iron	5.0–9.0
Chromium	14.0–16.0	Copper	0.20 max.
Nickel	70.0 min.		

Modulus of elasticity and Poisson's ratio

Temp. (° F.)	Modulus in tension (psi)	Modulus in torsion (psi)	Poisson's ratio
80	31,000,000	11,000,000	0.29
500	28,700,000	10,200,000	—
1,000	25,000,000	9,000,000	—
1,200	23,000,000	8,100,000	—
1,350	21,000,000	——	—
1,500	18,500,000	——	—

Hardness	Rockwel
Annealed at 1,850°–1,950° F. (air-cooled)	77B–25C
Equalized at 1,650° F., 2 hours (air-cooled and aged at 1,300° F. for 16 to 20 hours)	34C–42C
Spring temper	36C–45C
Spring temper (direct age-hardened at 1,200° F. for 2 to 4 hours)	42C–50C

Relaxation (% load loss) of helical springs

Thermal treatment	Test stress (psi)	Temp. (° F.)	% Relaxation after time and stress at temperature			
			7 days	14 days	21 days	28 days
1	50,000	750	4.8	6.1	6.3	6.8
2	50,000	750	2.1	2.2	2.15	2.2
3	50,000	750	5.8	6.2	6.9	7.4
4	50,000	750	1.0	1.2	1.2	1.5
5	50,000	750	0.9	1.5	2.0	2.5
6	50,000	750	0.7	1.1	1.1	1.1

Thermal Treatments

(1) Spring temper wire, cold-pressed, aged at 1,300° F. for 4 hours.

(2) No. 1 temper wire (1B & S reduction), cold-pressed, aged at 1,300° F. for 16 hours.

(3) Same as (1) except cold-pressing of springs was omitted; aged at 1,350° F. for 16 hours.

(4) Same as (2) except cold-pressing of springs was omitted; aged at 1,350° F. for 16 hours.

(5) Spring temper wire, cold-coiled (not pressed); aged at 1,300° F. for 4 hours and heat-loaded (clamped at 60,000 stress at 850° F. for one hour) and tested at 750° F. at 50,000 stress.

(6) Same as (5) except using No. 1 temper wire (1B & S reduction after final anneal).

Age-hardening Treatments

(1) Equalizing; heat to 1,650° F. for 2 hours and air-cool.

(2) Equalizing and aging; heat to 1,650° F. for 2 hours, air-cool, age at 1,350° F. for 16 hours.*

(3) Direct aging of spring temper material; heat at 1,200° F. for 2 to 4 hours.

* The normal aging temperature for "Inconel-X" is 1,300° F. The 1,350° F. treatment is recommended in preference to 1,300° F. for spring applications, since test results indicate slightly lower relaxation or load-loss at elevated temperatures.

"Permanickel" is a modified form of "Duranickel" and contains about 98 per cent nickel (see Table 58).

TABLE 58. *"Duranickel" and "Permanickel"*

(For properties of spring wire, see Table 60.)

Composition	"Duranickel"	"Permanickel"
Carbon	0.30 max.	0.40 max.
Copper	0.25 max.	0.25 max.
Silicon	1.0 max.	0.35 max.
Sulphur	0.01 max.	0.01 max.
Iron	0.60 max.	0.60 max.
Manganese	0.25–1.00	0.20–0.60
Aluminum	4.00–4.75	——
Titanium	——	——
Magnesium	——	0.20–0.50
Nickel	balance	balance

Properties of cold-rolled strip, spring temper

	As-rolled spring temper	Age-hardened
Tensile strength (psi)	155,000–190,000	180,000–230,000
Yield strength (0.2% offset) (psi)	120,000–150,000	130,000–175,000
% Elongation in 2"	8–2	10–2
Modulus of elasticity (psi)		
In tension	——	30,000,000
In torsion	——	11,000,000
Endurance limit (c.d. rod) (psi)	55,000	59,000

Relaxation (% load loss) of helical springs		"Permanickel"	
	400° F.	550° F.	600° F.
Stress * to produce 2% relaxation in 7 days (psi)	75,000	30,000	15,000
Stress * to produce 4% relaxation in 7 days (psi)	75,000	75,000	50,000
Stress * to produce 6% relaxation in 7 days (psi)	75,000	75,000	70,000

* Includes Wahl curvature correction factor.

"Duranickel" springs will withstand somewhat higher stresses than "Inconel" at the lower temperatures consistent with their generally higher level of mechanical properties.

Table 59 shows the suggested working stresses for cold-coiled compression springs made from the various grades of high-nickel alloys. These stresses include the Wahl curvature correction factor.

TABLE 59. *Suggested Working Stresses for Cold-Coiled Compression Springs*

Material	Light service	Average service	Severe service
Nickel	40,000 (psi)	35,000 (psi)	30,000 (psi)
"Duranickel"	70,000	60,000	45,000
"Permanickel"	70,000	60,000	45,000
"Monel"	55,000	45,000	35,000
"K-Monel"	65,000	55,000	40,000
"Inconel"	65,000	60,000	45,000
"Inconel-X"			
Direct-aged	80,000	65,000	50,000
Equalized and aged	65,000	60,000	50,000
Aged and heat-treated	65,000	60,000	50,000

Table 60 shows the minimum tensile strengths of the different spring temper materials in various diameter wires for comparative purposes.

Table 60. *Minimum Tensile Strength (in psi) of High-Nickel Alloy Spring Temper Wires*

	Diameter of Wire			
Metal (spring temper)	0.031″	0.062″	0.125″	0.250″
"Duranickel" and "Permanickel"				
As-drawn	165,000	160,000	155,000	150,000
As-drawn, heat-treated	200,000	195,000	190,000	190,000
"K-Monel"				
As-drawn	165,000	155,000	150,000	145,000
As-drawn, heat-treated	180,000	175,000	170,000	170,000
"Inconel" as-drawn	185,000	175,000	170,000	165,000
"Monel" as-drawn	160,000	150,000	140,000	140,000
Nickel as-drawn	135,000	135,000	125,000	125,000
"Inconel-X"				
As-drawn	210,000	200,000	200,000	185,000
Age-hardened	250,000	240,000	230,000	215,000
Overaged	165,000	165,000	165,000	165,000

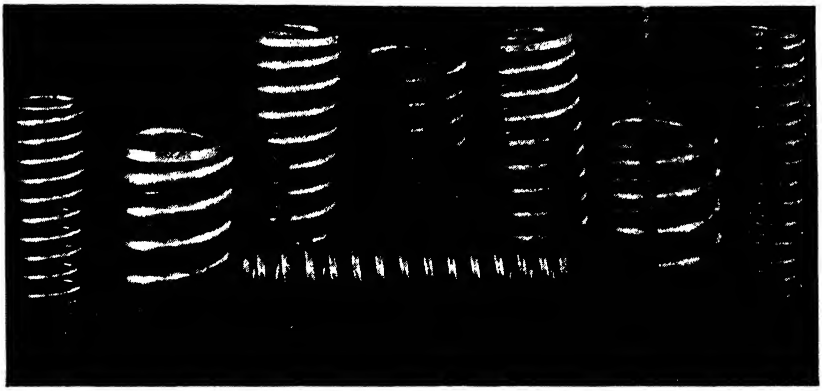
"Ni-Span C," a new, age-hardenable, constant-modulus alloy has recently been introduced for precision springs. It is composed of 42 per cent nickel, 2.5 per cent titanium, 5.5 per cent chromium, 0.06 per cent carbon, and iron; its advantages for control, measuring and timing equipment are that temperature changes between −50° and +250° F. cannot expand, weaken or soften it.

Another important spring alloy of nickel[17] is called "Elinvar." It has a constant modulus from −150° to +300° F. It is an austenitic alloy, containing 33 to 35 per cent nickel, 4 to 5 per cent chromium, 1 to 3 per cent tungsten, 0.5 to 2.0 per cent manganese, 0.5 to 2.0 per cent silicon, 0.5 to 2.0 per cent carbon, and 53 to 61 per cent iron. As a result it can be hardened only by cold work. "Elinvar" possesses great resistance to oxidation and corrosion, is immune to magnetic effects, and has low thermal expansion. The elastic limit is about 45,000 psi, and in use it is limited to stresses considerably under this.

Figure 40 shows a number of "K-Monel" springs. No. 1 and No. 2A springs were cold-coiled, using ¾″ and ½″ diameter, cold-drawn spring temper rods, heat-treated after coiling. No. 3, No. 4, and No. 5 springs were hot-coiled using 1⅜″, 1$\frac{9}{16}$″ and 1¾″ diameter hot-rolled rod, heat-treated after coiling.

GENERAL

The choice of spring materials for use under various corrosive conditions entails the consideration of many factors, which so affect the behavior of the materials that it is difficult to decide upon the relative corrosion resistance of alloys except as they react under a particular set of conditions.



(*Courtesy International Nickel Co., and American Locomotive Co., N. Y.*)

Figure 40. K-Monel springs.

One alloy may have greater resistance to corrosion than another under one set of conditions; but if the conditions are changed, the resistance values may be reversed. Therefore the selection of spring materials for corrosive conditions must be made after careful consideration of each individual application.

The selection of spring materials for use at elevated temperatures must in most cases be governed by the corrosive conditions which are also present. It is generally accepted that "Inconel" is the preferred alloy for most high-temperature applications, although "Monel," stainless steel, and the heat-resistant steels will give satisfactory service in many such applications. When a spring has been subjected to unsafe ranges of stress, subsequent rest and mild heat treatment may prolong its life. Bending or buckling of the spring caused by the loading not being truly axial can produce, at certain points on the section of the wire, ranges of stress appreciably greater than those given by torsional stress only.

Where values were given in this chapter for allowable stresses for compression springs the following facts are to be noted:

(a) For wire diameters under 0.020 inch, the values are to be increased by 20 per cent. For diameters over 0.020 to 0.057 inch, the values are to be increased by 10 per cent.

(b) For compression springs that are preset and shot-peened, increase the values 10 to 15 per cent.

(c) For torsion, flat, cantilever, clock and power springs, increase the values by 50 to 75 per cent.

(d) For extension springs reduce the values 10 to 20 per cent.

(e) For suddenly applied loads, reduce the values by 50 per cent.

(f) For elevated temperature operation, reduce the values by 50 per cent.

Figure 41 shows a typical failure of a helical counter balance spring caused by a longitudinal seam in the original 1-inch diameter rod of silico-manganese steel.

Figure 42 shows at 5X magnification the microstructure of the cross-section of the spring rod adjacent to fracture, indicating extent of decarburization (white) and location of the two photomicrographs following.

Figure 43 shows at 75X magnification the microstructure of the cross-section at the point (A) in Figure 42. This shows clearly the surface defect (crack) and extent of the surface decarburization (white area). Figure 44 shows at 150X magnification the character of the surface-decarburized zone

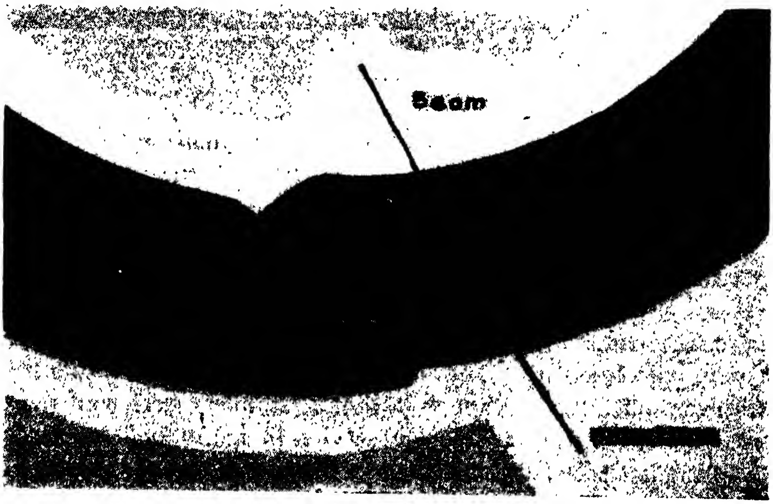


Figure 41. Counter-balance spring.

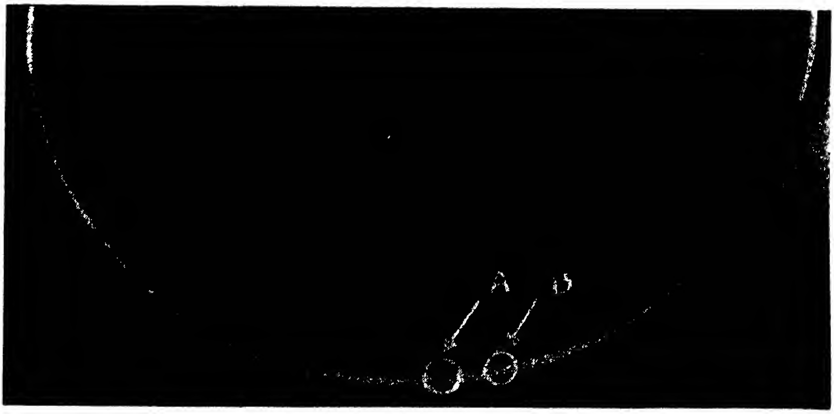


Figure 42. Macrostructure of crack shown in Figure 41.

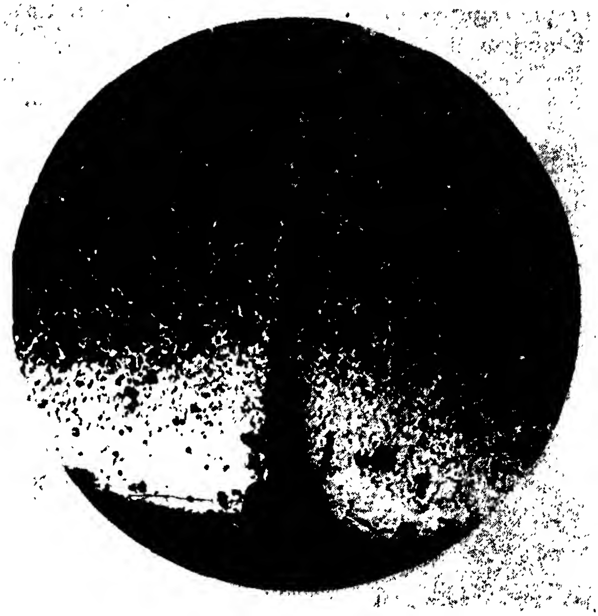


Figure 43. Microstructure of crack shown in Figure 42, circled A.

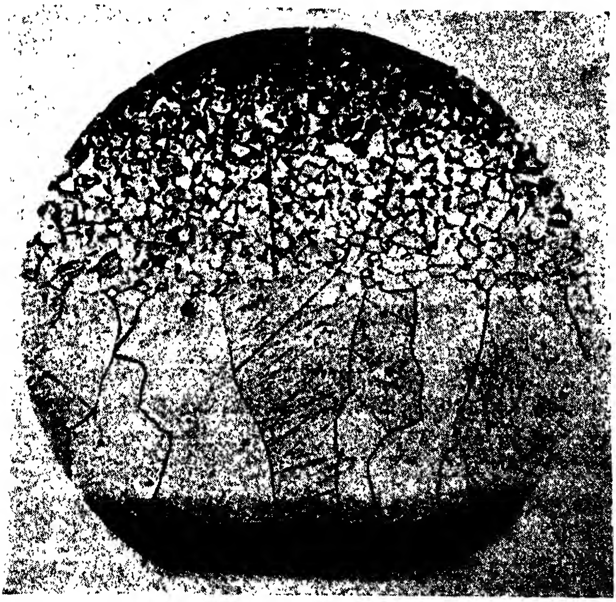


Figure 44. Higher magnification of crack shown in Figure 43.

at the point (B) in Figure 42. Here can be noted the abnormally large radial grains of carbonless iron in the outer surface.

Figure 45 shows a marine coupling spring that failed in fatigue.

Figure 45. Broken marine coupling spring.

PHYSICAL TESTS—(A.S.T.M.)

(a) The properties specified in sections (b), (c), (d) and (e) shall be determined in the order specified on each spring which has met the requirements for dimensions. The springs shall not be rapped or otherwise disturbed during the test.

(b) *Solid Height.* The solid height is the perpendicular distance between the plates of the testing machine when the spring is compressed solid with a test load of at least 1¼ times that necessary to bring all the coils in contact.

(c) *Free Height.* The free height is the height of the spring when the load specified in paragraph (b) has been released, and is determined by placing a straightedge across the top of the spring and measuring the perpendicular distance from the plate on which the spring stands to the straightedge, at the approximate center of the spring.

(d) *Loaded Height.* The loaded height is the perpendicular distance between the plates of the testing machine when the specified working load is applied.

(e) *Permanent Set.* The permanent set is the difference, if any, between the free height and the height (measuring at the same point and in similar manner) after the spring has been compressed solid three times in rapid succession with the test load specified in paragraph (b).

DEFINITIONS

Baking is a term applied to low-temperature heat treatment of springs and used to distinguish this heat treatment from hardening and tempering. Baking temperatures seldom exceed 700° F.

Coil is one complete circumference of a spring helix.

Deflection is the change in length in inches of an extension or compression spring which is caused by a change in loading of the spring.

Initial Tension is the maximum load which can be applied to a close-wound spring without causing extension.

Patenting includes the complete operation of heating wire to above the critical temperature and quenching in either lead or air. The process is performed continuously by drawing strands of wire through a furnace.

Resilience is the amount of work in inch-pounds which a spring is capable of doing upon complete release of load.

Set in a compression spring is the loss of length in inches after the spring has been deflected equivalent to a stress greater than the elastic limit of the wire.

Solid Height is the length of a compression spring when compressed until all coils touch.

Spring Index is the ratio of the mean diameter of coil to the wire diameter and should never be less than 3.

Spring Rating is the pounds pressure required to extend or compress a spring one inch.

References

1. McAdam, D., "Fatigue and Corrosion Fatigue of Spring Materials," *ASME Trans.* (Dec., 1928).
2. Zimmerli, F., "Effect of Temperature upon the Torsional Modulus of Spring Materials," ASTM, 1930.
3. Stott, L., "Beryllium-Copper Springs Require Modified Design," *Machine Design* (May, 1936).
4. Tour, S., "Springs of Stainless Steel," *Iron Age* (Oct. 15, 1936).
5. Wahl, A., "Spring Materials," *Machine Design* (Oct., 1940).
6. Carson, H., "Spring Steels," *Product Engineering* (Jan. and Feb., 1942).
7. Betty, B., "Relaxation Resistance of Nickel Alloy Springs," *ASME Trans.* (July, 1942).
8. Carson, H., "Stainless Steel for Springs," *Product Engineering* (June, 1947).

9. Zimmerli, F., "Selecting, Testing and Fabricating Spring Materials," *Materials and Methods* (September, 1947).
10. Barnes-Gibson-Raymond Co., "BGR Springs," bulletin (1941).
11. Instrument Specialties Co. bulletins.
12. International Nickel Co. publications.
13. Wallace Barnes Co., "Design of Flat Springs," bulletin.
14. Wallace Barnes Co., "Mechanical Springs," bulletin.
15. Associated Spring Corp., "The Main Spring," bulletins.
16. Wickwire-Spencer Steel Co., "Treatise on Springs," bulletin.
17. Zimmerli, F., "Proper Use of Spring Materials," S.A.E. preprint (June, 1947).
18. Zimmerli, F., "Selecting, Testing and Fabricating Spring Materials," *Materials and Methods* (September, 1947).

Chapter VIII

Bearing Materials

A bearing is a machine element designed to transmit loads or reaction forces to a shaft which rotates relative to the bearing.[25] Journal bearings are cylindrical (full cylinders or cylinder segments) and are used when the shaft load is essentially perpendicular to the shaft axis. Thrust bearings are ring-shaped (full rings or ring segments) and are used when the shaft load is in the direction of the shaft axis.

It is generally recognized that the function of a bearing is purely to prevent or minimize damage due to failure of lubrication. Under normal or ideal conditions the bearing has little, if any, influence on the operation of a machine, and its virtues become apparent only when lubrication is suspended. Knowledge of the conditions that follow the suspension or failure of the oil film is essential to the intelligent selection of the bearing alloy.

Specifying materials for bearings has in the past been largely a matter of trial and error. Certain combinations of metals have been found by experience to work well together in bearing applications under certain load, lubrication and speed conditions, and engineers have tended to specify bearing materials on an empirical basis only. Suggested substitutions have been regarded with suspicion, and engineers have been reluctant to change traditional workable bearing combinations on the basis of laboratory tests.

Bearing materials have frequently been specified and purchased on the basis of physical properties, such as tensile strength, yield point, ductility, and impact strength at room temperature. However, these properties fail completely to tell the true story of whether an alloy is or is not satisfactory in a specific bearing application.

✓The only physical properties of any significance in a bearing are hardness, compressive strength, and possibly impact and fatigue strength at the operating temperature of the bearing. Even these properties fall far short of determining with any accuracy whether or not an alloy will make a successful bearing metal.

Recently much work has been done on laboratory tests for evaluating bearings on the basis of simulated service conditions, using specialized equipment. Although this is the only method of evaluating bearing metals accurately, laboratory tests have not developed to a point where they are generally standardized and are accepted by engineers. However, much progress has been made, and eventually laboratory tests simulating service conditions should be the only criteria for acceptance or rejection of bearing alloys.

Fluid Film Theory

According to the fluid film theory of bearing action, in a well lubricated bearing the material of shaft and bearing is unimportant as long as there is an adequate supply of lubricant during operation, since there is no metal-to-metal contact. As shown in Figure 46, the shaft is continually floating in a wedge of oil under normal operating conditions at constant load and speed. With proper clearance between bearing and journal, the shaft lifts off the bearing as it begins to rotate and assumes a position in the bearing where the shaft and bearing are not concentric. Oil-film pressures are maximum at the point of closest approach of journal to bearing, and are negative at a point somewhat beyond it. Thus, according to this theory, there is no metal-to-metal contact, and hence, materials are of no significance.

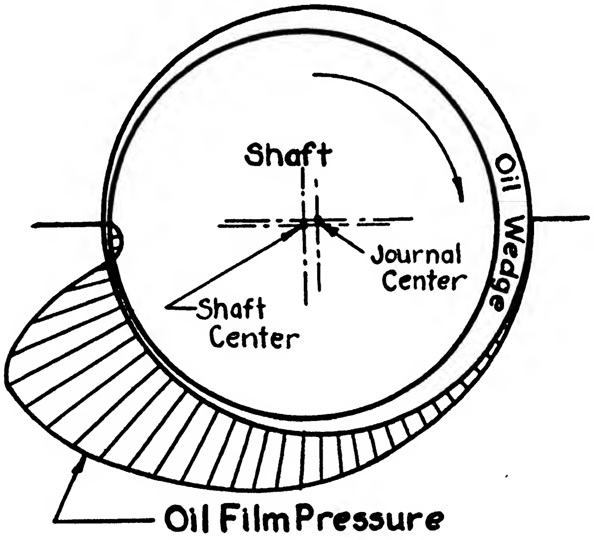
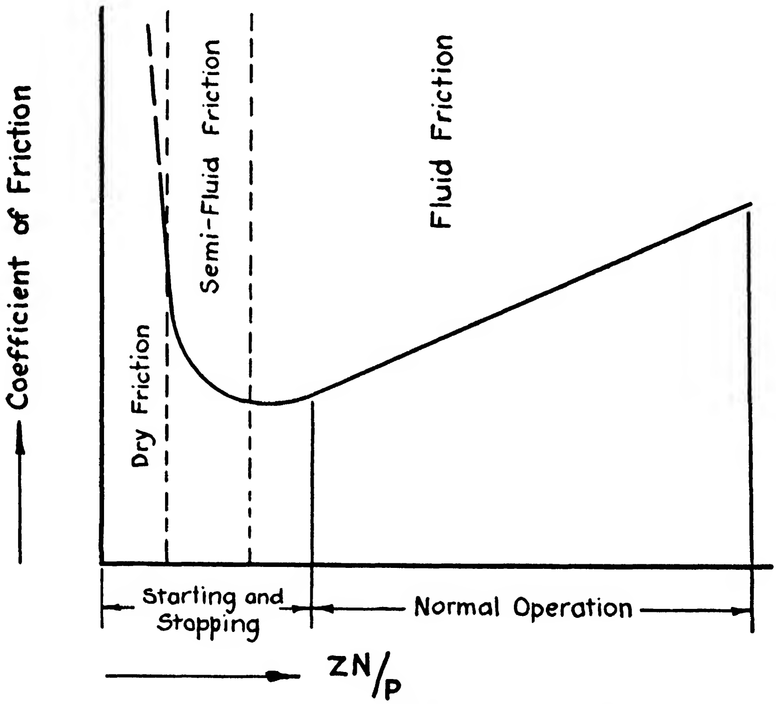


Figure 46. Bearing action.

The coefficient of friction of the shaft in the bearing, according to this theory, varies directly with the viscosity of the oil (Z), and the rotational speed (N) of the shaft, and inversely with the pressure (P). However, it has been found[9] that the coefficient of friction under actual operating conditions varies with the formula ZN/P as shown in Figure 47. From this curve it can be seen that for a certain range of operating conditions, the coefficient of friction is indeed low, varying directly with ZN/P. However, at low values of ZN/P the coefficient increases rapidly. These are the conditions obtained during starting, stopping, and accelerating of the shaft.

When the shaft is rotating ideally in a film of lubricant, the bearing materials are of no significance. However, in actual service there are probably many times in the life of a bearing when the fluid film is broken and the conditions are no longer ideal. In such cases as starting, stopping, and accelerating, and sometimes of misalignment or doubtful lubrication, the bearing may be operating on the left-hand portion of the curve in Figure 47. Grit and surface roughness in the shaft or bearing also will cause departure from ideal conditions. Hence, in actual installations, the choice of proper bearing materials is of vast significance and the engineer must use his knowledge and ingenuity in specifying materials for specific load, speed, lubrication and temperature conditions.



(Courtesy International Nickel Co., Inc., N. Y.)

Figure 47. Coefficient of friction variation.

Furthermore, the probability[11] of maintaining a condition of full fluid lubrication in a dynamically loaded bearing subject to misalignment, shaft deflection, occasional overloads, and so forth, does depend on the mechanical properties of the bearing material. A lack of adequate conformability or elastic deformation will accentuate lubrication film breakdown and metallic contact. Highly stressed bearings, even when the mechanical properties are favorable, undoubtedly operate partially and at times totally, under conditions of boundary friction. It is in this circumstance that the chemical composition of the bearing material comes into full play, and decides whether the bearing will fail or continue in operation through the emergency.

In addition, it has been established that the microstructure or mechanical structure of a bearing material has even greater influence on its ability to meet bearing requirements than has its composition. The mechanics of the progress of fatigue failure in engine bearings indicate that the structure of the bearing alloy is of vital importance.

To summarize, in a bearing assembly of given dimensions and with adequate stiffness, the coefficient of friction is not affected by the materials of the bearing or the shaft, nor by the composition or "oiliness" of the lubricant, as long as there is an ample supply of lubricant; and that it is affected by the pressure on the bearing, the speed of the shaft and the viscosity of the lubricant at the operating temperature in such a manner as to decrease with pressure, increase with speed and increase with viscosity.

Bearing Requirements

Among the properties of a good bearing alloy, the following are important:

(1) Adequate yield strength in compression, especially at operating temperature, to prevent measurable permanent deformation or a brinelling of the bearing material under load.

(2) Sufficiently high softening point to withstand any service temperature.

(3) Sufficient but not excessive hardness to permit embedding of grit and dirt particles contaminating the lubricating fluid.

(4) Plasticity or ability to deform under load to take care of alignment and to conform to the shaft.

(5) Sufficient ductility and absence of brittleness to withstand pounding and torque without flaking or cracking.

(6) Low modulus of elasticity to permit elastic deflection.

(7) Low coefficient of friction to prevent galling, abrading and seizing.

(8) Ability to maintain an oil film on its surface or to absorb certain compounds of the lubricant.

(9) High thermal conductivity to remove and dissipate frictional heat from the surface.

(10) Good wear resistance.

(11) Good corrosion resistance to the action of the lubricant or products which may be developed in the oil by use.

In bearing service three kinds of wear are encountered: (1) abrasion due to foreign particles in the oil film, (2) mechanical wear due to metal-to-metal contact between the bearing surfaces, and (3) corrosion of the bearing surfaces due to oxidation or chemical reaction by active compounds in the lubricant.

Types of Bearing Alloys

In general, bearing metals are of three different types structurally. The largest group of non-ferrous bearing alloys is composed of a soft, plastic matrix in which are embedded hard, wear-resistant particles of a second phase. The matrix is usually a pure metal, a solid solution, or a binary or ternary eutectic. The wear-resistant particles are frequently intermetallic chemical compounds. "Babbitt" metals are of this general structural type.

The second type of structure used in bearing applications is one in which the matrix is sufficiently strong, tough, and wear-resistant to carry the bearing loads. Embedded in this are particles of a softer phase which act as a lubricant in operation. This type of bearing is frequently successful under conditions of doubtful lubrication. Examples are cast iron, in which the graphite flakes act as a lubricant, and copper-lead alloys, in which the insoluble lead globules reduce the coefficient of friction and the tendency to gall and seize. In most of these alloys the soft particles of the lubricating material are lead, cadmium, bismuth or some other metal which smears readily. The thought has been advanced recently, not without justification, that this type of alloy owes its success in bearing applications to the very thin smear of metal over the entire surface of the bearing.[16]

It was formerly believed that all bearing materials required the two-phase structure for successful operation. However, recent work has disproved that theory. Thus, the third type of bearing alloy has a single-phase homogeneous structure. Pure tin, lead, bismuth, silver, and cadmium, or slightly alloyed pure metals (but still maintaining a single phase) have been reported by several investigators[1, 2, 6] to have excellent bearing characteristics up to the limits of their load-carrying capacities. Successful use of pure silver recently in aircraft engine bearings is ample proof that the two-phase structure is not essential.

Although bearing alloys are of three general structural types, recent experimental work on the theory of the action of bearing metals may prove that all three resist friction by the same fundamental mechanism. It has been stated[21] that the hard particles in the two-phase alloys of the first structural type play no part in the basic friction and wear properties. Experiments on tin-base babbitts and special alloys of the same structure and composition as the matrix in the tin-base babbitts showed no fundamental differences in their wear properties. Thus the frictional behavior seems to be determined by the single-phase matrix only. The third structural type of bearing alloy is, of course, a single-phase, homogeneous alloy. Experiments on alloys of the second structural type[16] revealed that the frictional properties of these alloys were similar to those of the single-phase soft, smearable metal alone. Thus, as previously stated, the frictional behavior of the second structural type appears to be governed by a thin smear of the soft second phase over the entire surface of the bearing.

In general, this new approach to the fundamental theory of the action of bearing metals directly contradicts the earlier idea that a duplex structure was necessary for successful bearing alloys. Further work along the lines of this new concept of the theory of bearing metals will be of great interest to the engineer and the metallurgist.

Babbitt Metals

The name "babbitt" metal is derived from the name of its inventor Isaac Babbitt, who in 1839 first developed the tin-base alloy containing antimony and copper. Originally, the name "babbitt" was used for this alloy only. However, more recently, it has been applied to all white-metal bearing alloys. Today there are babbitts of various base compositions: lead, tin, cadmium and zinc are all used as bases for the alloys commonly misnamed "babbitt metals."

These alloys are of the first structural type as previously mentioned. They are characterized by a soft matrix in which are embedded hard particles of a second phase. In this type of alloy there is a certain optimum particle size for the hard constituent. With too small a particle size the matrix is strengthened sufficiently so that it cannot deform plastically and carry the bearing load. Extremely large particles tend to score the shaft; the matrix is too soft for proper load-carrying and the bearing will not wear well. In general they are relatively soft materials, have excellent anti-seize characteristics and can be used at high sliding speeds. To improve their load-carrying capacity they must be supported by a bearing shell made of a stronger material such as steel, or, in some cases bronze.

Lead-Base Babbitts. Lead-base babbitts are widely used in applications where loads are light to moderate and speeds are low. Since their melting points are relatively low, they are limited to applications where loads and speeds will not generate excessive temperatures in service.

Two types of lead-base alloys are in common use for bearings. The first

Table 61. *Composition and Physical Properties of White-Metal Bearing Alloys (Lead-Base Babbitts)* *

Alloy grade	Specified composition of alloys				Sp. gr.	Compositions of alloys tested				Compressive yield strength (psi)		Johnson's apparent elastic limit (psi)		Compressive ultimate strength (psi)		Brinell hardness		M.P. (° F.)	Temperature of complete liquefaction (° F.)	Proper pouring temperature (° F)
	Cu %	Sn %	Sb %	Pb %		Cu %	Sn %	Sb %	Pb %	68° F.	212° F.	68° F.	212° F.	68° F.	212° F.	68° F.	212° F.			
No. 6	1.5	20.0	15.0	63.5	9.33	1.5	19.8	14.6	63.7	3,800	2,050	3,550	1,800	14,550	8,050	21.0	10.5	358	531	655
No. 7	—	10.0	15.0	75.0	9.73	0.11	10.0	14.5	75.0	3,550	1,600	2,500	1,350	15,650	6,150	22.5	10.5	464	514	640
No. 8	—	5.0	15.0	80.0	10.04	0.14	5.2	14.9	79.4	3,400	1,750	2,650	1,200	15,600	6,150	20.0	9.5	459	522	645
No. 9	—	5.0	10.0	85.0	10.24	0.06	5.0	9.9	84.6	3,400	1,550	2,400	950	14,700	5,850	19.0	8.5	459	493	620
No. 10	—	2.0	15.0	83.0	10.07	0.12	2.05	15.7	82.0	3,350	1,850	2,250	1,200	15,450	5,750	17.5	9.0	468	507	630
No. 11	—	—	15.0	85.0	10.28	0.19	0.09	14.8	84.7	3,050	1,400	2,750	1,100	12,800	5,100	15.0	7.0	471	504	630
No. 12	—	—	10.0	90.0	10.67	0.12	0.11	9.9	89.4	2,800	1,250	2,250	950	12,900	5,100	14.5	6.5	473	498	625
No. 15	—	1	15	bal.	10.05	0.5	1.0	15.0	82.5	—	—	—	—	—	—	—	—	479	538	662
No. 16	—	10	12.5	bal.	9.88	0.5	10.0	12.5	77.0	—	—	—	—	—	—	—	—	471	495	620
No. 19	—	5	9	bal.	10.50	—	5.0	9.0	86.0	—	—	—	—	15,600	6,100	17.7	8.0	462	495	620

* From A.S.T.M. Standard Specifications for White-Metal Bearing Alloys.

and most widely used consists of a lead-antimony or lead-antimony-tin alloy, with copper or arsenic frequently added as a hardener or to prevent segregation during casting. Typical lead-base babbitts are numbered 6 to 12 in Table 61. The second type usually contains about 98 per cent lead, with calcium and other alkaline or alkaline-earth metals added. Composition of such alloys is given in Table 62.

TABLE 62. *Alkaline-Earth Lead-Base Alloys*

Alloy	Composition						
	Pb	Ca	Ni	Ti	K	Sn	Al
"Bahnmetall"	98.6	0.7	0.6	.04	.03	—	0.2 max.
"Satco"	97.4	0.15	—	—	.07	2.4	——

The lead-antimony alloys are generally soft and weak, and are suitable only for very light loads and low speeds. They contain up to 18 per cent antimony which acts as a hardener for the lead. Their microstructure usually consists of primary grains of the soft, lead-rich solid solution (99.75 Pb, 0.25 Sb) surrounded by the harder eutectic containing 12.5 per cent antimony and 87.5 per cent lead. Alloys having more than 12.5 per cent of antimony will show primary grains of antimony surrounded by the lead-antimony eutectic.

As tin is added to the lead-antimony alloys, a third constituent, the SbSn intermetallic compound, appears in the microstructure. With increasing proportions of tin up to a maximum of about 20 per cent, the proportion of intermetallic compound increases. In these alloys, the ground mass is the ternary eutectic containing 84 per cent lead, 4 per cent tin and 12 per cent antimony, which melts at 358° F.

Lead-tin-antimony babbitts are stronger and more suitable for higher speeds, higher loads and higher operating temperatures than the lead-antimony alloys. They are cheap, easy to cast, have good frictional properties and reasonably good corrosion resistance, and are successfully used for railway application and heavy machinery generally where speeds and stresses are moderate. Because of the low melting point of the ternary eutectic, they are limited to low-temperature service. Under more severe service conditions, the tin-base babbitts are more frequently used.

The second type of lead-base babbitts, containing about 97.5 per cent lead, are precipitation-hardening alloys, commercially known as "Bahnmetall" and "Satco." Intermetallic compounds such as Pb_3Ca and Na_2Pb_5 precipitate out in these alloys to form structures which have given excellent service as bearings, particularly in railway service. They are superior to other lead-base babbitts in that they retain their hardness better at elevated temperatures and resist impact better. However, they are less corrosion-resistant, must be poured for casting at a higher temperature, and dross easily, making remelting difficult. Their coefficient of expansion, shrinkage and rate of wear are all high. They are used where loads are light to moderate.

A lead-base babbitt containing approximately 12.5 per cent antimony, 3 per cent arsenic and 0.75 per cent tin has recently been marketed.[14] It is claimed that this alloy is superior to conventional lead-base babbitts because the addition of arsenic helps to retain the hardness and strength at elevated temperatures and also imparts higher fatigue strength.

During the past war, the government forbade the use of white metals containing over 12 per cent tin. These were replaced by the emergency alternates shown in Table 63. Unless special permission was granted for use of standard white-metal alloys by the appropriate government agency, the emergency alternate alloys were used. These alloys are all lead-base babbitts to replace tin-base babbitts, which became scarce because of the critical shortages of tin.

Table 63. *Emergency Alternate Bearing Alloys*

Alloy grade*	Tin (%)	Sb (%)	Pb (%)	Cu (%)	Ag (%)	As (%)	Brinell hardness		Pouring temp. (° F.)
							68°	212°	
No. 13	2.0	15	bal.	0.25 max.	2.5	—	—	—	—
No. 14	0.75	12.75	bal.	—	—	1.5–3.0	22	15	689
No. 15	0.9–1.25	14.5–15.5	bal.	0.6 max.	—	0.8–1.1	21	13	—
No. 16	10	12.5	bal.	0.4–0.6	—	—	27.5	13.6	621
No. 17	6	10	bal.	0.25 max.	—	—	20	11	—
No. 18	1.0	17	bal.	0.4–0.6	—	0.8–1.4	29	16	875

* A.S.T.M. Grades.

Tin-Base Babbitts. Tin-base babbitts are essentially alloys of tin, antimony, and copper in varying proportions. The antimony and copper are used as hardening elements. Cadmium or nickel is sometimes added to improve their properties. Zinc and aluminum are to be avoided entirely, and arsenic, bismuth, and iron should be limited in amount. Analyses and properties of the standard A.S.T.M. grades of tin-base babbitts are numbered 1 to 5 in Table 64.

They have low frictional resistance, low wear, good running-in properties, good emergency behavior upon failing lubrication, and lower coefficient of expansion than the lead-base alloys. In general, these alloys are used for more severe service than lead-base babbitts. They are successful where speeds, loads and stresses are moderate to high. Lead-base babbitts lose strength rapidly at elevated temperatures, but tin-base alloys do not soften so much. These alloys are more expensive than lead-base babbitts and must be cast at a higher temperature. However, for such severe appli-

TABLE 64. *Composition and Physical Properties of White-Metal Bearing Alloys (Tin-Base Babbitts)**

Alloy grade	Specified composition of alloys				Sp. gr.	Compositions of alloys tested				Compressive yield strength (psi)		Johnson's apparent elastic limit (psi)		Compressive ultimate strength (psi)		Brinell hardness		M.P. (° F.)	Temperature of complete liquefaction (° F.)	Proper pouring temperature (° F.)
	Cu %	Sn %	Sb %	Pb %		Cu %	Sn %	Sb %	Pb %	68° F.	212° F.	68° F.	212° F.	68° F.	212° F.	68° F.	212° F.			
No. 1	4.5	91.0	4.5	—	7.34	4.56	90.9	4.52	none	4,400	2,650	2,450	1,050	12,850	6,950	17.0	8.0	433	—	825
No. 2	3.5	89.0	7.5	—	7.39	3.1	89.2	7.4	0.03	6,100	3,000	3,350	1,100	14,900	8,700	24.5	12.0	466	669	795
No. 3	8.33	83.33	8.33	—	7.46	8.3	83.4	8.2	0.03	6,600	3,150	5,350	1,300	17,600	9,900	27.0	14.5	464	792	915
No. 4	3.0	75.0	12.0	10.0	7.52	3.0	75.0	11.6	10.2	5,550	2,150	3,200	1,550	16,150	6,900	24.5	12.0	363	583	710
No. 5	2.0	65.0	15.0	18.0	7.75	2.0	65.5	14.1	18.2	5,050	2,150	3,750	1,500	15,050	6,750	22.5	10.0	358	565	690

* From A.S.T.M. Standard Specifications for White-Metal Bearing Alloys.

cations as automotive and aircraft connecting-rod bearings, tin-base-babbitts have been successfully used for many years.

Typically, the microstructure of tin-base babbitts contains needles of CuSn in a matrix of a solid solution of antimony and copper in tin.[10] With antimony above about 8 per cent, cubes of SbSn appear. CuSn needles, freezing first from the melt of the higher-antimony alloys, tend to prevent segregation of SbSn crystals, which freeze at a lower temperature. Zinc is detrimental in that it causes the cubes of SbSn to coalesce and form star-shaped groups. Aluminum causes the cubes to disappear entirely. Bismuth is objectionable in these alloys because it forms a eutectic with tin which melts at about 260° F., making the alloy unsuitable for use at high temperatures.

Addition of cadmium to the tin-base babbitts up to about 3 per cent appears to increase the endurance limit, hardness and strength at elevated temperatures. In high-tin alloys, lead is limited to 0.035 per cent maximum to prevent formation of a lead-tin eutectic which melts at about 360° F., making the bearings fragile above this temperature. Lead up to about 30 per cent is sometimes added to decrease the cost of tin-base babbitts for applications of low to moderate severity.

Tin-base babbitts work against soft shafts with little tendency to score. They allow low clearance, which is an aid to effective lubrication; they are high in embedability and conformability, and bond reasonably well to bronze and steel backings. Their only drawback is the low melting point of tin and the rapid decrease in strength as the melting point is approached.

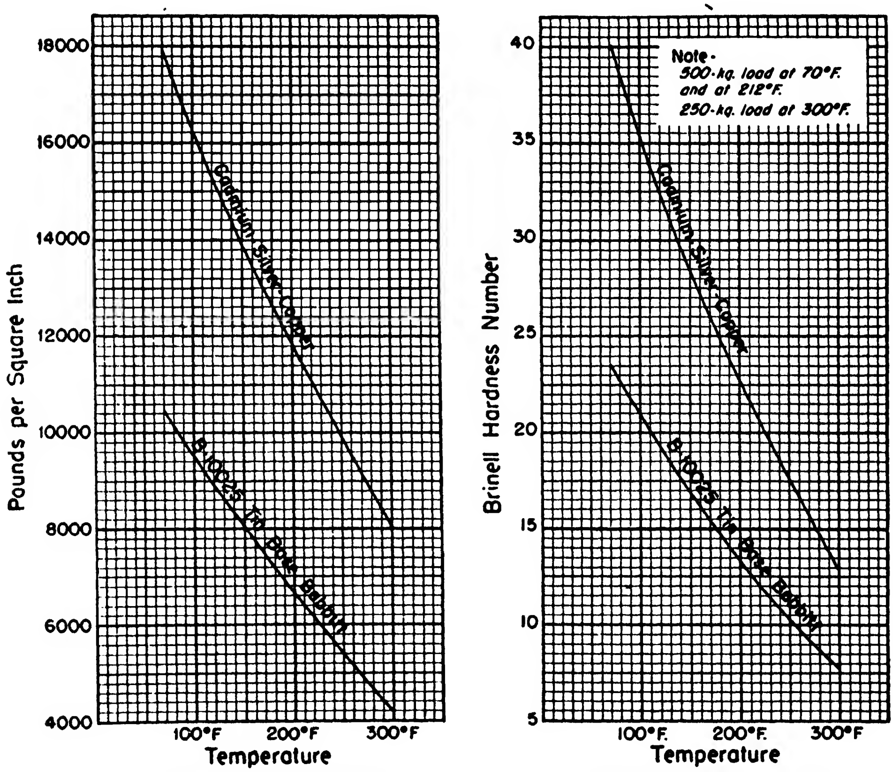
Cadmium-Base Babbits. For extreme conditions of stress and temperature, such as are met in modern aircraft engines, cadmium-base babbitts, containing 97 to 99 per cent cadmium and the balance nickel, silver or copper, have recently come into wide use.[8] They are superior to tin-base babbitts in strength and high-temperature resistance, and to the leaded bronze types in that they do not score shafts easily. Their cost is high, however, and some difficulty is encountered in bonding the babbitt to a steel backing. They are more subject to corrosion than ordinary white-metal babbitts in organic acids developed in lubricating oils during service. They are used with shafts having a minimum hardness of 250 Brinell.

The most commonly used cadmium-base babbitts contain nickel up to 3 per cent, the balance being cadmium.[11] The low-nickel alloys (under 0.25 per cent nickel) consist of a matrix of cadmium containing crystals of the compound $NiCd_7$. Nickel strengthens and hardens these alloys. With nickel above about 0.25 per cent the structure consists of $NiCd_7$ crystals in a matrix of the cadmium-$NiCd_7$ eutectic.

The cadmium-silver-copper type babbitt[4] consists of a matrix of the cadmium-rich cadmium-silver solution surrounded by the relatively hard eutectic mixture of $CuCd_3$ crystals and the cadmium-silver solid solution.

One of the objections to the cadmium-base babbitts has been their lack of resistance to corrosion in lubricating oils. Recently, these bearings have been indium-plated[7] and the indium diffused into the lining by heating for two hours at about 340° F. This treatment markedly reduced the corrosion of a silver-copper-cadmium babbitt.

Figure 48 is a chart showing how strength and hardness of tin-base babbitt and cadmium-silver-copper are reduced as temperature increases.



Tensile Strength

Brinell Hardness

Figure 48. Charts showing strength and hardness versus temperature.

Zinc-Base Babbitts. An alloy consisting of 85 per cent zinc, 10 per cent copper and 5 per cent aluminum has been successfully used as a bearing where loading is steady and no shocks are encountered in service at high speeds. It has a low coefficient of friction, but the alloy has a tendency to become brittle under the effects of heat, and requires a great deal of attention. In general, the zinc-base alloys are very hard, approximately 120

Brinell, and also very brittle. Zinc and zinc-rich solid solutions are likely to seize at elevated temperatures, a characteristic which restricts their use. They have limited service as bushings in applications where bronze bushings have been used.

Copper-Lead Bearing Alloys

For very severe service where babbitts will not withstand the conditions, copper alloys containing up to about 35 per cent lead are frequently used. Since lead is insoluble in copper, the lead is distributed throughout the matrix as pools or globules, which are easily distinguished in a microscope. The alloys are very difficult to produce free from segregation; they require additional clearance and also hard shafts and uninterrupted lubrication. At high operating temperatures, however, they will withstand much higher loading than the best white-metal bearings[14]—to the extent of 75 per cent higher above 150° F. The 30 to 35 per cent leaded copper alloys have excellent bearing properties, but the strength is low and the alloys are subject to failure by fatigue cracking.

The higher the lead content of the copper-lead alloys, the lower is their fatigue strength and the higher their anti-frictional characteristics. Silver and tin can be substituted for part of the copper for the purpose of increasing fatigue strength, but only at the sacrifice of anti-frictional properties.

To prevent seizing, a thin coating of lead is sometimes plated over these bearing materials. Corrosion is a major problem, as these alloys are easily corroded by improper oils. Electroplating and diffusion of indium on the surface increases their resistance to corrosion.

Typical copper-lead alloys are SAE 48 and SAE 480, of which the following are the specific analyses (Table 65).

TABLE 65. *Copper-Lead Alloys*

Composition (%)	S.A.E. 48	S.A.E. 480
Copper	67–74	60–70
Lead	25–32	30–40
Silver, max.	1.5	—
Zinc, max.	0.1	—
Phosphorus, max.	0.025	—
Iron, max.	0.35	0.35
Tin	—	0.05

Very approximate limits[26] for the properties of sand-cast bearings of these materials are given in Table 66.

TABLE 66. *Sand-Cast Properties*

Lead (%)	30	40	50
Tensile strength (psi)	8,000–9,000	7,500–8,500	6,000–7,000
% Elongation (2″)	6–8	6–8	5–7
Compressive strength (psi)	3,000	2,500	2,000
Brinell hardness	22.5–32.5	20–30	15–25

Figure 49 shows a number of steel-backed copper-lead-lined bearings, and also several different types of copper-lead bearings.

The alloys of copper and lead find extensive use in the automotive and aircraft fields and in the field of general engineering. They are used almost as steel-backed bearings, and also to a great extent as bushings, liners and sleeves.

(*Courtesy Johnson Bronze Co., New Castle, Pa.*)

Figure 49. Copper-lead bearings.

Bronzes and Leaded Tin Bronzes

Frequently nickel or silver is added to copper-lead alloys to prevent segregation. Tin is often included to strengthen the matrix, which has little galling resistance by itself. Analyses such as 4 per cent tin, 21 per cent lead, balance copper, or 10 per cent tin, 15 per cent lead, balance copper, are commonly used in heavy-duty aircraft engine bearings.

Recent shortages in tin have spurred research in emergency substitutes for the lead-bearing tin bronzes. An alloy containing 80 per cent copper, 10 per cent lead, 2.5 per cent zinc, and 5 per cent manganese has been recommended[15] as a substitute for 80 per cent copper, 10 per cent lead, 10 per cent tin bearing bronze for severe service conditions.

Two new bearing bronzes containing 8 per cent nickel, 1 per cent antimony, 1 per cent zinc, 10 per cent lead, balance copper, and 8 per cent nickel, 2 per cent tin, 1 per cent antimony, 1 per cent zinc, 10 per cent lead, balance copper, were developed as a substitute for the commonly used 80 per cent copper, 10 per cent tin, 10 per cent lead-bearing alloy. Amsler tests showed that these new bearing alloys had three to four times the wear resistance of the older ones.

Manganese bronzes containing 55 to 60 per cent copper with manganese, aluminum, iron, tin and zinc, and also phosphor bronzes containing 8 to 13 per cent tin, are high-strength casting alloys frequently used for bushings and heavy cast bearings. They operate well against hardened steel shafts at low speeds and heavy loads.

Aluminum bronze is a copper-base alloy containing 8 to 13 per cent aluminum, with iron frequently added as a hardener. The higher aluminum alloys are heat-treatable to high hardness by quenching and tempering. In the heat-treated condition the wear resistance against hard steel is excellent. Aluminum bronze is frequently used for bushings under conditions of doubtful lubrication. Its resistance to pounding is excellent.

Lower aluminum bronzes are used against soft steel shafts with success. These alloys are not heat-treatable, as are the higher aluminum bronzes, but they operate well against soft steel, which would be scored by higher-hardness bronzes. The greater the aluminum content, the better the wear resistance under conditions of poor lubrication.

Phosphor bronze containing about 95 per cent copper, 4.5 per cent tin, and 0.05 to 0.5 per cent phosphorus is used as a bearing material at low loads and speeds where lubrication is good. In general this bronze is not too satisfactory as a bearing material. Sometimes an addition of 1 per cent lead is made to this bronze to improve its machinability and bearing qualities against hardened steel shafts.

The bearing bronzes[25] are substantially alloys of copper with from 5 to 20 per cent tin and a small percentage of residual phosphorus. These alloys are sometimes referred to as "phosphor bronzes." Zinc is sometimes added instead of phosphorus, in which case from 2 to 6 per cent zinc may be present in the bronze, which is then quite generally referred to as "Gun Bronze," "Composition G Government Bronze," "Admiralty Bronze," or "Zinc Bronze."

Tin bronzes both with and without lead are used in large quantities as bushings. Typical compositions of the leaded bronzes (plastic bronzes) are given in Table 67.

TABLE 67. *Leaded Bronzes*

Composition	S.A.E. 791	S.A.E. 792	S.A.E. 793	S.A.E. 794
Copper	bal.	bal.	83 min.	68.5–75.5
Tin	3.5–4.5	9–11	3.5–4.5	3–4
Lead	3.5–4.5	9–11	7–9	21–25
Zinc	1.5–4.0	0.5 max.	——	——

A large number of these alloys with wide variations in composition are being marketed by different manufacturers. Each has its peculiar characteristics and is recommended for specific bearing applications.

Table 68 shows the typical properties of some copper-base bearing alloys.

TABLE 68. *Physical Properties of Some*

Metal	Composition	Tensile strength (psi)	Yield strength (psi)	Elongation % in 2"
Copper-tin-lead (Cast)	70% copper—20% lead—10% tin	50,000	17,000	16
Copper-tin-lead (S.A.E. 64) (Cast)	80% copper—10% lead—10% tin	39,000	20,000	29
Phosphor bronze (Wrought)	95% copper—4-5% tin—0.05-0.50% phosphorus	60,000	35,000	
Aluminum bronze (Cast)	10% aluminum—1% iron—89% copper	70,000	30,000	25-35
Aluminum bronze (heat-treated)	10% aluminum—1% iron—89% copper	87,000	47,000	9-16
Manganese bronze (Cast)	23% zinc—5% manganese—5% aluminum—3% iron—balance copper	85,000	42,000	15
Aluminum-silicon-bronze (Duronze) (Wrought)	7% aluminum—2% silicon—91% copper	85,000	43,000	20
88-4-4-4 bronze	88% copper—4% tin—4% zinc—4% lead (hard temper)	65,000	59,000	20
Leaded phosphor bronze	94% copper—4-5% tin—1% lead—0.05-0.50 phosphorus	55,000	30,000	15
Sintered bronze ("Compo," "Oilite," etc.)	89% copper—10% tin—1% graphite	15,000-25,000 (Compressive)		

Resistance to pounding	Brinell hardness				Modulus of elasticity (psi)	Coefficient of expansion inches per inch per (° F.)	Remarks
	75° F.	150° F.	250° F.	350° F.			
Fair	59	58	57	52	10×10^6	10.3×10^{-6}	Moderate to high speeds. Good where lubrication is questionable. Subject to porosity. Machines easily. Use hardened journal.
Fair	63	61	58	55	8×10^6	10.3×10^{-6}	One of most widely used bearing bronzes. Good under doubtful lubrication conditions. Heavy loads and severe usage. Pressures up to 8,800 psi at 800–1,000 ft. per minute satisfactory. Use hardened journal.
Good	100				15×10^6	17.8×10^{-6}	For bearings at light loads and low speeds. Difficult to machine. Use only with good lubrication.
Excellent	100–140				15×10^6	9.1×10^{-6}	Corrosion resistant. Retains strength at elevated temperature. Use mild steel shaft.
Excellent	140–225					9.7×10^{-6}	Used for high stresses where lubrication is good. High fatigue strength. Use mild steel shaft.
Excellent	170–195						Used for heavy-duty gears. High strength. Difficult to machine. May be used as a bearing for heavy loads at low speeds.
Excellent	150				14×10^6	9.2×10^{-6}	Good machinability. Use as a bearing with light loads and good lubrication. Used for worm wheels mating with case hardened worms.
Good	147				15×10^6	17.3×10^{-6}	Free-machining bar stock for moderate loads and speeds. Hardened steel journal.
Good	100				15×10^6	17.8×10^{-6}	Low to moderate load at low speeds. Fair machinability. Use with hardened steel journals.
Poor							Bearings of this type are impregnated with oil. Hence they can be used where lubrication is doubtful.

Silver Alloys for Bearings

Numerous investigations[8-19] have disclosed that silver of 99 per cent purity is an excellent bearing material for severe service at high temperatures. It has almost no tendency to gall on steel and has a low dry coefficient of friction against steel. Compared to 28 per cent Pb, 1 per cent Ag, balance Cu, and 25 per cent Pb, 3 per cent Sn, balance Cu alloys, the pure silver bearing showed a higher relative resistance to seizure in laboratory tests than either copper-base alloy. On engine tests these results were corroborated, but it was discovered that the silver was more susceptible to seizure than either bronze alloy if grit was present in the lubricating oil, or if the surface finish of shaft or bearing was poor at the start of the test. These silver bearings rendered excellent service when bearing and shaft were smoothly finished before testing, and when lubricants were kept free from grit.

In general, silver has high heat conductivity, fatigue resistance, resilience, seizure resistance, and ability to hold strength at high temperature; but it also has a high coefficient of expansion, poor oiliness characteristics, and no appreciable embedability.

Recently, pure silver electroplated on a steel backing has been plated with a thin film of lead to improve its galling resistance and then replated with a very thin film of indium. The indium is diffused into the lead by a heat treatment at a temperature of about 350° F. The thin film of lead-indium alloy thus formed on the surface of the silver bearing improves the galling resistance. The indium-lead alloy has higher corrosion resistance than the pure lead film would have. Such composite bearings are used under the severest service conditions in the largest modern aircraft engines.

Aluminum-Base Bearing Alloys

Aluminum-base bearing alloys with excellent bearing characteristics[24] have been marketed and used in service during the past few years.✓Aluminum manganese alloys containing lead and antimony or calcium have been used in Germany to replace white-metal babbitts. An aluminum alloy containing 5 per cent magnesium and 5 per cent zinc with small additions of manganese, silicon and sometimes lead has been used in service. As a substitute for babbitts in automobiles, some European manufacturers used an alloy of aluminum containing up to 20 per cent lead and some antimoney. England used aluminum-base bearing alloys containing 4 to 7 per cent tin, 1.5 to 2.0 nickel, 0.5 to 1.0 per cent magnesium, 0.5 to 1.0 per cent copper, up to 0.6 per cent silicon, balance aluminum, for big-end bearings and connecting-rod bearings. ✓

In the United States one wrought and two cast aluminum alloys have recently been developed for bearing material by the Aluminum Company of America. All have proved very satisfactory in use and in tests at extremely high unit pressures, high speeds and high oil temperatures. The symbols are 750 and XA750 for the cast alloys, and XA80S for the wrought alloy. Alloy 750 with heat treatment T533, and alloy XA750 with heat treatment T7 are commonly furnished as permanent mold castings. Alloy XA80S is available in flat sheets. The properties[22, 23] of these alloys are shown in Table 69.

Alloy 750 contains approximately 6.5 per cent tin, 1 per cent nickel, 1 per cent copper, and balance aluminum. It was found that adding silicon to this aluminum-tin alloy gives effective improvement in resistance to scuffing. As a result, alloy XA750 was developed containing approximately 6.5 per cent tin, 2.5 per cent silicon, 1 per cent copper, 0.5 per cent nickel and balance aluminum. This latter material retains all the superior characteristics of the former alloy, together with a distinct improvement in frictional and anti-seize properties.

TABLE 69. *Typical Properties of Aluminum-Base Alloys*

	Alloy 750		*Alloy XA750*	
Properties	Cast, heat-treated T533	Cast, heat-treated, cold-worked 4¼ % red.	Cast, heat-treated T7	Cast, heat-treated T7, cold-worked 4¼ % red.
Tensile strength (psi)	20,000	22,000	22,000	23,000
Yield strength (psi)	8,500	1,600	9,000	17,500
% Elongation in 2 in.	10	7	10	7
Compressive yield strength (psi)	8,500	1,600	9,000	20,000
Compressive shear strength (psi)	14,000	——	14,500	——
Brinell hardness	35–50	40–55	45	50

	Alloy XA80S		
Properties	Annealed	3 % Reduction	20 % Reduction
Tensile strength (psi)	21,000	21,000	25,000
Yield strength in tension (psi)	8,000	15,000	23,000
% Elongation in 2 in.	25	15	6
Rockwell hardness, H scale	75	80	95
Specific gravity	2.83	2.83	2.83

Light bearing alloys have excellent cold-working properties, high capacity for oil absorption, and good heat conductivity. Aluminum has three to four times the heat conductivity of steel and five times that of ordinary babbitt. Further, aluminum bearings do not have bonding planes which may act as barriers to heat transfer. The very rapid dissemination of heat in aluminum allows dissipation of local thermal rises before damage can be done. The uniform structure of aluminum bearings is a great advantage when considering fatigue resistance, and is superior to that of the babbitts or the copper-lead alloys because the bond is the usual point of fatigue failure. For certain applications, aluminum bearing alloys can run successfully on soft-steel shafts. However, for extreme speeds and loads it is best to use a hardened steel shaft of 300 Brinell or higher.

It is generally claimed that aluminum-base alloys have 1½ times the fatigue resistance of the copper-lead alloys and about six times the fatigue resistance of the tin-base babbitts. Its embedability is about the same as that of the copper-lead alloys, and a half to a third that of the lead-base and tin-base alloys. Nevertheless, aluminum-base alloys are plastic enough to conform to any ordinary misalignment and to allow for good embedability of dust particles which may be a source of scoring. Their corrosion resistance is equal to that of the lead- and tin-base babbitts and much higher than the copper-lead alloys. Their resistance to scoring is about equal to that of the tin- and lead-base alloys, if not inferior; it is about the same as that of silver bearings, but about double that of copper-lead alloys and almost triple that of the cadmium-silver alloys.

Among the advantages claimed for aluminum bearing alloys are:

(Courtesy Aluminum Co. of America, Pittsburgh, Pa.)

Figure 50. Typical aluminum bearings of Alcoa 750 alloy.

(1) long bearing life; (2) high fatigue strength; (3) high resistance to corrosion; (4) high thermal conductivity; (5) ability to withstand high bearing pressures; (6) good conformability and embedability, and (7) simplicity and economy in fabrication. ✓

Figure 50 shows several typical aluminum alloy bearings. Figure 51 shows the results of the rod machine test and adapter sleeve test on aluminum bearing alloys.

Rod Machine Test

Cast X750–T533 Alloy Reduced Width (0.75″)

Test Bearing Inserts

6 hours at 2150 rpm–1800 psi
6 hours at 2500 rpm–2440 psi
10 hours at 3000 rpm–3520 psi
200 hours at 3200 rpm–4000 psi

Adapter Sleeve Test

American Locomotive Company crankshaft steel (Brinell hardness 140) used. Ground finish. Photograph shows high load side. Average wear in 222 hours: L.H. 0.0004″; R.H. 0.00055″.

(Courtesy Aluminum Co. of America, Pittsburgh, Pa.)

Figure 51. Aluminum bearings after test.

Powder Metal Bearings

A recent development in bearings has been the use of sintered alloys of about 88 per cent copper, 10 per cent tin with about 2 per cent graphite. These bearings are porous; the pores are impregnated with oil, which acts as a reservoir of lubricant for the bearings under conditions of poor lubrication. "Compo," "Oilite," and "Durex" bronze bearings are of this general type. Another type of powder metal bearing alloy is typified by "Durex" iron. This sintered product contains about 1 per cent carbon in iron. Its physical properties are higher than those of the copper-base sintered bearings, and these bearings can be used at PV values up to 75,000 compared to PV values of 50,000 for sintered bronze.

The development of powder metal bearings has opened new fields of bearing design as well as new techniques of high production. Figure 52 is a photograph of a number of different designs of "Compo" Bronze oilless bearings.

(Courtesy Bound Brook Oil-less Bearing Co., Bound Brook, N. J.)

Figure 52. "Compo" bronze oilless bearings.

Nonmetallic Bearings

For some specialized applications, nonmetallics such as fabric-synthetic resin "Micarta," "Ryertex," or oil-impregnated wood have been used satisfactorily. These materials operate satisfactorily at low speeds and pressures. Water-lubricated rubber operating with hardened "K-Monel" shafts makes excellent bearings for such heavy equipment as rolling mills, ship propeller shafts, etc.

Anti-Friction Bearings

Where service requirements are extremely severe or a shaft is subjected to frequent starting and stopping, it is necessary to use anti-friction [18] bearings of the ball, roller, or needle type. These bearings are relatively expensive and hence should be used only where absolutely necessary.

The principal advantages of anti-friction bearings are: (1) reduced friction and wear; (2) increased accuracy; (3) low maintenance cost; (4) high loading possibility; (5) very high speeds; and (6) accurate interchangeability. In this type of bearing, the load is not supported by a continuous oil film but by metal-to-metal contact in the bearing itself. Thus, it is the best possible bearing to use in cases of poor lubrication.

Since anti-friction bearings fail in fatigue rather than by galling or wear, as do babbitts or bronze bearings, high-strength steels are used in them. Most frequently, balls and races for these bearings are made of SAE–52100 steel, a 1.5 per cent chromium—1 per cent carbon steel, heat-treated to 60/62 Rockwell C. Wear resistance of this steel is excellent. Also, carburized alloy steels such as AISI–4620 and AISI–8720 are used for balls and races.

For extreme corrosion resistance in ball bearings SAE–518100 steel is used for balls and races. This is the 18 per cent chromium—1 per cent carbon grade and it is hardened to 56/60 Rockwell C. It is slightly softer than the SAE–52100 grade, but is satisfactory for the application.

For certain nonmagnetic applications, such as in aircraft compasses, special ball bearings and races of "K–Monel" or beryllium-copper have been developed.[18]

Selection of a Bearing Material

Bearings are used in various types of machinery, under conditions so widely different that the properties required of a bearing material cover a very broad range. A good bearing alloy must be selected on the basis of a specific application. This selection requires knowledge of the physical, mechanical, and metallurgical properties and characteristics of the material, the character of the installation, and the service conditions. Some of the more important factors in appraising a specific bearing application are: (1) type of load; (2) magnitude of shaft load; (3) speed; (4) bearing temperatures; (5) corrosive conditions; (6) lubrication and type of oil supply; (7) dirt conditions; and (8) shaft hardness.

As a further aid in selecting the proper bearing material, Table 70 shows the relationship of the four functional properties of bearing materials.[19] Comparisons are made against copper-lead alloys, which are given a merit rating of 10.

TABLE 70. *Comparison of Functional Properties of Bearing Materials*
(Copper-lead base characteristics Equals 10)

Material	Fatigue resistance	Score resistance	Embedability	Corrosion resistance
Copper-lead	10	10	10	10
Silver	30	20	5	30
Cadmium-silver	7	8	16	20
Lead-base babbitt	4	20	25	30
Tin-base babbitt	2	20	22	30
Aluminum-base alloy	15	20	12	30

The Aluminum Company of America[26] has published the operating characteristics of various bearing alloys. This tabulation, covering a tin-base babbitt, a lead-base babbitt, a cadmium-base alloy, a copper-lead alloy and an aluminum-base alloy, has unusual value to the design engineer in selecting the proper bearing material. These comparative data are given in Table 71.

TABLE 71. *Operating Characteristics of Some Bearing Metals*

Metal	Maximum permissible unit pressure (psi)	Minimum permissible ZN/P	Maximum permissible PV	Maximum oil temperature (°F)	Minimum journal hardness
Tin-base Babbitt 3.5 Copper 7.5 Antimony 89.0 Tin 0.25 max. Lead	1,000	20	35,000	235	Not important
Lead-base Babbitt 5–7 Tin 9–11 Antimony 82–86 Lead 0.25 max. Copper	1,800	10	40,000	225	Not important
Cadmium-base Alloy 0.75 Silver 0.5 Copper 98.75 Cadmium	1,800–3,850	3.75	90,000	260	250 Brinell
Copper-lead Alloy 65 Copper 35 Lead	over 1,800	3.75	90,000	260	300 Brinell
Aluminum-base Alloy Alcoa 750–T533	4,000	3.50	150,000	275	300 Brinell

References

1. Goodman, J., "White Metals for Engineering Purposes," *Engineering*, **129** (1930).
2. Boegehold, A., "Development of Automotive Materials," A.S.T.M. Symposium, 1930.
3. Schwartz, C., and Phillips, A., "Comparison of Certain White-metal Bearing Alloys, Particularly at Elevated Temperatures," *Proc. A.S.T.M.*, 33, Part II (1933).
4. Denham, A., "New Cadmium-Silver-Copper Bearing Alloys," *Automotive Industries* (November, 1934)
5. Harder, O., and Cole, C., "Study of Six Bearing Bronzes," *Trans. AFA* (April, 1933).
6. Underwood, A., "Automotive Bearings: Effect of Design and Composition on Lubrication," A.S.T.M. Symposium on Lubrication, 1937.
7. Smart, C., "Indium-Treated Bearing Metals," *Trans. A.I.M.E.*, **128** (1938).
8. Dayton, R., "Possibilities of Silver-Rich Alloys as Bearing Materials," *Metals and Alloys* (December, 1938).

9. Tichivinsky and Fisher, "Boundry Frictions in Bearings at Low Loads," *J. App. Mech.* (September, 1939).
10. Ellis, O., "Constitution of the Tin-Antimony-Copper Alloys as Bearing Metals," "Metals Handbook," 1939.
11. Swartz, C., "Properties of the Cadmium-Nickel Alloys," "Metals Handbook," 1939.
12. Anon., "Aluminum Alloy Bearings," *Metals and Alloys* (December, 1940).
13. Hewitt, C., "Today's Ball Bearing Metallurgy," *Steel* (July, 1940).
14. Phillips, A., and Smith, A., "Properties of Certain Lead-Bearing Alloys," *Proc. A.S.T.M.*, 41 (1941).
15. Dayton, R., and Gillett, H., "Substitutes for Leaded Bearing Bronze," *Metals and Alloys* (December, 1942).
16. Bowden and Tabor, "Lubricating Effect of Thin Metallic Films," Australia Council Sci. Ind. Bull. #155, 1942.
17. Schwartz, "Zinc Bearing Alloys," *Metall. v. Erz.*, 41 (1944).
18. Deck, "Aluminum Bearings," *Tech. Rundschau* (October, 1944).
19. Etchells, "Silver Bearings," *S.A.E. Journal* (May, 1945).
20. Eash, J., "Nickel-Antimony-Lead-Copper Bearing Alloys," *Trans. A.I.M.E.*, (1945).
21. Tabor, "Frictional Properties of Some White Bearing Alloys," *J. App. Phys.* (1945).
22. Hunsicker and Kempf, "Aluminum Alloys for Bearings," *S.A.E. Journal* (June, 1946).
23. Wood, "Important Engineering Data on Aluminum Bearings for Engines," *Automotive and Aviation Industries* (June, 1946).
24. Woldman, N., "Selecting Nonferrous Bearing Materials," *Iron Age* (September 5 and September 12, 1946).
25. Anon., "Bearing Materials," A.S.M. Subcommittee reports. (See Metals Handbook, 1948.)
26. Aluminum Company of America publications.

Chapter IX

Threaded Fasteners*

Screw threads may be divided into two classes according to their uses: (1) those used for fastenings, and (2) those used for communicating motion. The term "fastenings" is applied to any device used to hold two or more pieces together, either rigidly or by constraining any relative motion between them.

Screw fastenings may be subdivided into (1) bolts, (2) studs, (3) machine screws, (4) cap screws or tap bolts, and (5) set screws.

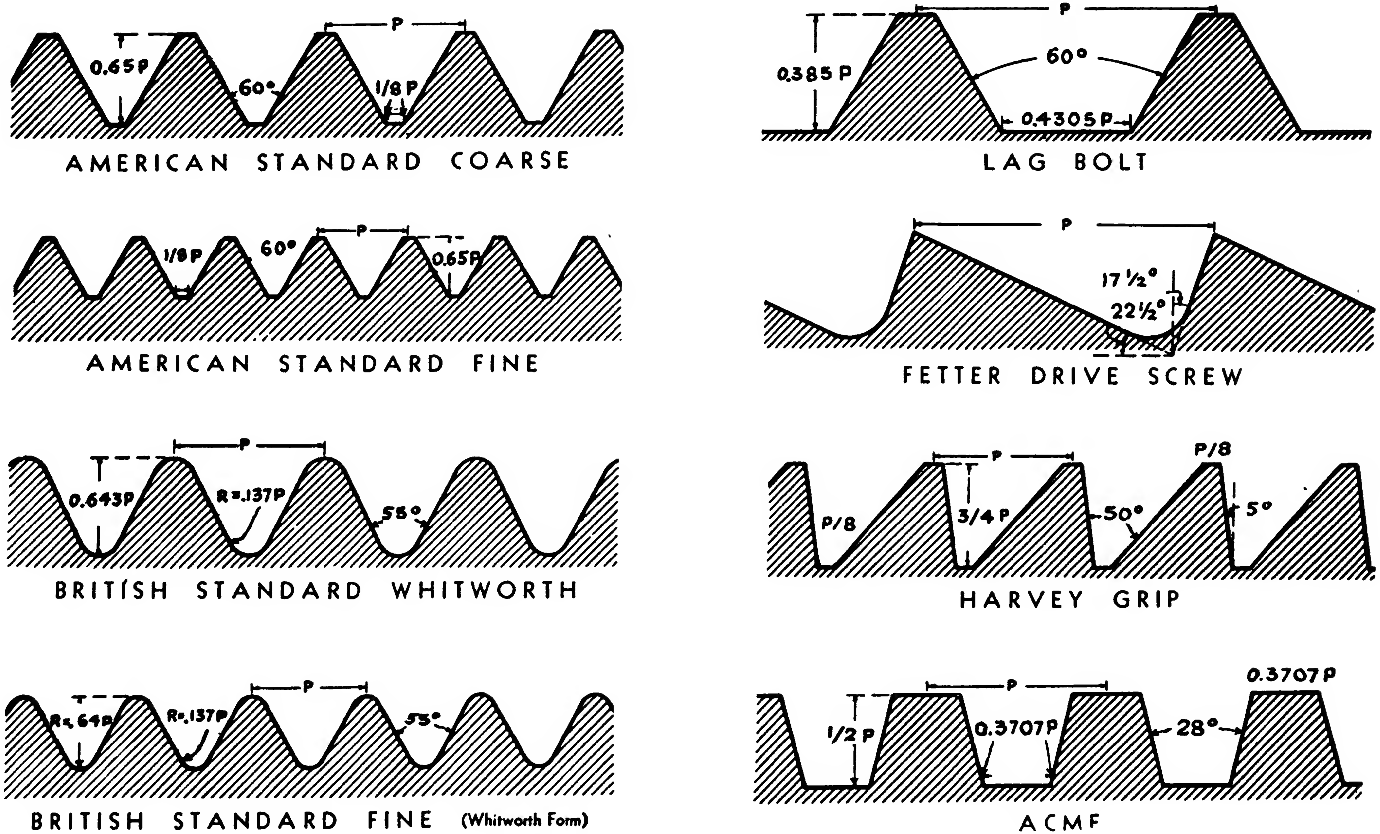
The form of thread depends on the services required and on the engineering standards of the country in which the thread is used. In general the V thread or the modified V thread are best adapted for fastenings. These combine strength and cheapness.

Classification

In Figure 53 are shown the forms of threads used for fastening. The American and British standards are used in most cases. The other forms of threads are used in special applications. In the V thread the sides make an angle of 60 degrees with each other, the top and root of the thread being sharp. The U. S. (American) Standard thread is the same as the V thread with the top cut off and the root filled in. The amount taken from the top and added to the root is one-eighth of the height of the V thread, thus making the U. S. Standard thread three-fourths the depth of the V thread. It is considered superior to the V thread in that it does not cut so deep into the stock, thus leaving a stronger root. In the Whitworth or British standard thread the tops of the threads are rounded off and the roots filled in. The angle of the sides with each other is 55 degrees, and the amount taken from the top and added to the root is one-sixth of the height of the V thread. With few exceptions all threaded fastenings use the U. S. Standard form of thread. The V thread is little used today, except for special purposes.

---

* The declaration of accord for the international unification of screw threads was adopted during the period this manuscript was in the process of printing. There is therefore appended at the end of this chapter a digest of the new unified screw thread system.



AMERICAN STANDARD COARSE

AMERICAN STANDARD FINE

BRITISH STANDARD WHITWORTH

BRITISH STANDARD FINE (Whitworth Form)

LAG BOLT

FETTER DRIVE SCREW

HARVEY GRIP

ACMF

Figure 53. Types of screw threads.

Figure 54 shows the three forms of machine bolts that are most used. The square head and nut bolt as shown at (a) is the one most generally employed. The hexagon head and nut bolt as shown at (b) is substituted for the square when the nut comes in a place difficult to get to with a wrench. The snap or round head machine bolt as shown at (c) differs from the others only in the form of its head.

When the character of the assembly is such that one of the parts that are being secured together can be tapped, a stud bolt or cap screw may be used. In Figure 55 are shown two standard studs at (a) both threaded ends are of equal length, while at (b) one threaded end is shorter than the other. The short thread is usually made slightly larger than the long one, as it is intended to fit closely the tapped hole in the work. The stud, when set, extends above the surface an amount sufficient to receive the work and a nut on the outside.

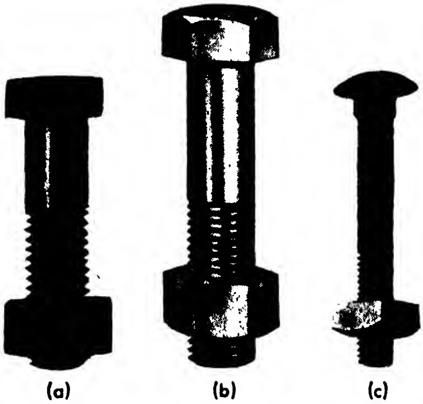

(a) (b) (c)

Figure 54. Machine bolts.


(a) (b)

Figure 55. Studs.


Figure 56. Cap screw.

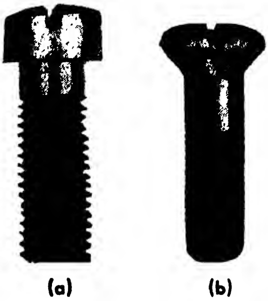

(a) (b)

Figure 57. Slotted cap screws.

Cap screws are similar to coupling bolts without nuts. However, square-head cap screws are not used much at present. Figure 56 shows a typical hexagonal head cap screw, Figure 57 two cap screws with slotted heads for a screw driver; at (a) is the fillister type head while at (b) is the standard flat head type.

Thread pitches conform to the American National Standard, which is divided into coarse thread and fine thread series as given in Table 72.

TABLE 72. *Table of American National Threads*

Size	Threads per inch, coarse thread series	Threads per inch, fine thread series
5	40	x
6	32	x
8	32	36
10	24	32
12	24	28
1/4	20	28
5/16	18	24
3/8	16	24
7/16	14	20
1/2	13	20
9/16	12	18
5/8	11	18
3/4	10	16
7/8	9	14
1	8	14
1 1/8	7	12
1 1/4	7	12
1 1/2	6	12
1 3/4	5	x
2	4 1/2	x

Screw-Thread Terminology

Four dimensions are important to the proper understanding of screw threads. They are the major diameter, the minor diameter, the pitch diameter and the pitch.

Major diameter is the largest diameter of a screw thread. This term replaces "outside diameter" as applied to the thread of a power screw, and also "full diameter" as applied to the thread of a nut.

Minor diameter is the smallest diameter of a screw thread. This replaces such terms as "root diameter" as applied to the thread of a power screw, and also "inside diameter" as applied to the thread of a nut.

Pitch diameter is the diameter of an imaginary cylinder whose surface would pass through the threads at such points as to make equal the width of the threads and the width of the spaces cut by the surface of the cylinder. The pitch diameter is equal to one-half the sum of the major diameter and the minor diameter.

Pitch is the distance from a point on a screw thread to a corresponding point on the next thread, measured parallel to the axis.

$$\text{Pitch in inches} = \frac{1}{\text{Number of threads per inch}}$$

Lead is the distance a screw thread advances axially in one turn.

Angle of thread is the angle included between the sides of the thread, measured in an axial plane.

Helix angle is the angle made by the helix of the thread, at the pitch diameter, with a plane perpendicular to the axis.

Crest is the top surface joining the two sides of a thread.

Root is the bottom surface joining the sides of two adjacent threads.

Depth of thread is the distance between crest and root measured normal to axis.

Depth of engagement is the depth of thread contact of two mating parts, measured radially.

Length of engagement is the length of contact between two mating parts, measured axially.

Figure 58 is a diagrammatic sketch of the screw and nut threads showing the location of the important dimensions.

Screw Thread Fits

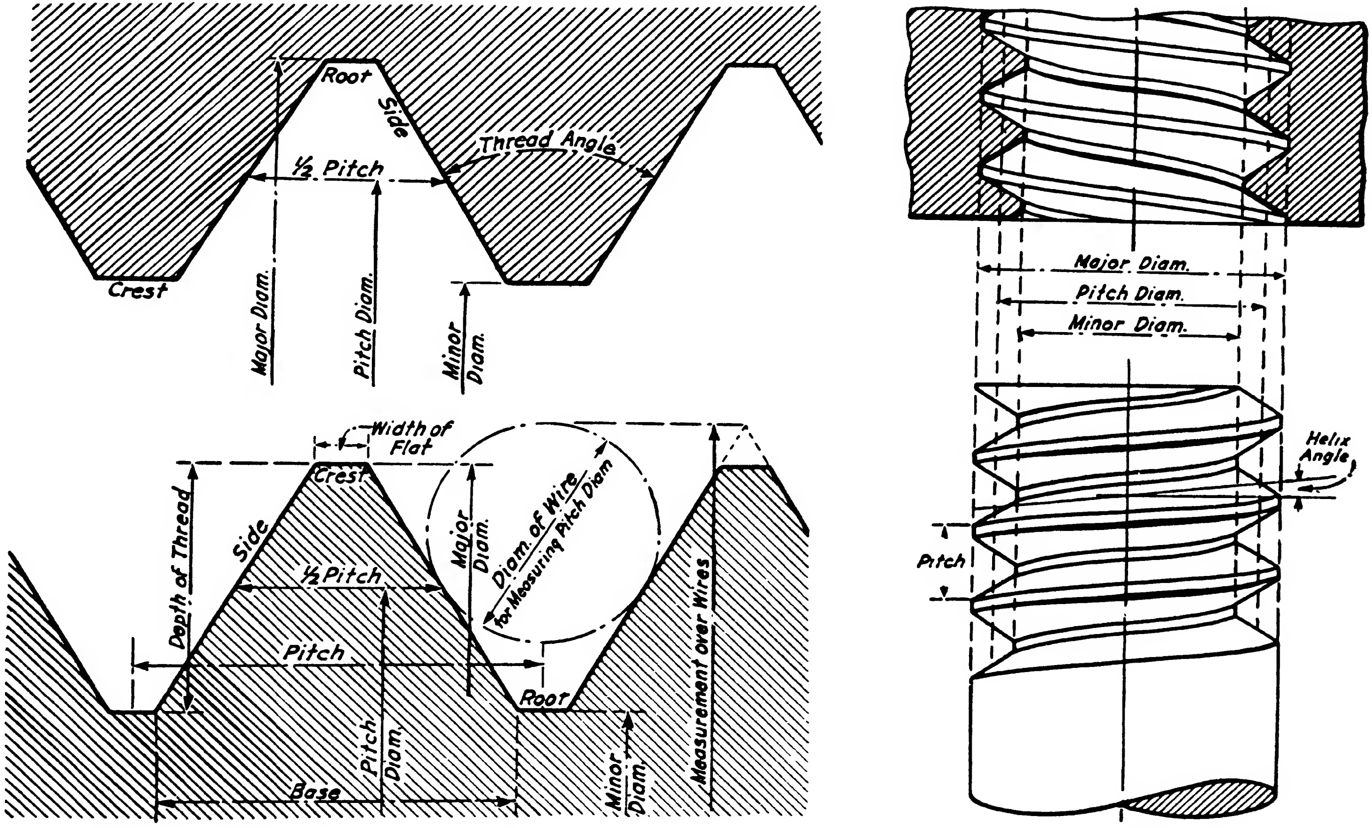
There are three classes of screw thread fits, ranging from Class 1, the loosest, to Class 3, the closest. They are produced by the application of specific tolerances, or tolerances together with allowances. *Allowance* is an intentional difference in the dimensions of mating parts; it is the minimum clearance or the maximum interference between mating parts. *Tolerance* is the amount of variation permitted in the size of the part, that is, it is the difference between the maximum and minimum dimensions given. Class 4 thread tolerance has been used to some extent in the past, but it is now becoming obsolete.

In the manufacture of industrial fasteners tolerances in thousandths of an inch are common practice. Such precision makes possible complete interchangeability of parts and accuracy of fits.

Machine screws and tapped holes are produced within tolerance to allow ease of assembly and interchangeability. Such screws are easily applied with the fingers and naturally have shake or side play.

Fabrication of Threads

Threads are commonly cut, ground, or rolled. Cutting threads and grinding threads are essentially the same operation in that material is removed from the shank of the bolt or stud in forming the thread. In rolling, the



Screw

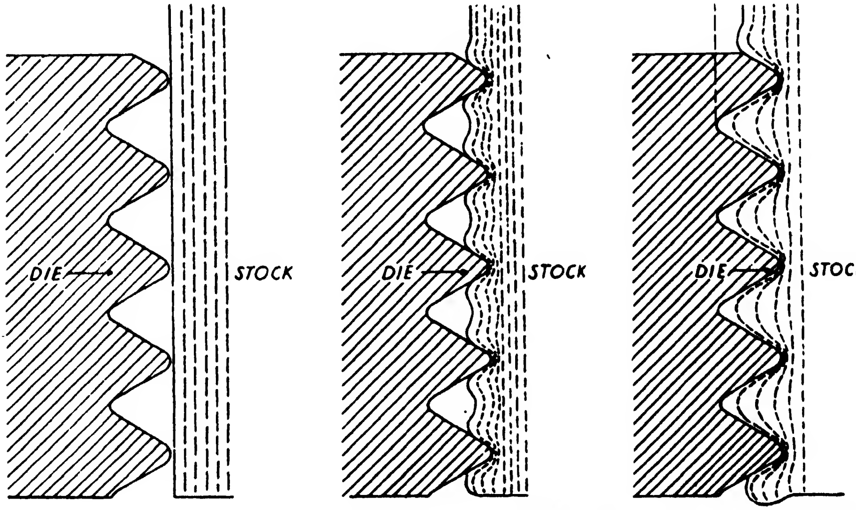
Screw

Figure 58. Screw-thread terminology.

threads are built up by the rolls from the material in the shank so that no material is lost. This economy of material is one of the features of the rolled thread operation.

The blank for threading may be cut from bar stock or upset-headed. When threads are to be cut, the shank is equal in diameter to the outside or nominal diameter of the thread. In roll threading, the section of the shank to be threaded must be reduced in diameter by approximately half the difference between the nominal diameter and the root diameter of the thread; otherwise the thread will be of larger diameter after rolling than the remainder of the shank. The most common method of obtaining this reduced diameter is to extrude the shank for the length of the thread. This may be a disadvantage when the material does not adapt itself readily to extrusion. Special techniques have been developed so that nearly all the alloy steels and most of the non-ferrous alloys may be extruded successfully.

When threads are to be cut, full size stock is used. For roll-threading the stock is reduced by drawing or extrusion to the pitch diameter of the thread, so that when it is rolled, the outside diameter is the same as that of the cut thread; that is, a rolled thread bolt has a shank of scant diameter, smaller than the outside diameter of the thread. In other words, the shank diameter of the bolt is halfway between the major diameter and the minor diameter of the thread.



(*Courtesy G. Case, Lamson & Sessions Co., Cleveland, Ohio*)

Figure 59. Three steps in the action of the die in producing rolled threads.

Roll-threading is a cold-forming process whereby a bolt has threads formed on its external surface by compression between rotating or reciprocating dies. The action of the dies on the metal causes the surface to be indented by the crest of the die threads, while the metal between the die threads is freed outward to form the apex of the thread. Figure 59 shows three steps in the action of the die in producing rolled threads. The lines extending through the bolt stock are indicative of the directional lines of flow in the steel and show how the process affects them.

The type of bolt referred to commercially as "cut thread" may be made with a thread that has been actually cut, or has been extruded and rolled. Here the shank diameter is equal to the major diameter of the thread.

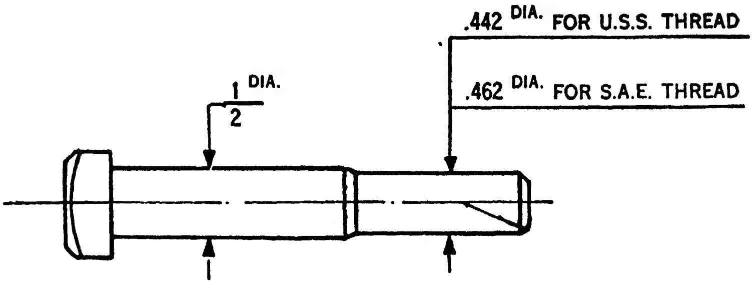
Figure 60 shows sketches of the headed and extruded bolt blank ready for roll thread, headed bolt roll-thread wire, and headed bolt cut-thread wire.

All cut-thread bolts in small sizes have finished points, but all rolled-thread bolts do not have finished points. A finished point is not necessary on a rolled-thread bolt. When a thread is cut with chasers the last thread at the end of the bolt has a razor edge which is very easily damaged in handling. A cut-thread bolt of small size must have a finished point or it may be difficult to assemble with the nut. Larger cut-thread bolts are not necessarily pointed. The rolling operation leaves the crest of the last thread in a rounded shape which is not easily damaged.

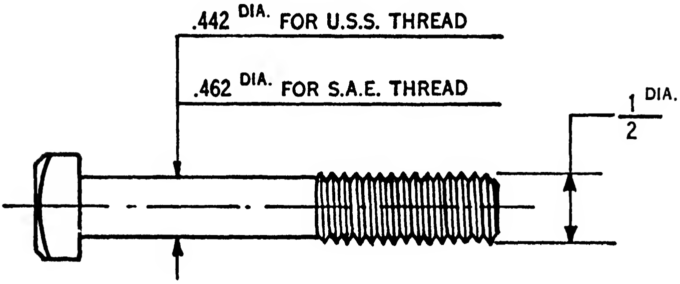
When the thread is rolled, the bolt is about 10 to 15 per cent stronger than with cut thread because of the cold-working of the metal in rolling and the fact that the flow lines in the metal are continuous and have not been cut. If the metal is subsequently heated for hardening, this cold-working property is not retained in the same proportion, but impact tests demonstrate that rolled thread has higher values than cut thread, even after heat treatment to the same hardness.

The cutting of threads[16] with a chaser has certain inherent disadvantages. As there is a constant wear on the thread-cutting tools, the machine is set up to cut as loose a thread as the tolerance will allow. The cutting tools are then used until the threads just fit the Go-gauge. Moreover, every lot normally contains bolts throughout the entire range of the allowable limits, whereas rolled threads in one lot are practically alike. In the cutting operation skill is required to maintain a commercially smooth and accurate thread. Through variations in the setting, they may easily have an "off-lead" or an imperfect profile, or be otherwise defective. A little dirt or chip may cause the cutting head to stick and produce a few defective threads. A cut-thread bolt appears to have a closer fit than it actually has, because of small feather burrs and irregularities left by the cutting tool. Rolled thread is always smooth and accurate.

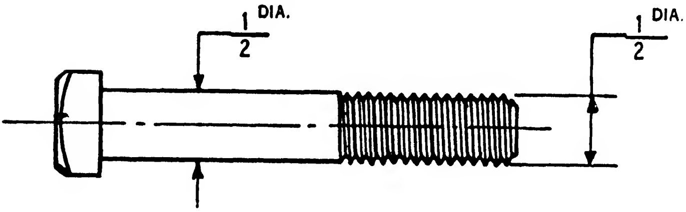
The commercial rolled-thread type of bolt has only two defects com-



HEADED AND EXTRUDED BOLT READY FOR ROLL THREAD



HEADED BOLT ROLL THREAD WIRE



HEADED BOLT CUT THREAD WIRE

Figure 60. Headed bolts.

pared with the cut-thread type: one is the scant shank, and the other is the lack of a finished point.

In general,[8] rolled threads are usually better than ground threads, and ground threads are sometimes better than cut threads. However, this is by no means always true. Only where accuracy is required, such as in tool work, are ground threads better than cut threads. Fatigue strength of ground thread is slightly less than that of cut thread. The rolled thread is far superior (twice) in fatigue to either, if rolling is done after heat treatment.

Factors other than the process by which the threads are formed must be considered, such as the sharpness of the root groove or the state of residual stress at the root after the thread is formed. Perhaps the rolling process offers the best assurance of maintaining smooth radii, because the die surfaces can be accurately formed and readily inspected, and also because the process does not involve cutting, tearing or variable wheel dressing. The state of residual stress after forming favors the rolling, provided the part is not heat-treated—except perhaps a very low drawing after rolling.

The fatigue susceptibility of ground, cut and sometimes rolled threads can be decreased by compressively stressing the material at the thread roots by a superficial rolling operation. Commercial rolled threads can and often do take advantage of compressive prestressing, intentionally or otherwise. If rolled threads are heat-treated after rolling, the prestress is lost. To retain prestress, rolled threads should not be heated sufficiently to relieve the stress set up by the rolling, or the bolts should be given a final rolling after heat-treating.

Cutting threads and milling the end section does not cold-work the underlying metal, but extruding the end and rolling the threads intensifies the strengthening effect.

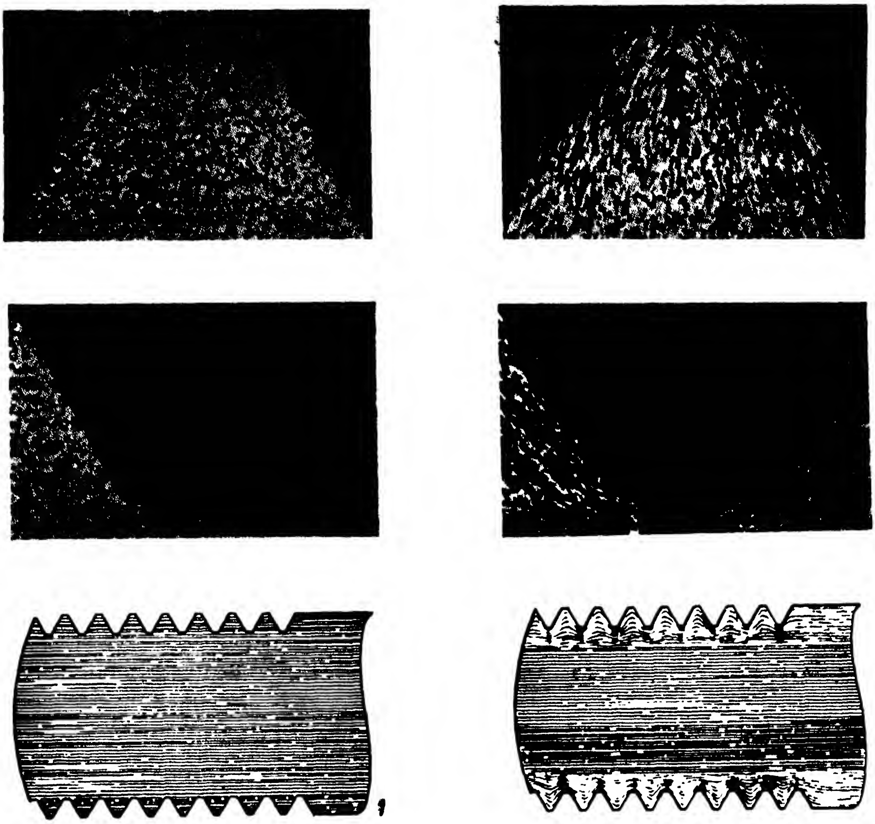
The static tensile and bending strengths of rolled and machined threads are practically identical, but in the case of dynamic loading a rolled thread offers the advantage of greater fatigue strength.

Coarse threads[18] strengthen more than fine threads. Bolts that are heat-treated after threading have substantially the same thread-strengthening effect on the tensile strength, whether the threads are cut or rolled. In the case of untreated bolts, the strengthening effect depends on the manner of forming the threads and increases in the following sequence: (1) fine-cut threads; (2) coarse-cut threads; (3) fine threads rolled on milled ends; (4) coarse threads rolled on milled ends; (5) fine threads rolled on extruded ends; (6) coarse threads rolled on extruded ends.

Figure 61 shows the microstructure and also diagrammatic sketches illustrating grain and fiber flow of the metal in a cut thread and in a rolled thread. A ground thread would show a fiber flow similar to the cut thread.

Shaping of Bolts

There are three methods[4] of shaping fasteners, depending largely on their size, shape and the quantities involved: (1) machining, (2) hot-forming, and (3) cold-forming. The latter two methods are also referred to as upsetting or upset-heading. In other words, bolts can be formed by mechani-



Cut Thread

Rolled Thread

Figure 61. Flow lines of cut and rolled thread.

cal working the metal by forging, cold-heading or hot-heading. However, the most popular way of manufacturing bolts of small size is by cold-heading, the material used being in the form of wire.

The division between cold-heading and hot-heading, as far as size is concerned, is made at ¾ inch diameter and 6-inch length, bolts over these dimensions being generally hot-headed. A machine which hot-heads and rolls the threads on a blank in one heat cycle is the highest development in the mechanics of hot-forming.

The first method consists of milling blanks for bolts, screws or studs from the bar stock on automatic or hand screw machines.

The upset-headed bolts, whether hot or cold, will give slightly greater toughness because the fibers of the material flow from the shank into the head in such a direction that the maximum resistance to shear is offered by the bolt. The toughness will be somewhat less for the bolts machined from bar stock, because the fibers in the head and shank are parallel and in such a direction that the resistance to shear is reduced.

Figure 62 shows fiber flow lines in bar stock (*A*), in machined bolt (*B*), and in hot-forged bolt (*C*).

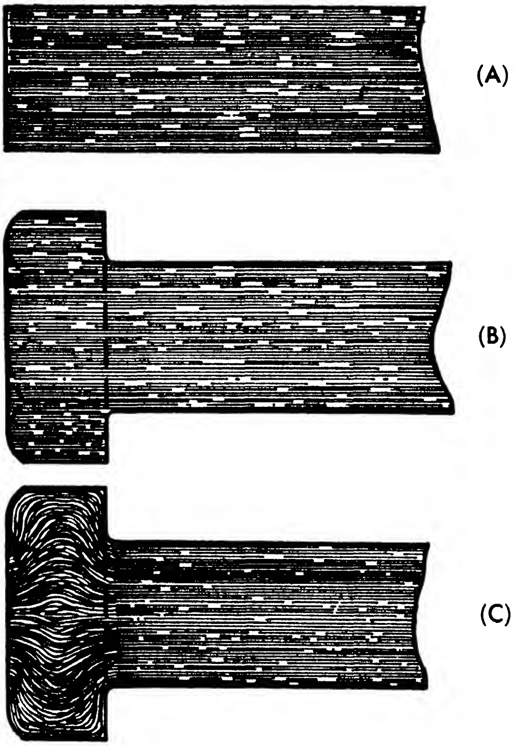


Figure 62. Sketch illustrating flow lines in bar stock (A), in machined bolt (B), and in hot forged bolt (C).

When bolts are used in structures subjected only to static stresses, it is of little importance whether the bolt is made by the hot-forging method or by being machined from the solid. However, for bridges, aircraft and other structures in which fatigue strength and resistance to impact are important, bolts should be made from heat-treated, cold-rolled material or hot or cold forgings, whereby the flow lines of the material in the head result in a fiber structure that offers maximum resistance to dynamic stresses, as such stresses are directed at right angles to the flow lines in the material of the bolt head.

MATERIALS

The materials of which threaded fasteners are made comprise the straight-carbon steels of low and medium carbon content, many alloy steels, stainless and corrosion-resistant steels, heat-resistant steels, copper alloys, brasses and bronzes, nickel, nickel alloys, such as "Monel" and "R-Monel," and also aluminum alloys.

The selection of the material best suited to a particular threaded fastener application is generally the result of a composite evaluation, taking into account most or all of these factors: (1) strength, (2) general resistance to corrosion, (3) resistance to stress corrosion, (4) cost, (5) hazard to life and property in event of failure, (6) capacity for cold-heading, (7) hot-forgeability, (8) machinability, (9) electrical conductivity.

Steel

It is desirable[4] that fastenings have a high or moderate degree of plasticity, that is, the ability of the metal to undergo a permanent change in shape without rupture. For this reason steel fastenings are seldom made from high-carbon steel, but rather from low-carbon steel, or from medium-carbon steel heat-treated to produce a moderate degree of plasticity. It is also necessary that the fastening have a high yield strength so that it holds the connected members firmly. Plasticity and high yield strength are mutually opposed, so that a compromise must be made. They must be tough and at least slightly ductile in the threaded section.

✓The low-carbon steels, containing from 0.08 to 0.25 per cent carbon, constitute a group of materials from which most common, low-stress fasteners are made. In this class are the cold-finished bars of bessemer and basic screw stocks AISI 1113 and 1120; bars and wires of AISI 1010, 1015, and 1020; and others of still different carbon ranges. To provide fasteners of higher strength the carbon content may be raised to around 0.50 per cent and the manganese content to 1.8 per cent. Heat-treating carbon steel parts by quenching and tempering increases the strength and hardness still further. ✓

In the alloy ranges the carbon-molybdenum, chromium, nickel-chromium, nickel, chrome-molybdenum and chrome-vanadium steels are the most popular materials. Any of these make fasteners of excellent quality. The carbon contents will vary from 0.15 to 0.50 per cent, as indicated by the AISI numbers 2330, 3135, 4140, 5140, 6130, 6150, etc. There is little advantage in using an alloy steel unless a tensile strength of over 150,000 psi is needed.

In the still higher carbon ranges and without other alloying than with manganese, the straight-carbon steels merge into the spring steels with their well-known excellent properties. There may, indeed, be a gain in toughness but not in stiffness; for the modulus of elasticity is the same for all steels and an alloy steel will stretch as much as a carbon steel, each up to its elastic limit.

Both low- and medium-carbon steels are used for bolts.[4] The advantages of using low-carbon steels are that the initial cost of the material, and the cost of heading and threading are considerably less. The disadvantage is that the tensile strength is not as great as can be obtained from a medium-carbon heat-treated steel. A basic open-hearth, semi-killed steel (AISI-C1018) is most commonly used. In utilizing this material, the basic principle is to retain the high tensile strength of the cold-drawn wire. After cold-heading, the bolts are given a process anneal at about 1,000° F. to return some degree of plasticity to the highly cold-worked head of the bolt. The threaded section of the bolt is also somewhat reduced in tensile strength by this process anneal. However, the process anneal can be eliminated by using a heavier-gauge wire, and later extruding the bolt blank in the threaded section. The medium-carbon steel bolts are made of carbon or alloy steels of 0.35 to 0.55 per cent carbon content. In the lower-carbon range (unalloyed) the bolts can be water-hardened; but in the higher carbon range (alloyed) they are oil-hardened. Of course the size of the bolt also has a bearing on whether oil- or water-hardening is preferable.

Since a spheroidized structure in medium-carbon steels has superior heading properties, the wire for bolts is usually treated before cold-drawing by annealing between 1200 and 1300° F.

Hot-headed bolts may be made from material receiving no further heat treatment. The most obvious way to increase the strength of hot-formed bolts is to increase the carbon content and secondarily the manganese content. Table 73 shows typical hot-formed carbon-steel bolt materials and Table 74 their approximate tensile properties.[4]

TABLE 73. *Typical Hot-Formed Bolt Materials*

Type of steel	A.I.S.I. classification	Chemical Composition			
		C max.	Mn max.	S max.	P max.
Low-carbon	C–1017	0.20	0.60	0.050	0.040
	C–1018	0.20	0.90	0.050	0.040
Sulphurized carbon	C–1116	0.18	1.40	0.23	0.045
Bessemer	B–1112	0.13	1.00	0.23	0.120
Sulphurized carbon	C–1117	0.20	1.30	0.13	0.045
Medium carbon	C–1038	0.42	0.90	0.050	0.040
	C–1045	0.50	0.90	0.050	0.040
Sulphurized carbon	C–1137	0.39	1.65	0.130	0.045

For cold-heading, the character of the microstructure of the bolt wire will naturally affect its physical properties. The wire is usually purchased

TABLE 74. *Approximate Tensile Properties*

A.I.S.I. classification	Physical Properties in Tension Yield point (psi)	Tensile strength (psi)	Elongation % in 2 in.	Reduction of area (%)	Hardness Rockwell "B"
C–1017	32,000	61,000	38	62	61
C–1018	37,000	65,000	37	68	67
C–1116	42,000	67,000	38	62	67
B–1112	48,000	68,000	35	59	70
C–1117	49,000	73,000	33	54	69
C–1038	48,000	68,000	30	51	75
C–1045	53,000	86,000	26	45	79
C–1137	57,000	99,000	27	48	88

to a maximum tensile strength requirement and a minimum elongation or reduction of area requirement. A typical requirement is as follows:

TABLE 75

Wire diameter (in.)	Tensile strength (psi) maximum	Reduction of area, % minimum	Hardness Rockwell "B" maximum
Over 0.430	105,000	35	90
Under 0.430	115,000	35	95

AISI 1018 steel is usually recommended as standard material for cold-headed, medium-strength bolts, and AISI 1045 or 1141 steels for hot-headed, medium-strength bolts.

Table 76 shows the chemical composition of typical alloy steels used for threaded fasteners. Other steels not shown in this table can and are being used. Many manufacturers and consumers have their own specifications for fastener materials; their chemical compositions are slight modifications of the standard alloys to produce specific properties for fixed engineering applications.

TABLE 76. *Typical Alloy Steels for Fasteners*

A.I.S.I. classification	Typical Chemical Composition C (%)	Mn (%)	Cr (%)	Ni (%)	Mo (%)	V (%)
1335	0.35	1.7	—	—	—	—
2330	.30	0.7	—	3.5	—	—
2335	.35	.7	—	3.5	—	—
3135	.35	.7	.65	1.3	—	—
3140	.40	.8	.65	1.3	—	—
4037	.37	.9	—	—	.25	—
4042	.42	.9	—	—	.25	—
4137	.37	.8	.95	—	.20	—
4640	.40	.7	—	1.8	.25	—
5140	.40	.8	.80	—	—	—
6130	.30	.8	.80	—	—	.15
6150	.50	.8	.80	—	—	.15
8640	.40	.85	.50	0.55	.20	—

Table 77 shows the representative physical properties of screw, bolt and stud steels at various hardnesses for highly stressed service. Actually, any bolt over 170,000 psi in tensile strength with corresponding low ductility may be dangerous to use unless carefully made and applied. Also, any alloy under 115,000 psi tensile strength does not fully utilize the alloy. Therefore, all alloys fall pretty much in the same category except for very special cases, as brought out later in this chapter.

TABLE 77. *Representative Physical Properties of Screw, Bolt and Stud Steels*

(Oil-quenched and tempered to hardness shown)
(Heat-treated 1-inch diameter bars)

	2330	3135	4135	4640	6150	6130
Tensile strength (psi)	218,000	214,000	220,000	205,000	217,000	190,000
Yield strength (psi)	192,000	195,000	160,000	180,000	197,000	160,000
% Elongation	12.5	14	11	12.5	12	14
% Reduct. of area	42	50	43	46	41	57
Izod impact	9	7	14	20	17	17
Brinell hardness	415	415	415	415	415	415
Rockwell C	44	44	44	44	44	44
Tensile strength (psi)	190,000	190,000	186,000	181,000	187,000	178,000
Yield strength (psi)	165,000	178,000	160,000	162,000	174,000	151,000
% Elongation	15	16	13	15	14	16
% Reduct. of area	50	56	50	50	45	59
Izod impact	11	20	22	26	23	25
Brinell hardness	372	372	372	372	372	372
Rockwell C	40	40	40	40	40	40
Tensile strength (psi)	165,000	168,000	161,000	160,000	165,000	157,000
Yield strength (psi)	132,000	158,000	133,000	140,000	157,000	139,000
% Elongation	17	18	17	17	15	17.5
% Reduct. of area	55	59	57	54	49	62
Izod impact	20	37	45	40	32	63
Brinell hardness	332	332	332	332	332	332
Rockwell C	36	36	36	36	36	36
Tensile strength (psi)	140,000	145,000	145,000	145,000	152,000	144,000
Yield strength (psi)	105,000	138,000	122,000	129,000	145,000	128,000
% Elongation	20	20	18	20	18	21
% Reduct. of area	57	60	60	57	53	62
Izod impact	37	52	70	50	67	80
Brinell hardness	297	297	297	297	297	297
Rockwell C	32	32	32	32	32	32
Tensile strength (psi)	125,00	125,000	138,000	130,000	139,000	128,000
Yield strength (psi)	90,000	118,000	115,000	110,000	130,000	112,000
% Elongation	22	22	20	21	20	24
% Reduct. of area	60	61	62	59	57	65
Izod impact	55	65	80	55	77	104
Brienll hardness	270	270	270	270	270	270
Rockwell C	28	28	28	28	28	28

Table 78 shows the minimum tensile properties in pounds of medium-strength bolts of coarse and fine thread for various diameters from ¼ inch to 1 inch. The properties are for steel equivalent to AISI 1141.

TABLE 78. *Minimum Tensile Properties of Medium-strength Bolts*

Diameter of bolt (in.)	Coarse (NC) thread		Fine (NF) thread	
	Yield strength (lbs.)	Tensile strength (lbs.)	Yield strength (lbs.)	Tensile strength (lbs.)
¼	1,800	2,300	2,100	2,600
5/16	3,000	3,800	3,300	4,200
⅜	4,500	5,600	5,100	6,300
7/16	6,200	7,700	6,900	8,600
½	8,200	10,200	9,300	11,500
9/16	10,600	13,100	11,800	14,600
⅝	13,100	16,300	14,800	18,400
¾	17,700	24,200	19,800	25,000
⅞	24,500	30,900	27,000	34,100
1	32,100	40,600	36,000	45,600

Elongation should not be less than ¼ inch over the original length of the bolt before failure in the tension test. The Brinell hardness is about 229–285, equivalent to 22–32 Rockwell C.

The bolt area is calculated from the mean diameter. The values shown in the above table, when divided by their respective bolt areas, will give approximately the following tensile strength in pounds per square inch (Table 79).

TABLE 79

	Yield strength (psi)	Tensile strength (psi)
½″ to ⅝″ inc. dia.	58,000	72,000
¾″ to 1″ inc. dia.	53,000	67,000

These values are to be used for reference only.

A typical high-strength alloy steel bolt is AISI 8637–H, analyzing 0.35–0.43 C, 0.7–1.05 Mn, 0.35–0.75 Ni, 0.35–0.65 Cr, 0.15–0.25 Mo, bal. Fe.

TABLE 80. *Minimum Tensile Properties of High-strength Bolts*

Diameter of bolt (in.)	Coarse (NC) thread		Fine (NF) thread	
	Yield strength (lbs.)	Tensile strength (lbs.)	Yield strength (lbs.)	Tensile strength (lbs.)
¼	4,300	4,800	4,900	5,500
5/16	7,100	7,900	7,800	8,700
⅜	10,500	11,600	11,900	13,200
7/16	14,400	15,900	16,000	17,800
½	19,200	21,300	21,600	24,000
9/16	24,600	27,300	27,400	30,500
⅝	30,500	33,900	34,600	38,400
¾	41,800	46,800	46,600	52,200
⅞	57,700	64,700	63,700	71,400
1	75,700	84,800	85,000	95,200

Bolts made of this alloy have the minimum tensile properties (in pounds) shown in Table 80.

Elongation should not be less than 3/32 inch over the original length of the bolt before failure in the tension test. The Brinell hardness is about 302–352, equivalent to 32–38 Rockwell C.

The values shown in the above table, when divided by their respective bolt areas, will give approximately the following tensile strength in pounds per square inch (Table 81).

TABLE 81

	Yield strength (psi)	Tensile strength (psi)
½" to ⅝" inc. dia.	135,000	150,000
¾" to 1" inc. dia.	125,000	140,000

These values are to be used for reference only.

Most common machine bolts and screws are strong enough if made of plain 0.20 per cent carbon steel, cold-drawn. High-carbon and alloy steel bolts, oil-quenched and tempered, give correspondingly higher properties: they must be heated in a non-scaling atmosphere to preserve the thread, and precision-cut or precision-rolled.

Low-alloy steels are used when high impact strength, toughness and resistance to fatigue are required. Such fasteners must be heat-treated to develop their full properties. This heat treatment increases tensile and impact strength, toughness and hardness, and resistance to fatigue failure. Heat-treating also includes cyaniding, gas carburizing or nitriding for surface hardening to resist wear and abrasion.

The chemical composition of the steel is related to the particular method of production and properties desired. In carbon steels there is little reason to specify definite chemistry unless free-cutting grades are desired for thread cutting with chasers. In higher grades of fasteners, where the use of alloy steel is essential, the effect of the alloying elements on the depth of hardenability is more important than the actual chemical composition. However, where corrosion resistance, weldability or other special properties are important the actual composition takes on a stronger meaning.

High-Temperature Bolts

As oil refineries, steam power plants and similar industrial processes adopt higher temperatures, fastening which will resist these conditions becomes an important problem.

A number of special low-alloy steels are used for bolts in high-temperature applications. Some of these alloys are shown in Table 82.

TABLE 82

Alloy	C (%)	Mn (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	V (%)
A	0.45	—	0.45	—	1.0	0.55	—
B	.35	—	.75	—	1.2	.55	—
C	.45	—	.75	0.3	1.2	.55	—
D	.30	—	.75	—	1.2	.55	0.25
E	.4	—	—	.15	0.9	.20	—
F	.43	1.45	.3	.3	.2	.35	—
G	.41	0.85	.3	.6	.5	.25	—
H	.48	1.08	.25	.6	.55	.3	—

Alloy H has the greatest creep strength at 850° F. Alloy D has the highest creep resistance at temperatures above 850° F., and up to 1000° F. when heat-treated to about 285 Brinell. Alloy E as well as alloys F, G and H would be satisfactory at 850° F. Alloy D is most satisfactory for applications at 900 to 1000° F., and when maximum creep resistance is desired this steel should be normalized rather than oil-quenched. For high-temperature service all these steels are usually heat-treated to 269–315 Brinell range. With steels of these types it is generally agreed that if the tempering temperature is 150 to 200° F. above the intended operating temperature, a satisfactory degree of stability will exist with respect to the physical properties.

In bolting pipe flanges together, bolts are initially stressed to some particular value which results in an elastic deformation in both the bolts and flange. With high temperature and with time, a creep deformation of the flange and a tendency to deform in the bolts take place, resulting in loosening of the flange joint and stress reduction or relaxation in the bolts. If this stress reduction is large, periodic tightening of bolts is necessary to prevent joint leakage. This maintenance can be reduced by proper selection of the initial stress in the bolt. This stress depends upon the behavior of the material when subjected to stress relaxation.

These high-temperature steels are generally heat-treated to give a minimum yield point of 105,000 psi and will behave elastically to a stress of about 90,000 psi. In actual practice the bolts are given something like 0.0015 inch per inch elongation for a stress of 45,000 psi. This gives an initial high compression to set the gasket firmly in place and stores up considerable springiness in the bolt to take care of subsequent relaxation at high temperatures. However, the loading is not too high to prevent allowances for: (1) torsion stresses set up in tightening the nuts, (2) bending that may be due to misalignment between spot-faced surfaces, nut-bearing surfaces and nut threads, (3) stress concentration at the root of the threads, (4) possible increase in load in initial service caused by the flange heating more rapidly and hence expanding more quickly than the studs. Yet these allowances can take care of themselves in a bolt of sufficient ductility.

In high-temperature applications where flanges may bend slowly, gaskets deform plastically and bolts relax, it is important to obtain as nearly equal loading as possible on each bolt. For example, if a flange connection, having bolts originally tightened to a load of 70,000 psi reaches a temperature of 850° F., the bolts may relax to an operating load of 15,000 psi after several weeks of service. Here the bolts that were originally tightened to 70,000 psi may have accounted for the major part of the total load. However, under high-temperature operating conditions they can support no more than their relaxation strength of 15,000 psi, and so a large portion of the original load is lost. On the other hand, if the tightening had been uniform, load loss would have been lower.

As shown in Figure 63, unevenly tightened bolts that operate under high temperature may relax enough to reduce the total load to a small fraction of its original value, while evenly stressed bolts maintain a high load on the connecting flange joint.

The modulus of elasticity of steel changes with elevated temperatures from 30,000,000 psi at room temperature to about 25,000,000 psi at 850° F., and about 20,000,000 psi at 1000° F. This means that at the higher temperatures a lower stress would be required to produce the same elongation obtained at room temperature.

For very high-temperature applications, highly alloyed nickel-chromium heat-resisting steels or highly alloyed non-ferrous alloys containing chromium, nickel, cobalt, molybdenum, tungsten and iron are used. One such non-ferrous alloy contains 0.15 carbon, 1.0 manganese, 20 per cent chromium, 20 per cent nickel, 20 per cent cobalt, 3 per cent molybdenum, 2 per cent tungsten, 1 per cent columbium, 0.14 per cent nitrogen and balance iron. The latter alloys, although they contain small or large amounts of iron, are not considered as steels but as non-ferrous alloys.

The 4 to 6 per cent chromium steels, the 12 to 14 per cent chromium steels, the 16 to 20 per cent chromium steels and the 25 to 30 per cent chromium steels may be used for different applications. The higher the chromium content the higher the oxidation temperature, and therefore the higher the resistance to scaling.

The austenitic stainless steels of the 18–8 type and the high-nickel alloys are also used extensively for high-temperature services.

Corrosion-Resistant Fasteners

Stainless steel of the 18 chromium–8 nickel type is used extensively for fasteners because of its high resistance to corrosion. Since this alloy cannot be strengthened by heat treatment, the maximum physical properties

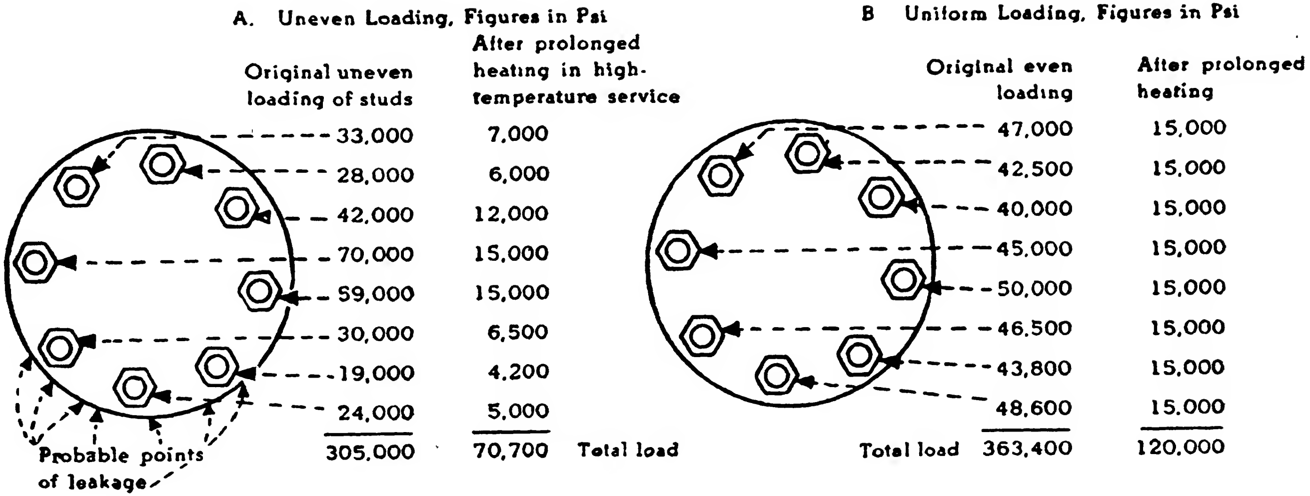


Figure 63. Bolt stresses due to uniform and uneven loading.

can be obtained only by cold-working, as in cold-rolled bars, rods and wire.

In the form of wood screws there are numerous uses for trim work on furniture, dairy equipment, cold-storage doors and building decorations.

The stainless steels[23] are expensive and more difficult to machine or to work mechanically than carbon- or low-alloy steels. All headed bolts of ¾ inch diameter and over are made by hot-forming; smaller bolts are made by cold-heading. Where the design permits, the latter is considered the most economical for the smaller fasteners because, theoretically at least, every bit of raw material is consumed in the cold-heading operation.

Where parts of a certain grade of stainless steel are to be joined, fasteners of the same material are usually employed, so that the entire unit will have the same corrosion resistance. When only the fasteners are to be of corrosion-resistant alloy, it becomes necessary to determine which grade will meet the conditions most economically. The four types commonly used are (1) 18 per cent chromium–8 per cent nickel steel, (2) 16 per cent chromium–2 per cent nickel steel, (3) 16 to 18 per cent chromium steel and (4) 12 to 14 per cent chromium steel.

Types (2) and (4) are the only ones which will respond to heat treatment for improved strength and hardness, and even these must be high enough in carbon content to respond satisfactorily to heat treatment. Tensile strength and hardness of the austenitic stainless steel alloys are increased by cold-working. For this reason rolled-thread stainless steel fasteners have a harder thread and a better tensile strength than the same size fastener with a cut thread. Fasteners machined from bar stock and headed fasteners with cut threads call for free-cutting grades of stainless steel. Since these contain small proportions of sulphur or selenium, they machine more freely and produce a better finish on the threads.

Stainless steel fasteners are usually passivated after fabrication to increase corrosion resistance by immersion in a 10 to 20 per cent solution of nitric acid at 140° F. for about 20 minutes, or in a 40 to 50 per cent solution at room temperature for one hour.

The 16–2 grade of stainless steel responds to heat treatment and has corrosion resistance approximating the 18–8 grade and a good deal better than the 16–18 chromium or the 12–14 chromium grade. It has been adopted as the stainless steel for Army and Navy aircraft bolts.

Stainless and heat-resistant chrome-nickel steels are also used for high-temperature service for their high resistance to oxidation and scaling, and also for their ability to maintain their strength at elevated temperatures more readily. In addition to the 18–8 type, the 25–12 type is used for higher operating temperatures. The composition of this latter steel is 25 per cent chromium and 12 per cent nickel.

Copper Alloys

Although copper is inherently softer and weaker than iron, its alloys become very tough after cold-working; thus they are strengthened considerably before brittleness becomes significant. Copper alloys are used because of their high general corrosion resistance and adaptability to electroplating. Such parts are machined from free-cutting brass rod or cold-headed from yellow brass wire, the threads being either rolled or machined. The yellow brass wire is well adapted for cold-headed and roll-threaded parts because of its moderate strength combined with good ductility, comparatively low cost and corrosion resistance.

Brass is in common use. Leaded brass containing 2–3 per cent lead is free-cutting and is used extensively in automatic screw machines for the machining and thread-cutting of fasteners. Naval brass, containing 59–62 per cent copper, 0.5–1.0 per cent tin, 0.3 per cent lead, balance zinc, is used where greater strength is required. Brass is one of the easiest alloys to make into fasteners by any of the manufacturing processes.

Silicon bronzes containing 3 per cent silicon and 1 per cent manganese, tin or zinc, have been used successfully for hot-headed, cut-thread bolts, as they have good strength and ductility. Those containing 1.5 per cent silicon and 0.25 to 1.0 per cent manganese, tin or zinc, will withstand severe cold-working and are used for cold-headed rolled-thread bolts and screws. The latter bronzes are readily extruded and roll-threaded, and at the same time retain high strength and toughness. For machined screws, bolts and nuts, a leaded silicon bronze is used, because its 0.4 per cent lead content improves the machining characteristics.

These alloys have an endurance value of approximately 30,000 psi in the bolt temper and a modulus of elasticity of 15,000,000 psi. They resist exposure to all types of water, to saline fogs, corrosive gases and vapor, and stresses caused by unusual service conditions. They are nonmagnetic, have high strength values, and are easy to fabricate.

Service conditions involving continuous application of relatively high loads and exposure to atmospheric corrosion are best met by 1.5 per cent silicon bronze, which possesses high resistance to stress corrosion. Silicon bronze bolts, screws, studs and nuts are used for resistance to "season" or weather cracking. Naval brass and manganese bronze are sometimes used for such applications, but they do not have great resistance to stress corrosion.

When moderate strength requirements are encountered in salt-water exposures, naval brass and manganese bronze are most commonly used, although the more stress corrosion-resistant alloys, silicon bronze, nickel-phosphorus bronze, aluminum bronze and copper-nickel, are greatly to be preferred. Typical applications are deck bolts, valve-bonnet and pipe-flange studs, marine hardware and tank fittings. Most of these bolts, screws and studs from naval brass, manganese bronze, and aluminum bronze are hot-forged, but for higher strength requirements they are machined from hard rod. The other preferred alloys possess their most valuable properties of strength, toughness and corrosion resistance when furnished as cold-headed products.

Nickel-aluminum bronze is a practical material with good strength and high corrosion resistance. Nickel silver, a copper-nickel-zinc alloy, has minor but practical uses.

Where highest strength is the predominating factor, one of the aluminum bronzes is indicated, since these alloys are distinctly stronger than the other materials discussed here, although more costly. In general they are machined from rod to produce machine screws and studs for aircraft engines and accessories.

In the chemical industries the selection of an alloy is largely dependent upon resistance to the specific reagents. The silicon bronzes are generally used for moderate conditions and aluminum bronzes for severe applications, since they are highly resistant to the attack of most acids and alkalies.

The requirement for highest electrical conductivity dictates the use of copper fasteners. However, the comparatively low strength of copper frequently leads to the necessity for a compromise; this is best filled by nickel-phosphorus bronze, which possesses both good conductivity and moderately high strength.

A certain few applications involve severe service conditions and also a great hazard to life and property in the event of failure. Copper-nickel alloy of 30 per cent nickel content is highly recommended in such cases, because of its extreme resistance to stress corrosion.

The ratings given in the tabulated data for resistance to stress corrosion reflect both laboratory tests and long service experience. The rating "excellent," given only to copper and copper-nickel, implies virtual immunity under all conditions. The rating "good," given to other alloys of high copper content, means that these alloys have a very high resistance, although under some conditions they are somewhat susceptible to such attack. In this group particularly, attention is called to the fact that performance varies considerably with the temper of the rod or wire from which the part is made. In general, the hardest temper consistent with the size of the part and the type and degree of forming operations necessary is to be preferred, because the harder tempers give much better performance. The rating "fair" is used for materials having a relatively marked tendency toward stress corrosion failure; such materials are recommended only where conditions of use are favorable. The user is cautioned against application of too high stresses in proportion to the tensile or yield strengths, particularly in the alloys rated either "good" or "fair."

Typical Copper Alloys for Threaded Fasteners

Copper

Composition: Cu 100.
Tensile strength (psi): Half-hard wire 50,000.
Resistance to stress corrosion: Excellent.
Use: Cold-headed bolts and screws where highest electrical conductivity is required.

Yellow Brass

Composition: Cu 66 to 70; Zn 34 to 30.
Tensile strength (psi): Quarter-hard wire 70,000.
Resistance to stress corrosion: Fair.
Use: Cold-headed bolts and screws for general light service.

Free-cutting Brass

Composition: Cu 62; Pb 3.2; Zn 34.8.
Tensile strength (psi): Half-hard rod 60,000.
Resistance to stress corrosion: Fair.
Use: Machined bolts and screws for light service.

Naval Brass

Composition: Cu 60.5; Sn 0.8; Zn 38.7.
Tensile strength (psi): Hard rod 75,000; annealed rod 55,000.
Resistance to stress corrosion: Fair.
Use: Hot-forged or machined bolts, screws, and studs, principally for marine applications, salt water service.

Silicon Bronze, Type A

Composition: Cu 96; Si 3; Mn, Sn, or Zn 1.
Tensile strength (psi): Hard wire 95,000; annealed or as-forged 52,000.
Resistance to stress corrosion: Good.
Use: Cold-headed, machined or hot-forged bolts, screws and studs.

Silicon Bronze, Type B

Composition: Cu 97.5; Si 1.5; Mn, Sn or Zn 1.
Tensile strength (psi): Hard wire 90,000.
Resistance to stress corrosion: Good.
Use: Cold-headed bolts and screws for general applications requiring high strength, toughness and high corrosion resistance.

Phosphor Bronze

Composition: Cu 96; Sn 3.8; P 0.2.
Tensile strength (psi): Hard wire 85,000.
Resistance to stress corrosion: Good.
Use: Cold-headed or machined bolts and screws.

Nickel-Phosphorus Bronze

Composition: Cu 98.7; Ni 1.1; P 0.2.
Tensile strength (psi): Hard wire 97,000.
Resistance to stress corrosion: Good.
Use: Cold-headed bolts and screws where good strength and excellent heading quality are required.

Aluminum Bronze, Type I

Composition: Cu 89; Al 9; Fe, Ni, Sn and Mn or Si 2.
Tensile strength (psi): Hard rod 95,000.
Resistance to stress corrosion: Good.
Use: Machined bolts and studs for aircraft and chemical industries.

Aluminum Bronze, Type II

Composition: Cu 82; Al 9.5; Fe 2.5; Ni 5; Mn 1.
Tensile strength (psi): Hard rod 105,000.
Resistance to stress corrosion: Good.
Use: Machined bolts, screws and studs in high-strength applications.

Manganese Bronze, Type A

Composition: Cu 59; Zn 38.9; Sn 1.0; Fe 1.0; Mn 0.01.

Tensile strength (psi): Hard rod 85,000; as-forged 60,000.

Resistance to stress corrosion: Fair.

Use: Hot-forged bolts, screws, studs, principally for high-strength requirements.

Copper-Nickel, 30%

Composition: Cu 70; Ni 30.

Tensile strength (psi): Hard rod 70,000; annealed or as-forged 55,000.

Resistance to stress corrosion: Excellent.

Use: Cold-headed, machined or hot-forged bolts, screws and studs.

Aluminum Alloys

Some industries are using bolts, screws and nuts made of aluminum alloys because of satisfactory corrosion resistance and light weight. They are used in aircraft construction because their tensile strength is sufficiently high and they will not rust on exposure to the atmosphere. Here lightness is obviously an important consideration. Aluminum alloy fasteners are made in a variety of finishes—burnished, buffed and anodized for corrosion protection.

The two popular high-strength aluminum alloys for threaded fasteners are Alloy 11ST and Alloy 24ST, both heat-treatable. In addition Alloy 11ST has free-cutting characteristics and is very desirable from that standpoint.

Alloy 11ST has a typical composition of 5.5 per cent Cu, 0.5 per cent Pb, 0.5 per cent Bi, balance Al; Alloy 24ST has a typical composition of 4.2 per cent Cu, 0.6 per cent Mn, 1.5 per cent Mg, balance Al.

Some of the typical tensile properties of these two alloys are shown in Table 83.

TABLE 83

	Alloy 11ST	Alloy 24ST
Tensile strength (psi)	57,000	68,000
Yield strength (psi)	44,000	46,000
Elongation (%)	14	22
Shear strength (psi)	33,000	41,000
Brinell hardness	100	105

Nickel Alloys

Nickel and "Monel" metal are used extensively as fasteners for corrosion, heat and acid-resistant purposes. "Monel" metal is a nickel-copper alloy containing about 29 per cent copper. A modified grade is "R-Monel," which has free-cutting characteristics permitting threads to be cut more readily and with smoother surface finish. The merit in "Monel"[13] as a bolt material lies in its strength, ductility and corrosion resistance. It is superior to plain-carbon steel bolts and other non-ferrous bolt material in the combination of these properties.

Hot-forged bolts are necessarily less accurate as to tolerances than cold-upset or machined from solid bar. Since the mechanical properties of such bolts depend upon the amount and nature of the work done in heading, it is not safe to use the properties of the original rods. Generally, hot-forged bolts are thoroughly annealed at the shank and slightly harder in the head. For this reason the minimum mechanical strength properties of such bolts should be taken for annealed material. It is safer to use the hot-rolled values, however, in estimating minimum ductility.

Machined bolts are made, using either hot-rolled or cold-drawn rods, depending upon the properties desired.

Table 84 gives the minimum mechanical properties[13] of "Monel" bolt and nut stock of various tempers and sizes.

TABLE 84. *Minimum Mechanical Properties of Monel Bolt and Nut Stock*

Temper and size	Tensile strength (psi)	Yield strength (0.20% offset) (psi)	Elongation in 2 in. (%)
For cold-upset and roll-threaded bolts			
Cold-drawn			
No. 1 Temper (up to ⅜-in. diam.)	95,000	80,000	5 #
Annealed (⅜-in. diam. and over)	70,000	25,000	30
For machined bolts, studs or nuts			
Cold-drawn			
Rounds (to ½ in. incl.)	110,000	85,000	15
Rounds (over ½ in.)	90,000	70,000	17
Squares and hexagons (all sizes)	85,000	60,000	25
Hot-rolled			
Rounds, squares, hexagons (all sizes)	80,000	40,000	30
For hot-forged bolts †			
Hot-rolled	70,000	25,000	30
For cold-pressed nuts			
Cold-drawn			
Flats	85,000	60,000	25
Hot-rolled			
Flats	80,000	40,000	30

This apparently low minimum elongation value exists because of the low per cent elongation in 2 inches on small diameters. The reason for this is the lack of "necking-down" of small wires during tensile testing. These wires are just as workable as larger rods of equal strength, where the minimum elongation in 2 inches would be about 20 per cent.

† Tensile and yield strengths are for annealed material, and per cent elongations are for "as-rolled" materials, since some portions of hot-forged bolts are thoroughly annealed during manufacture.

Strength Factors

For many years both users and manufacturers of bolts, machine screws, studs and other threaded fasteners have been confronted with the problem of determining true tensile strength in the threaded section. Many different methods of calculation and formulas have been suggested, and as many results obtained, with no general agreement.

There are several methods now in common use for estimating tensile strength: one calculates the net area from the root diameter, the second uses the mean area calculated from the average of the root and the pitch diameters; and the third uses the pitch area calculated from the pitch diameter.

A test procedure is to pull the bolt or screw in an appropriate fixture, noting the load at which the fastener breaks, and then calculate this back to ultimate stress in pounds per square inch, using for area each of the three diameters noted. Experimental tests show that computing the strength on the area at the root of the thread gives a high value, and that computing it on the pitch diameter gives a low value. Calculation on the mean diameter gives values closer to the true tensile strength of the steel as determined by pulling machined test bars of the same material.

In testing [18] or specifying the properties of threaded parts the presence of threads is a complicating factor, as it involves a comparison of fastener strength with material strength. General information about the properties of materials is largely based on the results obtained by testing standard tensile test bars of 0.505 inch diameter; but threaded parts usually are tested simply by putting them in the tensile machine and pulling them apart in the threaded section. The results can be given in actual load and elongation for the specific part, or in pounds per square inch.

A threaded fastener,[18] especially a bolt, is inherently a tensile member in the assembly of other and more massive parts. To a lesser extent it is useful as a member to resist shear forces. The threads create a notched-bar member and render it somewhat unsuitable to resist bending, impact and fatigue stresses. However, by suitable tightening, the bolt can resist very high fatigue and impact loads, since the bolt load may not change.

In alloy steels, sharp notches materially reduce the strength and ductility of cylindrical test bars if the ultimate strength of the steel exceeds a value of approximately 200,000 psi. Cylindrical notched bars and bolts of high strength [5] were found to break at reduced loads in a brittle fashion if their strength level was above 150,000 psi. If bending is superimposed on the applied tension by means of shims placed under the heads or misalignments, the strength of high-strength bolts will be considerably reduced. Higher-strength bolts break underneath the head in a brittle fashion, rather than in the generally weaker threaded part. This embrittlement and loss in strength can be eliminated by providing a proper fillet under the head of the bolt.

It is known that there is an increase in the load [17] required to break the threaded section, as compared with the section reduced to the root diameter. This is due to the strengthening effect of the thread and is probably caused by the increased amount of metal in the thread above its root, and the form of the thread itself. Therefore, it may be said that the strengthening effect of the thread increases the tensile strength of a threaded part equivalent to a diameter that is between the root and pitch diameters. Thus strength of threaded sections can be calculated by using the mean diameter.

Furthermore, it has been observed[18] that the strengthening effect is usually much greater on the proportional limit than on the tensile strength, and that the latter is at a minimum in the case of the strongest bolts. The strengthening effect is also low on material of low strength if the bolt has high elongation in the threaded section.

In modern design[24] it is often necessary to take full advantage of the available strength of screw fastenings and thus reduce weight and size as much as possible. Intelligent use of screw-thread fastenings requires consideration of five types of stress, namely; (1) torsion, (2) tension, (3) impact, (4) shear, and (5) fatigue. These stresses should be considered not only in their relation to the function of the complete apparatus, but with respect to the assembling of the apparatus in manufacture as well.

In using screw-and-nut combinations as a clamping medium, friction is developed between the head of the screw and the surface upon which it bears, as well as between the threads of the screw and the threads of the nut. The value of the force required to overcome the friction under the head of the screw depends upon the additive finish and the smoothness of the surfaces involved. The value of the force required to overcome the friction between the threads of the screw and the threads of the nut also depends upon these factors.

The total torque values are the sum of these two forces plus the actual torque required to break the screw. The head and thread friction are present in any loosening of the screw-nut combination; obviously, the higher these friction values the less the tendency of the screw fastening to loosen. Once the fastening has been made tight, any failure of the screw is usually due to the tension, shear, or fatigue stresses.

Where shear or bearing governs in bolted connections, the entire bearing length of the bolt barrel should be full-bodied, with all the thread outside the enclosed bearing. So that there will be no bearing on the thread, the bolts should be equipped with a washer under the nut. However, in a well-designed joint, the shear-directed loads should be resisted by friction induced by bolt tension.

The effect of lubrication, of fiber washers and of a thrust ball bearing washer under the nut face, although not necessarily conclusive, is indicative of the controlling relation between the torque induced in the bolt and the torsional friction resistance of the washer base on the outside plate.

Lubrication has little effect. A fiber washer under the nut releases the induced torque to a considerable extent. A ball thrust bearing under the nut reduces the induced torque to practically zero. In each case the induced tension for a given torque increases as the induced torque in the bolt shank becomes less.

Locking devices have but little to do with bolt strength, but they are useful in view of the tightness requirements for bolted assemblies in structures subject to dynamic loads. The purpose of a lock nut is to prevent the nut from loosening.

In actual service, a stud or bolt is subjected to many other forces besides the axial pull: bending and torsion caused by installation forces resulting from tightening of the nut, and forces set up by the deformation of the assembled parts when under load.

A large percentage of bolts[8] and studs are subjected to bending loads of various magnitudes. Stress changes from repeated bending loads are generally of smaller magnitude than from tension loads, but since these occur simultaneously, the stress change in the bolt is usually their sum. As in the case of repeated tension loads, repeated bending loads, in normal designs, are reduced as the nut tightness is increased, and for the same reason. Also as in the case of tension loads, there is always a small change in bending load regardless of nut tightness, because of changes in the elastic deformation of the bolted members. When these changes are not symmetrical with respect to the bolt axis, bending will occur.

The action of screwing up bolts also puts torsional stress on the bolt, which may exceed tensile strength in the smaller sizes.

The condition[1] of repeated direct tensile stress suggests only one type of stress found in engineering structures. Studs, bolts and screws used in aircraft engines or other prime movers are also subjected to repeated bending or flexural stresses developed by such actions as direct loading misalignment, and vibration or whipping of the fastenings.

The strength of a bolt is subjected to a number of types of stress.[13] In the first place, tightening the nut creates a stress great enough to lead to actual fracture of small bolts, unless care is taken by the workman. In the case of large bolts, a similar type of overstressing may result from too large a wrench. The use of oversize wrenches is poor practice, but it often happens. The torque necessary to break a ¼-in. bolt of 60,000 psi ultimate strength is 87 inch-pounds; little pull, even with a small wrench, is required to fracture such a bolt when it is considered that a man can with ease apply a 200 inch-pound pull with a 4-in. wrench. Bolts of ⅝-in. diameter are about the smallest that cannot be readily broken with the wrench standard for the size.

A tightened nut subjects the bolt to a considerable tensile stress, which frequently approaches the elastic strength of the bolt. This stress is continuous, since the service requires that the nut remain so tightened.

Bolts are sometimes required to absorb shear stresses, though less frequently than tension stresses. Bolts fastening parts of both moving machinery and static assemblies often meet with double or single-shear stresses.

Finally, mention should be made of fatigue stresses—occasionally encountered and particularly important in view of the diminution of fatigue strength resulting from even slight corrosion—and the impact stresses that are characteristic of moving parts.

A properly tightened nut sets up a tension in the bolt equal to or greater than that produced by the design working load; under this condition the bolt cannot fail from fatigue, as there can be no reversal in stress regardless of fluctuations in external load. Maintenance of a tight connection between the nut and the bolt is important. The use of a lock nut helps, and by so doing minimizes the impacts suffered by the threads in a loose joint.

More than almost any other metal product, bolts require a high degree of ductility together with strength.[13] In some cases a bolt with high ductility and moderate to low strength is considered more desirable than one of moderate ductility and moderate to high strength. The reason for this point of view lies in the fact that overstressing of bolts is a common occurrence, and a positive high ductility is the best assurance against breakage. This point is a controversial matter depending upon whether the bolt is overstressed in assembly or in service. In assembly it is better for the bolt to break due to excess torque and be replaced. One that merely stretches may be damaged, but the damage may not be recognized.

It is common to consider strength and ductility as being independent of each other. The usual view is to accept the high strength value of a metal regardless of its ductility. However, a bolt having a tensile strength of 100,000 psi and an elongation of 25 per cent is more serviceable than one having the same strength and a lower elongation. Figure 64 illustrates the strength-ductility relationship of several metals.

The use of smaller diameter bolts, heat-treated to give the same strength, has been advocated as a means of increasing fastening efficiency, reducing weight and saving material. The torque required to load a bolt at a given stress per square inch varies as the cube of the diameter of the bolt, and that necessary to produce a given grip or pull varies directly as the diameter of the bolt. Thus standard wrenches, with a reasonable pull, produce relatively high strain in bolts of small diameter and a very low one in bolts of large diameter; in other words, smaller bolt diameters permit more effective fastening. Of course, for equal strength, the small bolt must have a higher unit tensile strength, which may be obtained by heat treatment.

In stud-fastened metal-to-metal joints subjected to repeated loadings, it is highly desirable that the initial tension produced in the stud by tightening the nut be equal to or greater than the peak stud load. Under such conditions the stud will not be subjected to repeated stress. Highly prestressing the stud causes the additional cyclic stress imposed by the peak cyclic loads to become almost negligible.

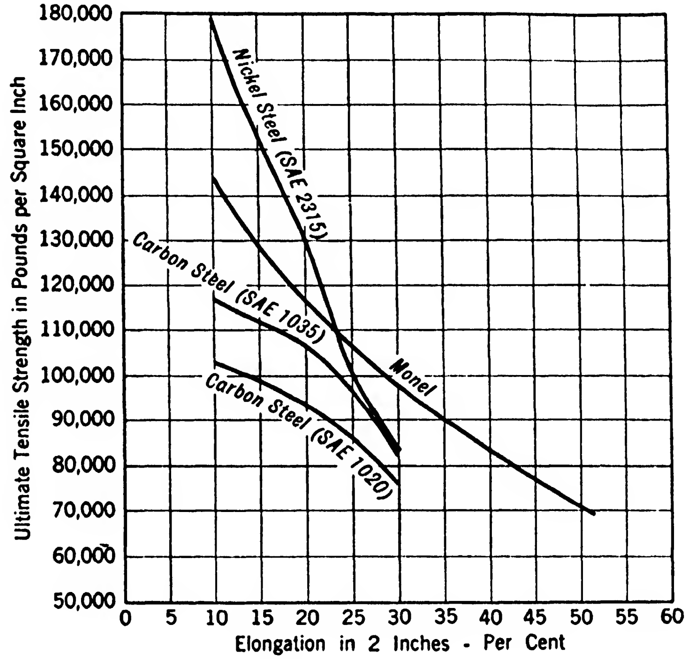


Figure 64. Strength-ductility relationships of various alloys.

Regardless of the type of thread, one of the most important factors in a stud fastening is the fit of the stud in the part into which it is screwed. Too much negative clearance will prestress the metal around the stud excessively. However, there should be zero clearance between the roots of the thread in the one member and tops of the thread in the other member. This is necessary to guide or position the stud definitely, so that side loads will not cause the stud to sway or vibrate. Any side motion of the stud will set up bending moments.

From strain measurements on conventional nut and bolt fastenings it has been found, in addition to the two types of deformation (bending and twisting), that the circumferential stretching, the "ring elasticity," and the bending of the wall of the nut have effects on the final distribution of the load of the same order of magnitude as do the axial strain and bending of the threads.

Photoelastic study of bolt and nut fastenings[22] has shown that by the application of either a tapered-thread nut or a nut with a tapered lip the strength of the fastening can be increased by more than 30 per cent. This improvement in strength can be expected only in cases where the type of loading or conditions of application are conducive to brittle failure, *i.e.*, dynamic loads or static loads at elevated temperatures.

In an actual bolt-and-nut connection[22] the highest stress occurs in the first thread groove at the bottom of the nut. This can be readily understood on the basis of the simple axial deformation of the bolt and the nut, respectively, the strain in the bolt being principally tension and that in the nut compression. Even if the threads of the bolt and nut match with perfect evenness in the unloaded condition, as soon as load is applied the bolt stretches while the nut is compressed; hence even contact along the threads is impossible, and the load is transmitted chiefly at one point of contact, *i.e.*, at the seat of the nut. This extreme concentration of load, from considerations of the axial strains alone, will be substantially lessened, however, as the bending deformation of the threads is taken into account. It has been shown that this is of the same order of magnitude as the difference in the axial deformation of the bolt and the nut, and that it permits the upper threads to participate in carrying the load, though the main concentration of load still remains at the bottom of the threads.

Fatigue Strength

Threaded parts generally fail[12] in the first few supporting threads in the nut, probably because the first few threads transmit most of the forces through the nut and the remaining threads carry a decreasing percentage of the load. The flow of forces from the bolt through the nut must make a 180° turn, which results in a concentration of forces on the first few threads. It is this concentration, combined with the notch effect of the threaded shape itself, which causes low fatigue resistance.

Many fatigue tests have been made on bolt threads alone, without a threaded connection. Such investigations have shown how improved fatigue resistance could be obtained by employing large root radii and certain thread forms. Values obtained in this manner are too high for design purposes. It becomes necessary to test the entire assembly so that the flow of force through the threaded parts is comparable to the force expected in service.

Major factors influencing the fatigue resistance of threaded connections are: (1) material in bolt and nut, (2) design, (3) bolt flexibility, (4) tightening force or preload, and (5) method of manufacture.

The advent of high-speed engines,[1] such as are employed for automotive and aviation uses, where parts are subjected to rapid vibrations and stresses, introduced a type of failure in fastenings primarily caused by low fatigue capacity and poor shock resistance. Fatigue starts from a variety of causes and is progressive in nature, eventually culminating in complete rupture.

One of the most prolific causes of fatigue failure is the presence of sharp corners, notches, grooves, holes and other sudden changes in section that develop concentrated stresses. Threads of the standard V type have long been known to cause fatigue failures because of the stress concentration set up at the root of the threads. The introduction of the Whitworth thread was an attempt to overcome such effects of stress concentrations. In this thread the V at the root of the thread was rounded off to a radius equal to 0.137 of the pitch.

The effectiveness of the radius at the root of the Whitworth thread is shown [2] in Table 85.

TABLE 85. *Fatigue Tests on ⅜–16 U. S. Threads*

	Medium carbon steel			S.A.E. 2320 steel		
	Tensile strength (psi)	Endurance limit (psi)	*R*	Tensile strength (psi)	Endurance limit (psi)	*R*
Plain specimen	57,400	37,000	—	109,000	73,000	—
U. S. Standard		13,000	0.35		19,000	0.26
Whitworth		21,000	0.57		22,000	0.30

R is the endurance limit of the threaded piece divided by the endurance limit of the plain piece.

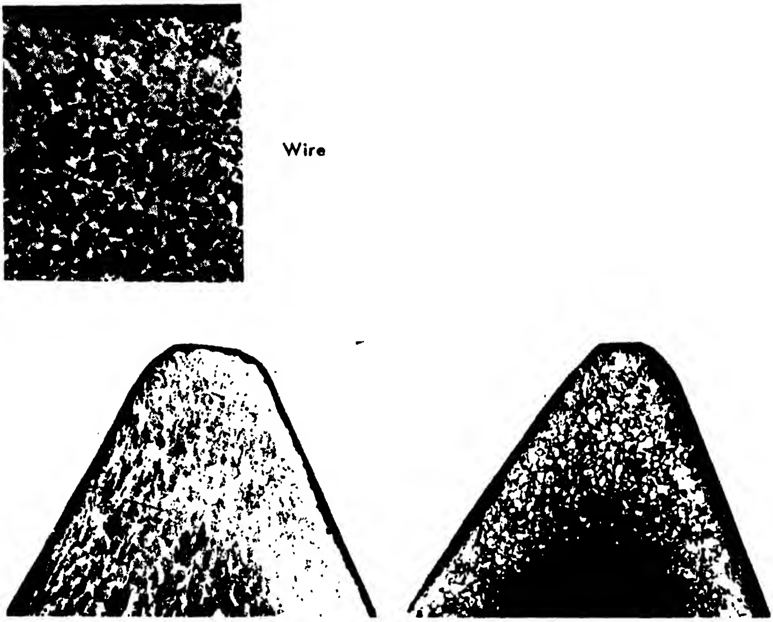
The fatigue tests were carried out under repeated applications of axial tensile stress that passed through a cycle from zero to maximum tension and back to zero.

Tensile strength values obtained on screw threads fail to detect the real significance of stress concentrations. Those of SAE2320 nickel steel were 90 per cent higher than in the case of medium-carbon steel, and the endurance limit increased about 97 per cent. However, when tests were made on screw threads, the U. S. Standard thread increased in endurance limit only from 13,000 to 19,000 psi, or about 46 per cent. The contrast is still more striking for the Whitworth thread, which showed an increase in endurance limit of 1,000 psi, or only 4.7 per cent, indicating that very little is to be gained with this type of thread by increasing the tensile strength of the steel. Such conclusions will not be arrived at from the tensile tests above. When both threads are cut in a medium-carbon steel the Whitworth thread has an increment of 54 per cent in the endurance limit; however, when the threads are cut in SAE2320 steel, the increment for the Whitworth thread is only 16 per cent.

Studs, bolts and screws used in engines are also subjected to repeated bending or flexural stresses developed by such actions as direct loading misalignment and vibration or whipping of the fastenings.

The endurance limit is affected by the shape of the threads. A round-bottom thread shows a higher ratio of endurance to tensile strength than a thread with a sharp V bottom. The spread between these two types depends upon the notch sensitivity of the material, as the V-bottom type has a higher stress concentration than the round-bottom type.

Screws with threads rolled on after heat treatment have a much higher fatigue strength than those with cut threads or with threads rolled on before heat treatment. In this connection it must be remembered that, while the fatigue strength of a smooth steel part can be increased by heat-treating and hardening, the notch sensitivity likewise is increased in the presence of threads, so that the net result may actually be a lowered endurance strength.



Wire

Bolt thread prior to heat treating **Bolt thread after heat treating**

(*Courtesy A. Jameson, International Harvester Co., Milwaukee, Wis.*)

Figure 65. Decarburization of bolt thread. Etchant Nital. Original magnification 100 dia.

The fatigue strength of threaded parts can be improved by making the length of the free thread between the head of the bolt and the nut at least equal to the diameter of the bolt. In addition, the length of the threaded part should be at least ½ times the diameter. It has been shown that for highest strength, the free thread above the nut should be at least twice the thickness of the nut. For a bolt threaded for only the thickness of the nut, the endurance strength drops to one-third.

Considerable improvement in fatigue strength has been obtained by reducing the material in the shank above the threaded section. This can be done by reducing the diameter of the shank, or by means of a concentrically bored hole along the longitudinal axis as far down as the beginning of the threaded portion.

Static tensile properties of materials often have been improved by means of stress-relieving notches. This treatment has been extended to threaded parts subjected to repeated stressing. Improvements in endurance have been obtained with a rounded circumferential groove in the shank immediately above the threads.

A decarburized surface layer in steel fasteners results in a decrease in endurance strength as well as in surface hardness. The endurance strength may decrease as much as 50 per cent. Conversely, both case-hardening and nitriding have been employed to increase fatigue strength. The decarburization of a bolt thread is clearly shown in Figure 65, illustrating the microstructure of the original material, and the microstructure of the bolt thread before and after heat-treating.

It was found[7] that for ⅜–24 thread fastener made from SAE1045 steel, the ratio of the endurance limit to the tensile strength of threaded section was about 68 per cent of the unthreaded section. Table 86 shows this ratio for differently fabricated threads on SAE1025 steel.

TABLE 86

Type of thread	Ultimate strength (psi)		Endurance limit	Ratio: $\frac{\text{Endurance limit}}{\text{Ultimate T.S.}}$	
	Wire	Specimen		Wire	Specimen
Cut thread	89,300	90,000	27,000	30.3	30.0
Single-extruded and rolled thread	89,300	99,700	33,000	37.0	33.1
Double-extruded and rolled thread	77,400	99,600	33,000	42.6	33.1

Therefore, for this steel, cut-threaded specimens had an endurance limit of 30 per cent of the ultimate strength of the threads and also of the original material. Single-extruded and rolled threaded specimens had an endurance limit of 33 per cent of the ultimate strength of the threaded specimen and about 37 per cent of the strength of the original material; while double-extruded and rolled threaded specimens had an endurance limit of about 33 per cent of the ultimate strength of the thread and about 42 per cent of the strength of the original material.

The vulnerability to fatigue[15] as a function of bolt tightness is shown in

Fig. 66. In the tests plotted, all bolts were subjected to a cyclic tension load of 9210 pounds, but were tightened to initial tensions of 1420, 5920, 7220 and 8420 pounds. Fifteen bolts were tested at each of the three lower loads in order to establish the scatter band for this kind of specimen. Only two bolts were tested in which the initial tension was 8420 pounds; one of these failed after 4,650,000 stress cycles but the second had not failed after 10,000,000. Bolts used in these tests were 3/8 in. diameter, accurately dimensioned and finished; threads were U. S. form, 24 threads per inch, and ground to close limits.

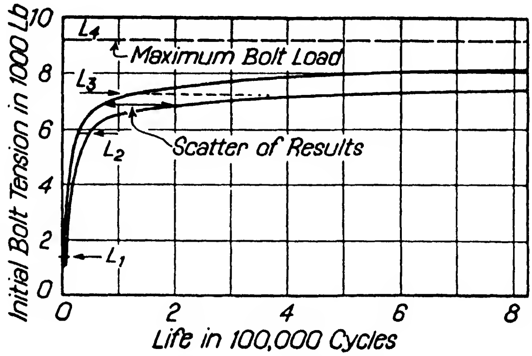


Figure 66. Effect of tightness (setting-up tension) on life of bolt in alternating tension.

The stress range to which these bolts were subjected is the difference between the initial tension and the maximum operating load; since it is known that the fatigue durability increases as the stress range decreases, we would expect results of the order obtained in the chart. All failures occurred in the threads except in a few cases in which the threads were rolled in a manner to pre-stress the roots in compression. In these rolled-threaded bolts the fatigue durability of the threads was increased sufficiently to cause failure in the shanks. When the surfaces of the bolt shanks were also compression pre-stressed by peening, the failures were again transferred to the threads but, of course, at prolonged durability. These tests also show that the fatigue durability of cut and ground screw threads can be increased by rolling, and that compression pre-stressing of the surface of pure tension members is effective in increasing their fatigue strength.

It is therefore evident that the fatigue strength of bolts and studs stressed in tension is dependent upon the *initial* tension applied by the nut, *plus* the elasticity of the bolted members. Thus washers, lock washers, gaskets and other units that add to the elasticity of the bolted assembly are definite fatigue hazards, and should be avoided whenever possible. The initial tension applied by the nut is difficult to determine unless the elongation of the bolt or stud can be measured. Measurement of the torque applied by the wrench gives very unreliable information because of the variability of friction.

The following facts regarding endurance limit must be considered when using hardened alloy steel bolts:

(a) The ratio of endurance limit to tensile strength for solid bars is about 45 to 70 per cent, depending on hardness.

(b) The ratio of endurance limit to tensile strength for threaded specimens is 12 to 16 per cent.

(c) For a tensile strength of 170,000 psi, the endurance limit of the solid bar is about 85,000 to 90,000 psi, but only 25,000 to 35,000 psi for threaded specimens.

(d) Heat-treated stock has a higher endurance limit when threaded after heat treatment than before.

(e) Milled thread has about the same endurance limit as ground thread on heat-treated stock, while turned thread has a higher endurance limit because of the relatively greater amount of work-hardening on the surface.

(f) When threads are ground before hardening the endurance limit is lower than when they are ground after hardening.

(g) When threads are machined before hardening the endurance limit is lower than when they are machined after hardening.

(h) Cut threads are weaker and have lower endurance value than rolled threads.

Applied Torque in Tightening

It has been said that the strength[8] of most highly loaded bolts and studs is determined by the operator with the wrench, and not by the designer, the metallurgist or the manufacturing process. In assembly the nut must be properly tightened against rigid members. A properly tightened nut is one that applies to the bolt or stud a tension load equal to or greater than the external load to be supported in service. When this condition is fulfilled and maintained against reasonably rigid bolted assemblies, the bolt cannot fail by fatigue. All bolted members should be as rigid as possible.

However, failure will occur where considerable flexibility is present. The variable stress in such bolt or screw fastenings increases with the flexibility of the connected parts, and if this flexibility is too great, the variable stress present may be high enough to cause eventual fatigue failures regardless of the initial bolt load.

Although properly tightened bolts are stronger as the rigidity of the bolted assembly and the elasticity of the bolt or stud are increased, a bolt or stud that is incapable of maintaining an initial tension equal to the external tension load is quite likely to fail in severe service. Thus we find relatively greater mortality among short bolts or studs than among long ones because of their lesser elastic yield. Greater safety is assured when the latter are used.

It will therefore be seen that among the major bolt and stud hazards, particularly when they are short, must be included loss of the bolted assembly as a result of surfaces that can imbed, soft-plated coatings that can be displaced, gaskets that can be plastically compressed, and materials that can yield at elevated operating temperatures.

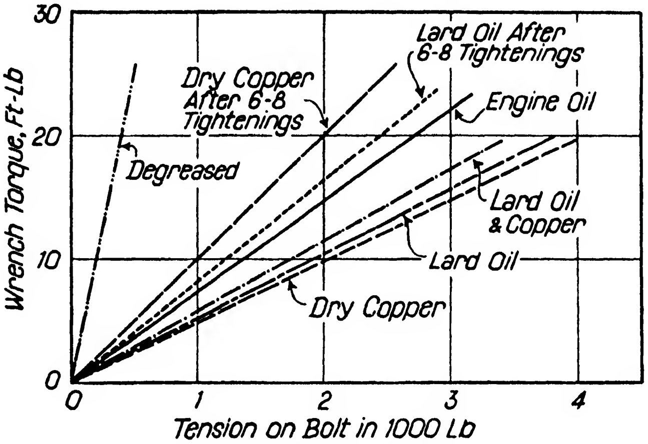


Figure 67. Effect of lubrication on bolt tension when set-up by a given torque on wrench.

A bolt or stud[15] should be tightened to a load that exceeds the maximum working load. When properly tightened against rigid members, a bolt or stud cannot fail because there can be no change in stress; the bolt load is static even though the load applied to the bolted members oscillates at high frequency from zero to a maximum. This rule must, however, be applied with caution because all bolted members are elastic in some degree and their design may be such that the applied load is greater than can possibly be supported by the fastenings.

Basically, bolt load or stress can be measured by only one method: checking bolt elongation. There are several ways to do this: (1) measure the bolt length before and after tightening, to determine its elongation; (2) heat the bolt to use its thermal expansion as a means of creating elongation; and (3) find by test the torque required on a nut to give the desired elongation or stress, and then check this torque on each succeeding bolt.

The constant-torque method of tightening bolts supplements the elongation method. For reasonable accuracy it is necessary to tighten sample bolts to the desired elongation while measuring the torque required. Once established, it can be repeated on other bolts, and presumably they will be given the same elongation and stress.

In tightening nuts,[8] it is far better to stress the bolt above the yield point of the material than to risk undertightness. Since for bolts of adequate size the load is practically static, there can be no harm in yield, provided that the plastic deformation is not so great as to reduce the static strength of the bolt. The amount of yield that can be tolerated will depend on the length and design of the bolt and the character of the material. When the body of the bolt or stud is equal in diameter to the outside diameter of the threads, yield will be concentrated at the roots of the threads whether the bolt is long or short. In such cases little yield, as measured by bolt elongation, can be tolerated. For bolts or studs in which the body diameter is equal to or less than the threaded root greater yield, as measured by bolt extension, can be tolerated, since yield will occur over the entire body length.

When nuts are tightened to any degree, just short of bolt failure, the bolts still have all their original tensile value available for resistance to external load. The use of oil on the threads and a washer under the nut has no appreciable effect upon this result.

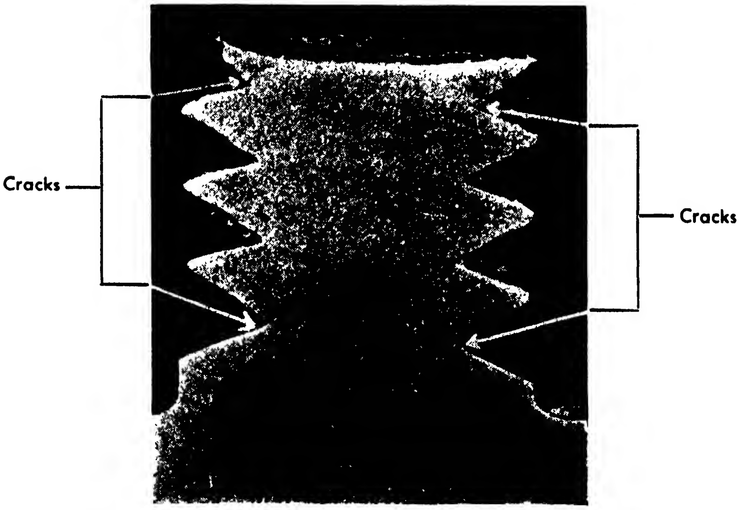


Figure 68. Longitudinal section through the $\frac{5}{16}$ –18 threaded end of stud.

Figure 68 is a photograph (8 times magnification) of the longitudinal section through a $^{5}/_{16}$–18 threaded end of a stud showing cracks at thread roots due to over-tightening of the part during assembly.

In tightening bolts or nuts, a major portion of the torque load is used to overcome friction at the threads and under the head. The friction absorbs about 90 per cent of the applied torque. Thus only a fraction of the torque loading is converted to tension stress on the bolt. Under assembly conditions the breaking torque is greater than theoretical because the friction under the head of the bolt or nut prevents the full torque load from reaching the shank of the bolt. This friction may cause 20 to 150 per cent more torque load to cause failure, depending on the smoothness of the surfaces in contact.

As previously mentioned, the best way to specify nut tightness[8] is by the use of torque wrenches. By specifying nut torque, all nuts of the same size are presumed to give the same bolt tension. However, the friction between the threads of the bolt and the nut are so variable that the bolt tension will vary over wide limits. Still, the torque wrench is the best means of applying the proper torque in tightening the nut to avoid under- or over-tightening.

Higher operating speeds, and the tendency toward reduced unit weight on modern equipment of all types has directed closer attention to the importance of applying proper torque values when tightening nuts and bolts. In practically every case the torque values to be used when torquing the nut are substantially lower than when torquing the bolt head. The necessity for this is proved by the fact that in all tests the threads inside the nut sheared to a greater extent than the threads on the bolt. The torque in inch-pounds is reduced when using lubrication primarily because the friction is less between the contact parts of the nut and plate. Consequently with less friction, a higher stress would be set up in the bolt as compared with the same applied torque with no lubrication. A greater torque in inch-pounds is required to produce the same stress when torquing the head of the bolt than when torquing the nut. However, if widths of nut and head are the same and the surfaces are the same, this difference in bolt stresses may be negligible.

Table 87 shows the average per cent torque to produce 30,000 psi stress in all sizes of steel bolts.

TABLE 87. *Average Per Cent Torque to Produce 30,000 psi Root Stress in All Sizes of Bolts*

Torquing of	Condition	%
Nut	No washers, no lubrication	100
Nut	Washer at head and nut, no lubrication	97
Nut	Vaseline-lubricated threads, no washers	63
Nut	Vaseline-lubricated threads, washers	61
Head	No washers, no lubrication	115
Head	Washer at head and nut, no lubrication	112
Head	Vaseline-lubricated threads, no washers	72
Head	Vaseline-lubricated threads, washers	70

Failure

Usually there are two types of failures in threaded fastenings: (1) rupture through the thread and (2) rupture under the head. Then again it may be said that a fastening fails because the part loosens and breaks out, the part breaks, or the threads strip.

In tension,[5] with little or no superimposed bending, ductile breaks through the threads occur except in the hardened steel bolts. Hardened bolts show brittle failures under the head at low and widely scattered loads, thus indicating greater notch sensitivity at this point than in the threads. Failures under the head can be prevented by adding a stress relief radius from shank to head. Superimposed bending at either the head or thread end causes brittle failures in these sections at considerably reduced load. Brittle breaks under the heads are suppressed by the use of a relief groove.

Failure can occur because a fastener is too soft or too hard for the application, or is overloaded; from concentration of stresses in a sharp corner or threaded section; or even from defective material or improper heat treatment. The design of threaded fasteners is such that the bolt breaks before the threads strip.

It is commonly believed that a bolt is twisted off in a simple torsional shear failure. However, there is a shearing stress in the bolt due to the torque applied by the friction between the threads of the bolt and the nut as the nut is turned. Results indicate that this torque approaches about 45 per cent of the applied torque. The combined mechanical advantage of the wrench leverage and of the thread incline results in an axial force or "clamping force" on the bolt, which causes primary tensile components dominating the failure process. The principal effect of the shearing stress in the bolt is to reduce the clamping force at failure to a point averaging about 80 per cent of the strength of the bolt in direct tension.

When the axial stretch of the threaded section of the bolt approaches its ultimate value, the threads of the nut no longer fit the threads of the stretched bolt; thus tremendous friction develops between the nut and the bolt, which will twist off the bolt if the twisting process is carried far enough. However, the bolt is actually pulled off rather than twisted off by the resultant axial tension in the bolt, which stretches the bolt beyond its elastic limit.[20]

Although it is frequently assumed that if a screw or bolt is tightened to a load greater than the applied external load, fatigue failure will not occur; this is true only if the connected members have a sufficiently high rigidity; it is not the case where considerable flexibility is present. It has been shown that the variable stress in such screw or bolt fastening increases with the flexibility of the connected parts, and, if this flexibility is too great, the variable stress present may be high enough to cause eventual fatigue failure regardless of the initial bolt load.

To repeat what was previously stated, threaded parts generally fail in the first few supporting threads in the nut. This is probably because the first few threads transmit most of the force through the nut, the remaining threads carrying a decreasing percentage of the load. The flow of force from the bolt through the nut must make a 180° turn, resulting in a concentration of force on the first few threads. It is this concentration of force combined with the notch effect of the thread shape itself which leads to low fatigue resistance.

During their service life[1] screw fastenings are often subjected to shock loads that must be sustained without failure or without the development of incipient cracks. The stress concentrations produced at the roots of threads are known to reduce greatly the resistance of the material to shock or impact loads. Poor shock resistance may be a direct cause of failure; or it may be an indirect cause resulting from very fine cracks, which act as nuclei from which fatigue cracks grow and spread to ultimate failure.

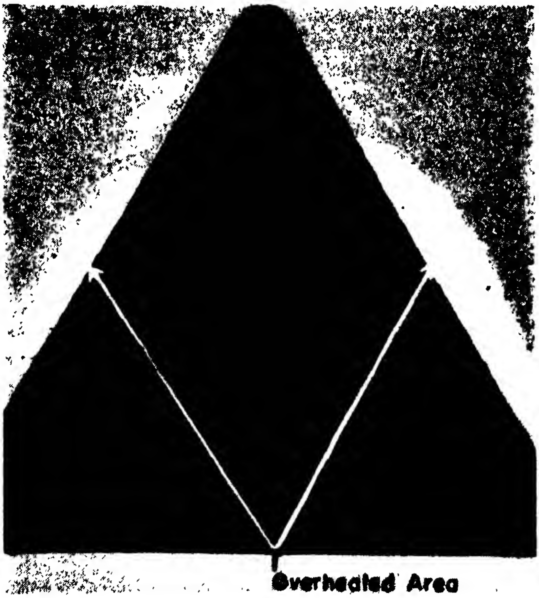


Figure 69. Screw threads overheated in grinding. 75x.

Normal design computations are usually based on tensile stresses which are average unit stresses, and which neglect residual stresses in the material.

However, it is not the average stress but the maximum stress that causes a part in simple tension to fail, particularly under repetitive loads. Maximum stresses may be several times the average. Residual stresses can be harmful or beneficial, depending on how they are superimposed on the stress pattern developed by the working loads. Since fatigue cracks originate in tension zones, a residual compression stress will increase fatigue life, and a residual tensile stress will decrease it.

Grinding the threads of unheat-treated steel bolts, studs and screws is sometimes the cause of failure because of residual stresses. Abusive grinding may cause hardening on the side of the thread due to overheating. This localized hardening leaves the thread in a highly stressed condition which, coupled with service stresses, may cause failure.

High-strength steel fasteners that are intentionally hardened by heat treatment before grinding of threads may be softened by the annealing caused by heat generated on the thread surface by abusive grinding. Figure 69 is a photomicrograph (100 × magnification) of screw threads overheated in grinding. The threads were ground after hardening of alloy steel blanks to 34–38 Rockwell C. The sides of the threads show temper colors and lower hardness due to partial anneal caused by heat developed in abusive grinding.

Figure 70 shows other serious causes of screw fastener failures[16] which are related to manufacturing rather than to design. At the left is a longitudinal quenching crack developed during hardening and at the right is a longitudinal seam indicative of defective material.

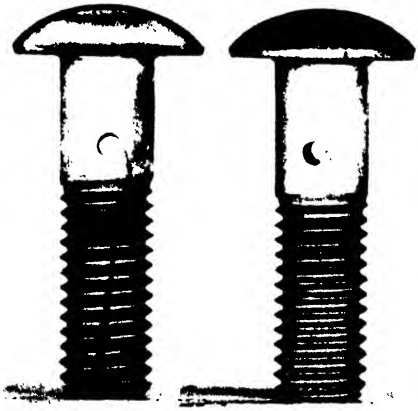


Figure 70. Cracked bolts. *Left:* Quenching crack. *Right: Seam.* Etched in 1:1 HC1.

(Courtesy A. Jameson, International Harvester Co., Milwaukee, Wis.)

Figure 71 shows a typical fatigue failure under the head of a threaded bolt. Figure 72 shows a number of broken heads of alloy steel bolts due to over-tightening in a torque-assembly test.

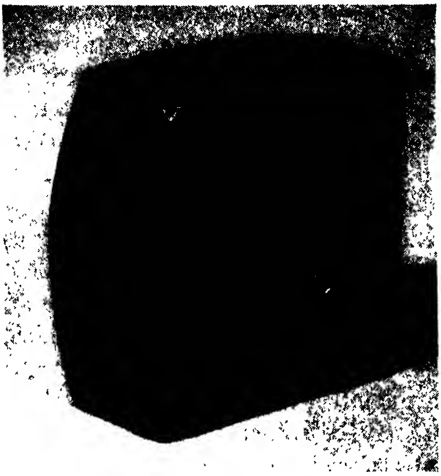


Figure 71. Broken head of threaded bolt.

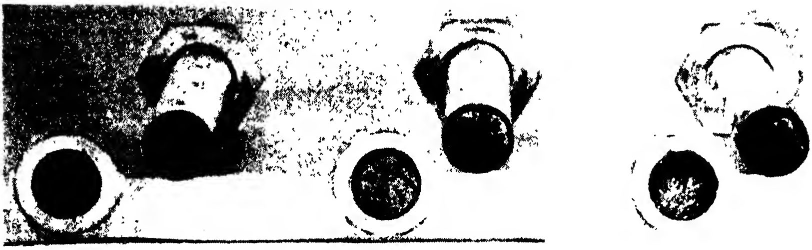


Figure 72. Broken bolt heads.

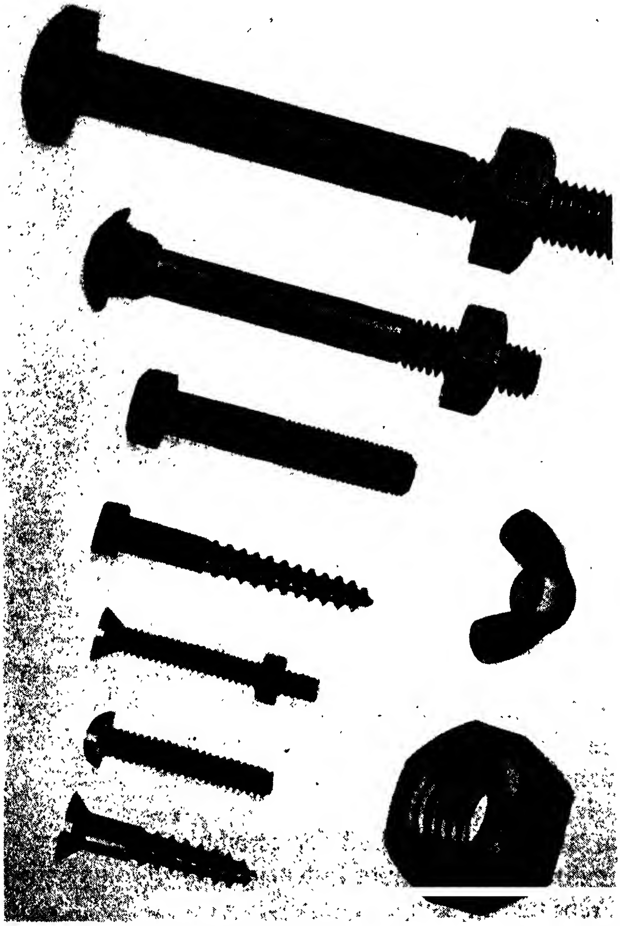
Corrosion

Metal stressed in its surface layers[13] and at the same time wet with moisture is subjected to conditions that tend to weaken it considerably. In the case of unprotected or poorly protected steels, exposure to moisture for a few days is sufficient to damage the metal seriously without simultaneous stress. When stress is applied simultaneously with exposure to corrosion the degree of damage is still greater. Corrosion fatigue and stress-accelerated corrosion are reflected in a drop in fatigue limit and are extremely important in practice. Bolts in service are almost always under stress if only from the tightened nut; and in most outdoor and other services the bolts are exposed either to moisture or to submersion conditions.

Although strength in fatigue is most sensitive to the damaging effect of stressless corrosion and stress-accelerated corrosion, simple bend strength and torsional strength are likewise affected, and to a lesser extent, simple tensile strength.

High-copper alloys are subject to the type of corrosion known as corrosion cracking, which results from the association of strains left in the metal by cold-working (*e.g.*, cold-upsetting of bolts) under certain corrosive conditions. The subsequent failure is a typical intergranular embrittlement. "Monel" metal is not subject to this type of failure.

In chemical plants and other industries where corrosion is a serious matter due to the use of corrosive media, "Monel" has the advantage of longer life and a greater safety factor.

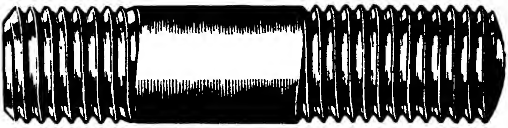


(Courtesy National Screw & Mfg. Co., Cleveland, Ohio.)

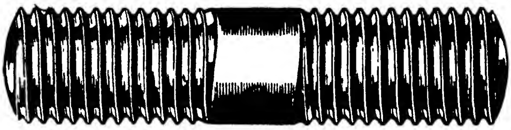
Figure 73. Types of bolts, nuts, and screws.

Plating and Finishing

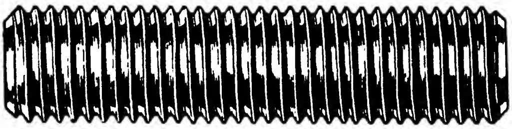
Finishes applied to fasteners are either for appearance or for corrosion prevention, or both. Another purpose is to prepare the surface for painting. Coatings include nickel, chromium, cadmium, brass, copper, tin, zinc, lead and the application of special rust preventive processes such as Parkerizing, sherardizing, etc. An electroplated coating is often left in a highly stressed condition and may initiate fatigue cracking. To prevent decrease in the endurance of the part, the plating procedure should be so adjusted that the deposited metal is left in an unstressed condition. Absorption of hydrogen during electroplating causes hydrogen embrittlement if parts are not baked. When heavy electroplates are required, ±0.001 inch in mating parts does not constitute sufficient clearance for mating without interference; in allocating additional clearance, it is erroneous to make clearance four times the required plating thickness.



Tap end stud



Double end stud



Continuous thread stud

(Courtesy Erie Bolt & Nut Co., Erie, Pa.)

Figure 74. Studs.

Aluminum alloys are anodized for maximum resistance to corrosion. However, anodizing of aluminum fasteners is not recommended if parts are subjected to repeated stressing.

Bolts, nuts, studs and screws are small, and therefore the importance of the proper selection of a fastener for a specific application has often been overlooked. Frequently the cost of the item is but a small percentage of the cost of the application, and both together are a small part of the cost of the finished unit; still, the functioning of the entire unit is largely dependent upon adequate joining of the parts. This emphasizes the predominant importance of proper selection and use of fasteners to the economy of the completed equipment and its servicing.

Figure 73 illustrates various bolts, nuts, and screws, and Figure 74 illustrates the tap end stud, the double end stud, and the continuous thread stud.

A DIGEST OF THE NEW UNIFIED SCREW THREAD SYSTEM [27]

On November 18, 1948, an agreement was signed between the United States, Canada and Great Britain concerning a Unified Screw Thread System which applies to international specifications.*

"*Thread Angle.* The thread form will have a 60° included angle the same as the American-National Form (the British are changing their thread from 55° to 60°.)

"*Crest of Screw.* We will continue our present flats but permit a round (the British will round theirs).

"*Root of Screw.* Described as a rounded root contour with the high limit similar to the round previously permitted by a worn tool and a low limit with a flat equal to our basic flat P/8 and now described as permissible with a new tool.

"*Crest of Internal Thread.* Both British and Americans will have flats created by the tap drill.

"*Root of Internal Thread.* Ours will be flat or slightly rounded but with flat limits between P/8 or P/24. (British will have rounded tapped hole roots but with major diameter greater than basic.)

Thread Series. The thread series will include our present Coarse and Fine Series, but only sizes from ¼" up are 'Unified.' The publication will also include present National Extra Fine, 8, 12, and 16 pitch. The Coarse thread series will be similar to the present American-National as to sizes but there will be a ½"-12 added because this was a popular British size and very much wanted by them. Our ½"-13 will also be listed but not considered as a 'Unified' size.

In the Fine pitch series, the 1" diameter thread will be 12 threads per inch instead of 14.

"*Thread Classes.* New tolerances have been developed known as 'A' tolerances for screws and 'B' tolerances for tapped holes. These tolerances are based on a formula that varies the tolerance with (1) the diameter, (2) length of engagement and (3) pitch. It will be remembered that in the American-National Coarse and Fine Thread Systems, the tolerances were the same for a given pitch, even though the diameters were different. For example: a ½"-20 thread had the same tolerance as ¼"-20 even though the diameters were different and the gages of different thicknesses. In the A and B systems of tolerances, ½"-20 will have a slightly greater tolerance than ¼"-20, etc. In other words, for a given pitch the tolerance is larger if the diameter is larger.

Tables will provide tolerances for what will be called 1A and 1B, 2A and 2B, 3A and 3B (A designates the screw and B the tapped hole). These new classifications will correspond in purpose to the previous Class 1, Class 2 and Class 3 Fits.

The 1A and 2A (screws) will have maximum pitch diameters below basic so as to provide an allowance or positive clearance between the maximum screw and minimum

---

* See American Standards publication ASA B1. 1 entitled "Unified and American Screw Threads For Screws, Bolts, Nuts and Other Threaded Parts." This American Standards publication includes thread sizes and system of tolerances on which Canada and England are in agreement, together with American standards not included in the new British standards.

tapped hole. These allowances will be the same for Class 1A and Class 2A. See Fig. A.

1A and 1B pitch diameter tolerances are greater than 2A and 2B while 3A and 3B tolerances are less than 2A and 2B. In the case of 3A and 3B, the maximum screw and minimum tapped hole can be basic, the same as in Class 2 and Class 3, i.e., no allowance. See Fig. B.

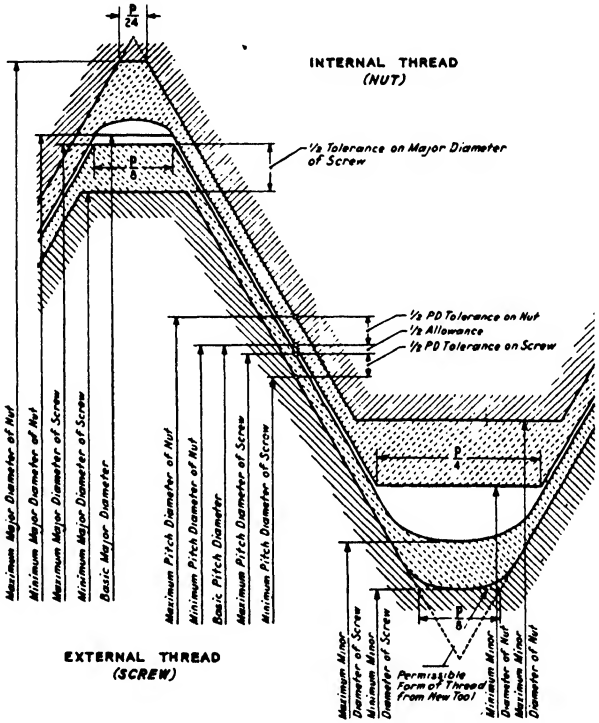


Figure A. Illustrating tolerances, allowance, and crest clearances for classes 1A, 1B, and 2A and 2B.

The publication will also include the past practice tolerances for Class 2 and Class 3 but will not be called 'Unified.'

Tables of tolerances for all the *different thread series* are provided.

Tolerances for Class 2A are derived from the formula, reflecting increments of pitch, diameter, and length of engagement. Tolerances for the other Classes are derived from 2A, as follows:

2B tolerance—130% of 2A tolerance
2A allowance—30% of 2A tolerance
1A allowance—same as 2A allowance
1A tolerance—150% of 2A tolerance
1B tolerance—195% of 2A tolerance
3A tolerance—75% of 2A tolerance
3B tolerance—97.5% of 2A tolerance

In all A and B tolerances the B (tapped hole) tolerance is 30% greater than the A (screw) tolerance.

"*Selected Specials*. Tables of tolerances are also provided for a selected group of special sizes in which the tolerances are based on a length of engagement of 9 threads.

"*Specials*. Another series of tables of tolerances are provided for special combinations of diameters and pitches. These are step tables that provide tolerances for different lengths of engagements as related to the diameters. For example: lengths of engagements equal to ⅓D, ⅔D, 1½D, etc.

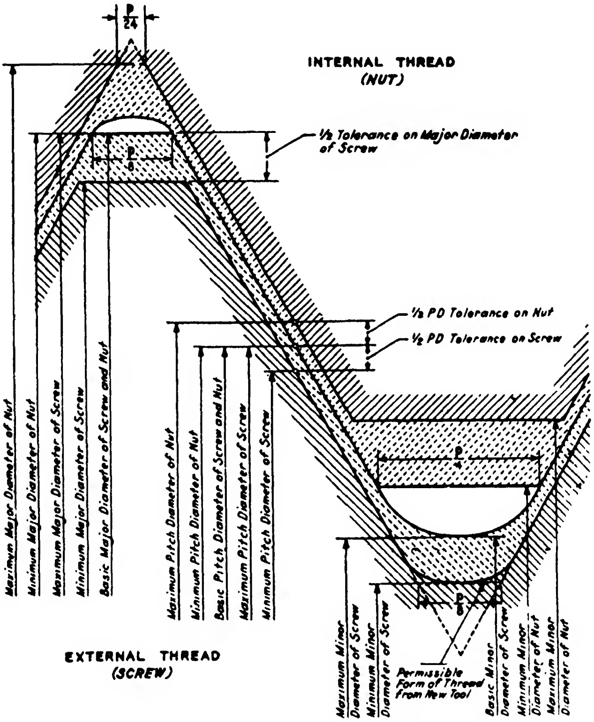


Figure B. Illustrating tolerances and crest clearances for classes 2, 3, and 3A and 3B.

"*Designations*. The designation for the unified screw thread will be UN. Thus, UNC indicates Unified Coarse Thread Series, UNF, Unified Fine Thread Series. Example: ¼ UNC-2A will mean a ¼"-20 screw Class 2A tolerance. The other thread series not included by the British have the designation N.E.F. for extra fine, N8 for 8 pitch series, N12 for 12 pitch series and N16 for 16 pitch series. Bear in mind that only the coarse and fine series from ¼" up and in the A and B Classes of tolerances are "Unified."

It is expected that old Class 2 and Class 3 fits will be continued in use for quite some time due to the investment in gagès but many new products coming along may specify the A and B tolerances and require new gages.

"*Allowance*. The purpose of the allowance in Class 2A and 2B system of tolerances is to provide limits that will ensure that the maximum screw is never as great in pitch diameter as the minimum tapped hole. This allowance or clearance is a desirable thing in the case of mass production assembly where often times under the old Class 2 and Class 3 Fit system there would be screws that would be too tight a fit in the tapped hole and thus require the assembly to be taken from the production line and sent to salvage.

In the Class 1A and 1B, the tolerances are wider to provide practically finger assembly and ample provision for plating.

In the Class 3A and 3B, there is no allowance provided for. Hence, the maximum screw could be as great in pitch diameter as the minimum tapped hole. The tolerances, however, are slightly wider for the Fine Pitch Series than for the Coarse Pitch Series.

It is interesting to know that in the case of Die Head Chasers, the same chasers can be used for the Unified system as for the American-National because it is simply a matter of adjusting the die head to provide pitch diameters on the screw within the tolerances specified. The thread profile of present chasers should meet the requirements of the new Unified Screw Thread profile."

References

1. Slaughter, E., "Tests on Threaded Sections," *Metal Progress* (March, 1933).
2. Pulsifer, H., "Strengthening Effects of Bolt Threads," *Steel* (Feb. 11, 1935).
3. Peterka, A., "Bolts and Nuts Keep Pace with Progress," *Iron Age* (March 18, 1937).
4. Moore, R., "Strength of Screw Threads," *Product Engineering* (November, 1939).
5. Moore, H., "Strength of Screw Threads under Repeated Tension," University of Illinois Eng. Expt. Station, Bulletin No. 264.
6. Smith, A., "Screw Threads," *Iron Age* (Aug. 22, 1940).
7. Williams, G., "Selection of Steels as Affected by Endurance Limit," *Metal Progress* (April, 1941).
8. Jameson, A., "Bolts: Material, Heat Treatment and Physical Properties," *Iron Age* (May 14, 1942).
9. Sacks, G., "Strength of Heat-treated Alloy-steel Bolts," *Trans. A.S.M.* (1943).
10. Hetenyi, M., "Photoelastic Study of Bolt and Nut Fastenings," *J. Applied Mechanics* (June, 1943).
11. Arnold, S., "Effect of Screw Threads on Fatigue," *Mech. Eng.* (July, 1943).
12. Almen, J., "Fatigue Failures in Common Machine Parts," *Metal Progress* (May, 1943).
13. Millard, A., "Machine Screw," *Mech. Eng.* (October, 1943).
14. Korn, A., "Torque-Stress-Load Relationship in Bolts and Screws," *Product Engineering* (November, 1943).
15. Almen, J., "Strength of Highly Stressed, Dynamically Loaded Bolts and Studs," *S.A.E. Journal* (April, 1944).
16. Jameson, A., "Automotive Bolts," *Iron Age* (Aug. 23, 1945).
17. Carr, L., "Flange Bolts," *Power* (February, 1946).
18. Maney, G., "What Happens When a Bolt is Twisted Off," *Fastener J.* (1946).
19. Crampton, D. K., Chase Brass and Copper Co., private communications.
20. Thum, E., "Book of Stainless Steel," American Society for Metals.
21. Hill, H., "Does Torque Weaken Bolts?" *Fastener J.*, Vol. 4, No. 1.
22. Vandervoort, W., "Machine Shop Tools and Shop Practice," Norman W. Henley Publishing Co.
23. "Engineering Properties of Monel Bolts," Inco Bulletin T-1.
24. "Metals Handbook Committee," American Society for Metals. (See Metals Handbook, 1948.)
25. "Bolts, Nuts and Screws," Lawson and Sessions Co. bulletins.
26. Anon., "Selection and Application of Fastening Devices," *American Machinist* (May 24, 1945).
27. Eastern Machine Screw Corp. "Die Headlines," Vol. III, No. 5 and No. 6, 1949.

Section III

Materials for the Electrical Industries

Chapter X

Magnetic Materials

A few metals have the distinguishing property of magnetism. Iron exhibits this property most strongly, nickel and cobalt less so. However, a group of special alloys, some of the constituents of which are nonmagnetic under ordinary conditions, can be prepared and treated to produce certain magnetic properties in excess of those of pure iron itself. These metals and alloys comprise the group known as "magnetic materials" or more properly "ferromagnetic materials," having magnetism similar to that of iron.[10]

The basic nature of magnetism is not completely known, although Bozorth and Shockley[3, 4] have published data indicating that there is a distinct relationship between magnetism and the electron arrangement of the elements in question. The fact that the three important magnetic elements also form the transition group of elements in the Periodic Table bears this out. Although ferromagnetism cannot be accurately defined, the external manifestation can be measured readily and used to advantage, namely, the force with which one ferromagnetic body attracts or repels another when one or both are magnetized. The distance over which this force is effective is a measure of the degree of the ferromagnetism of the material. This force can be controlled and directed to produce useful work.

Present theory, ably described by Bozorth,[4, 19] ascribes the property of ferromagnetism to the spinning electrons within an incomplete inner electron shell of the atom and to the spacing of the atoms. The electrons, spinning in clockwise and counterclockwise directions, act as tiny magnets. In many atoms the spins neutralize one another so that no excess spin remains to produce manifestations of magnetism. In iron, cobalt and nickel, however, there is an excess of electrons spinning in one direction and the spacing of the atoms is such that the effects can add up to produce a high degree of ferromagnetism. The electron shells in the iron atom can be pictured as in Figure 75. A few other elements such as manganese and chromium also have incomplete inner electron shells, but the normal spacing of the atoms does not fulfill the conditions necessary to produce ferromagnetism.

The magnetic properties of ferromagnetic materials vary in the same manner as the other physical properties of metals and alloys, in that the same factors, such as grain size, amount and distribution of impurities, heat treatment, and method of fabrication, all contribute to the resultant magnetic properties. As in other types of testing, as many variables as possible must be controlled when measuring for a specific property to insure reproducible results.

Magnetic materials fall roughly into two general classifications; namely, magnetically hard or "permanent" magnet materials, and magnetically soft or "electromagnetic" materials. Both are ferromagnetic, but the classes differ in respect to their ultimate properties and uses. Permanent magnet materials are used because of the high degree of magnetism (or residual magnetism) retained when the magnetizing force is removed; electromagnetic materials are used to increase the strength of an electromagnetic field, and retain little or no magnetism upon removal of the magnetizing force.

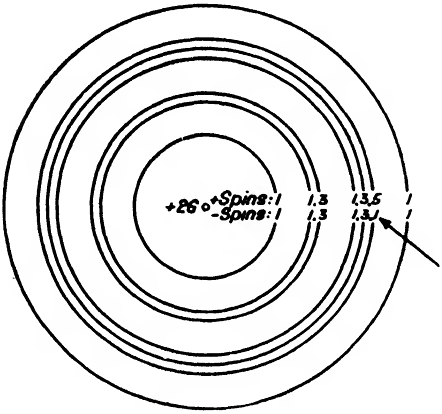


Figure 75. Electron shells in the iron atom.

Magnetic Properties

The principal terms used in describing the magnetic properties are defined in the following manner. The magnetic flux ϕ represents the total lines of force passing through the magnetized object; in the metric system the unit is the "maxwell," and in the English system the "line"or "kiloline" (1000 lines). The unit of magnetic force, called "magnetizing force," is denoted by the symbol H; in the metric system the unit is the "oersted," and in the English system the "ampere-turn." The unit of magnetic intensity, called the "magnetic induction," is the magnetic flux per unit area. It is denoted by the symbol B; in the metric system the unit is the "gauss," and in the English system the *line* or *kiloline* per square inch. The maximum number of lines or maximum magnetic induction which a material can absorb per unit area is called "saturation point," and the value of the induction is designated as B max. When a magnetizing force has been applied, a given magnetic induction attained, and the magnetizing force is removed, the magnetic induction does not return to zero, but an amount which is characteristic of the material is retained and designated as the residual magnetism, Br. In order to reduce this residual magnetism to zero, a magnetizing force of opposite direction to the original magnetizing force must be applied. The amount of this negative magnetizing force necessary to reduce the residual magnetism to zero is called the *coercive force, Hc.* The unit of residual magnetism, Br, is the same as for the magnetic induction, B, while the unit of coercive force, Hc, is the same as for the magnetizing force, H, as shown above. This property of magnetic materials results in a loss in magnetic energy directly proportional to the area enclosed by the completed loop known as the "hysteresis loop" (Figure 76). For permanent magnet materials, this loop is large, as a high residual magnetism and high coercive force are desirable, while for electromagnetic materials, it is small, as it represents an energy loss in an alternating-current circuit.

The hysteresis loss represents part of the core loss described below. The maximum hysteresis loss occurs in a given material when the original magnetizing force is sufficient to produce saturation (B max.), although a loop is always obtained when the magnetizing force is removed, even for values of this force less than that producing saturation (B max.).

The permeability or "magnetic conductivity" is represented by the symbol μ and is expressed as a number. It is derived from the equation $B = \mu H$. The permeability is not a constant, but varies with the induction, so that a permeability curve approaches a value at which an increase in the magnetizing force does not result in an increase in the induction. This value of the induction corresponds to the "saturation point" described above. The permeability curve is represented in Figure 76 by the curve OS, and the permeability value is actually the slope of the curve at any given point. The maximum permeability is the slope of the straight line drawn from point O, the origin, and tangent to the curve OS at its closest approach to the ordinate OB. The permeability, therefore, describes the ease with which the material can be magnetized, that is, how much flux can be produced for a given magnetizing force or electric current.

To magnetize a material, electrical energy must be supplied; some of this is lost as heat energy because of the electrical resistance of the conducting wire (commonly termed "copper losses"), and some as a result of the presence of the magnetic material (termed "core loss"). Part of the core loss is due to the magnetic friction or hysteresis loss described above. The balance of the core loss results from eddy currents induced in the magnetic core by the passage of current in the magnetizing coil. The eddy current and the current in the magnetizing coil are not physically connected, but the eddy currents are generated by change in flux in the core in accordance with the change in electric current in the coil when alternating current is used. For solid cores with no restrictions, the eddy current loss is large; for laminated cores where restriction occurs at each interface between laminations, it is reduced, being less for thin sheets than for thick sheets inverselv as the square of the thickness down to about 0.014 inch. Below this thickness, the eddy current loss increases slightly for some unexplained reason, particularly at high frequencies. In other words, decreasing sheet thickness will decrease the eddy current losses. The core loss is customarily measured in watts per pound at an induction of 10,000 gauss and using 60-cycle current.

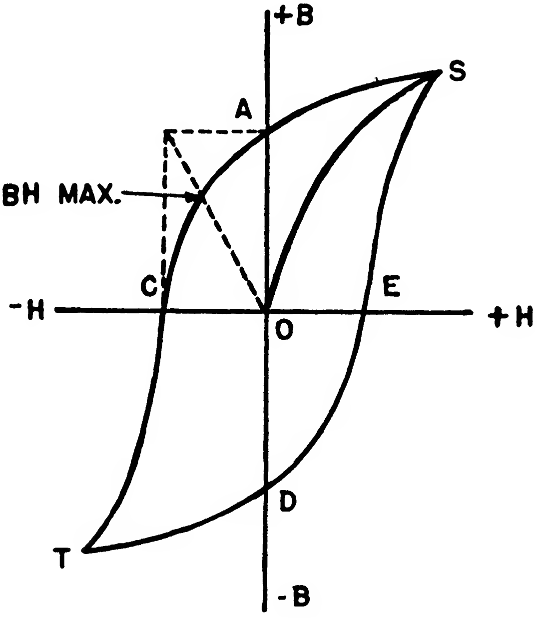


Figure 76. Typical hysteresis loop.

Ordinate "B"—Magnetic induction or flux density.
Abscissa "H"—Magnetizing force.
Curve OS—Normal induction or magnetization curve.
OA—Residual magnetism—Br.
AC—Demagnetizing curve.
OC—Amount of demagnetizing force necessary to reduce residual magnetism in zero-coercive force HC.
SACTDES—Complete hysteresis loop—total energy lost in one cycle.

The space factor is the ratio between the weight of a given volume of laminations under a given pressure to the weight of the same volume of solid steel of the same composition as the laminations. This is required in design to allow for magnetic material loss as a result of the air gap between the laminated sheets. The space factor is usually 90 to 96 per cent, being higher for thicker sheets and lower for thinner sheets. The energy product is a measure of the strength of a permanent magnet material and indicates the available magnetic energy. It is derived from the hysteresis loop of the material, and is obtained by plotting the product of B times H against B from the demagnetization curve (Curve AC in Figure 76). This results in the energy product curves[17] as shown on the right half of Figure 77. The values of B and H corresponding to the maximum energy product may be found approximately as shown by the dotted lines in Figure 76.

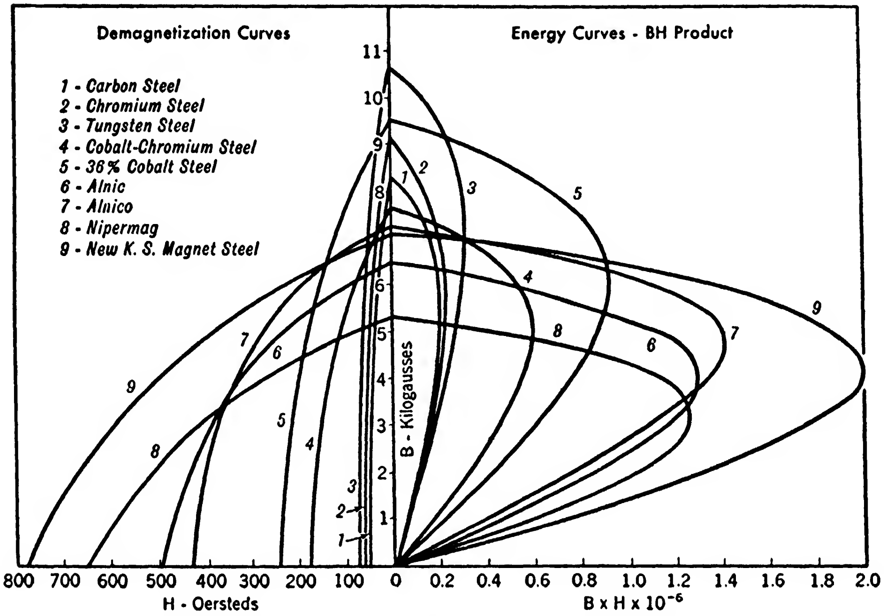


Figure 77. Demagnetization and energy product curves for various permanent magnet materials.

Magnetically Soft Materials

Magnetically soft materials require the passage of electric current and are referred to as *electromagnets*. They are characterized by the following:[12] (1) low residual induction, (2) high permeability, and sometimes high or constant permeability at low field strengths, (3) low hysteresis loss, (4) low eddy current loss (high electrical resistivity), (5) high saturation value (as high as other considerations permit), and (6) a definite change in permeability with change in temperature by certain alloys called *compensator alloys.*

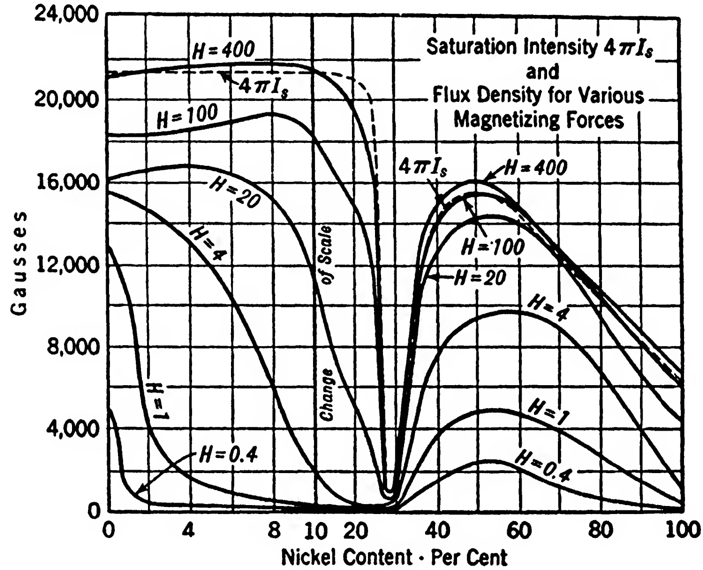
Magnetically soft materials include iron, iron-nickel alloys, iron-silicon alloys, iron-aluminum alloys, iron-aluminum-silicon alloys, iron-cobalt alloys, and iron-nickel-cobalt alloys. The iron-nickel alloys sometimes contain additions of chromium, molybdenum, or copper to emphasize one or more of the six characteristics listed above.

Certain impurities are normally present in all these alloys. Some of these adversely affect the magnetic properties and should be kept as low as possible. Since the magnetically soft properties are largely dependent upon the uniformity of a material, any impurity which obstructs the path of the magnetic flux will adversely affect the properties. This includes such impurities as carbon, phosphorus, sulphur, nitrogen, and oxygen, all of which form non-metallic or intermetallic compounds that precipitate out of the iron-rich matrix and become physical obstructions to the lines of magnetic flux. By the same token, grain boundaries act as disjunctive points, and as large a grain size as possible is desirable to minimize the number of grain boundaries across which the magnetic flux lines must pass. Any element that remains in solid solution in the iron-rich matrix, on the other hand, will not adversely affect the properties; for example, manganese below 0.80 per cent and copper below 0.25 per cent. These points will be discussed more fully in the following sections on the individual alloys.

Pure Iron. While pure iron may, in many respects, be regarded as the ideal ferromagnetic material, it has certain undesirable qualities that must be reduced by alloying with other elements. Yenson and Ziegler [2] have shown that the permeability of iron approaches infinity as the purity is increased. It has good demagnetization characteristics (low residual magnetism) when properly heat-treated, and a high saturation value. Pure iron has certain disadvantages which make it unsuitable for most commercial applications, *e.g.*, low resistivity (about 10.5 microhms per cubic centimeter), which necessitates the use of very thin sheets to keep the eddy current losses down; high cost due to the high purity necessary; and a relatively low recrystallization temperature, resulting in an aging phenomenon in which the magnetic properties are drastically reduced. For these reasons, iron alloys are now almost universally used where good magnetic properties are desired. Commercially pure iron such as "Armco" iron is widely used as part of the magnetic circuit in the form of yokes and pole shoes for high-output generators and motors and heel irons and cases for voltage regulators.

Iron-Nickel Alloys. The iron-nickel alloys, particularly those containing 45 per cent or more nickel, possess valuable magnetic properties. Certain of these alloys may, by special heat treatment, be made to emphasize one or more of the magnetic properties of this group. Figure 78 shows the saturation intensity and flux density of iron-nickel alloys for various magnetizing forces.[10, 12, 18]

The 45 to 50 per cent nickel alloys are characterized by high permeability for higher field strengths. The permeability is not so high as in the case of high-nickel alloys; the residual induction is higher, but the higher saturation value permits higher field strengths. The best magnetic properties are obtained after a high-temperature annealing in a hydrogen atmosphere. The annealing temperature most widely used is 2000 to 2100° F., followed by a very slow cool to room temperature at a rate not exceeding 200° F. per hour. These materials are very susceptible to work-hardening, which results in machining and forming difficulties, mainly overcome by light cuts at slow speeds or by frequent annealing in forming operations. A satisfactory annealing treatment for restoring workability during drawing or forming consists of heating to 1450 to 1500° F. in a controlled-atmosphere furnace followed by cooling as rapidly as desired in a controlled atmosphere. All mechanical operations must be performed before the magnetic anneal at 2000 to 2100° F. and the parts must be free from oil, grease, or other carbonaceous material, as these will discolor the material and adversely affect the final properties. Any moisture present in the hydrogen used for a protective atmosphere will have the same results.



(*After Yensen*)

Figure 78. Magnetic properties of iron-nickel alloys of electrolytic iron and nickel, melted and annealed *in vacuo*.

This difference in properties between discolored and bright parts has not been explained, probably because so little is actually known about the basic fundamentals of what ferromagnetism is and how it is controlled. It may be partially explained by carbon diffusion in the case of oil, grease and carbonaceous materials, and by oxygen diffusion in the case of moisture in the hydrogen. The susceptibility to strain-hardening is also present in the material after the magnetic anneal, and slight amounts of cold-working result in a disproportionately large drop in magnetic performance, particularly affecting permeability and increasing retentivity or residual magnetism. These alloys include the following trade mark materials: Westinghouse "Hipernik," General Electric "Nicaloi," Crucible "Audiolloy," Allegheny-Ludlum "Electrical Metal 4750," Carpenter "49 Alloy," and Western Electric "45 Permalloy."

The high-nickel alloys, containing 70 to 85 per cent nickel, are characterized by very high permeability at low field strengths and a low degree of magnetic "retentivity," or residual magnetism. As the saturation point is low, this series of alloys is of value in instruments, but their use is limited to this field. The heat treatment of these alloys for maximum magnetic properties is the same as for the 45 to 50 per cent nickel alloys, including the precautions necessary. These alloys, too, are susceptible to work-hardening and the same general comments apply as in the case of the 45 to 50 per cent alloys.

The straight iron-nickel alloys have been designated "Permalloys" by the Bell Telephone Laboratories and Western Electric Co., who were until recently their principal producers and users. "Permalloys" are usually prefixed by a number or chemical symbol indicating the content of nickel or other alloying element. For example, the 78.5 per cent nickel alloy is designated 78.5 "Permalloy," the 45 per cent alloy is designated 45 "Permalloy" and the alloys with chromium and molybdenum are designated 3.8–78.5 Cr "Permalloy" and 4–79 "Permalloy," where the 3.8 and 4 designate the typical percentage of chromium and molybdenum, respectively. The Allegheny-Ludlum "Mumetal" and Carpenter "Hymu" 80 belong to the group of high-nickel alloys, having similar magnetic properties. "Mumetal" contains approximately 76 per cent nickel, 6 per cent copper, and up to 1.5 per cent chromium, balance iron; "Hymu" 80 contains approximately 80 per cent nickel, 4 per cent molybdenum, balance iron. An alloy of German manufacture also has similar magnetic properties. This alloy is known as "1040" alloy and contains 72 per cent nickel, 14 per cent copper, 3 per cent molybdenum, balance iron.

An interesting development[9] consists of cooling high-nickel alloys from the 2000 to 2100° F. annealing temperature in a strong magnetic field. This treatment has been found to be most effective in the temperature range of the magnetic transformation point, and results in a marked increase in the desirable magnetically soft properties, such as abrupt saturation, low residual, and greater permeability.

Table 88 and Table 89 show the principle iron-nickel alloys[12] and their magnetic properties. These tables include alloys of foreign manufacture and the "Perminvar" and "Permendur" alloys described later under iron-cobalt alloys. Iron-nickel alloys find most application in electrical instrument manufacture, telephone circuits, and radio transmitters and receivers. A special group of iron-nickel alloys in the composition range 28 to 32 per

TABLE 88. *Magnetically Soft Iron-Nickel Alloys*

Name	Approximate Composition	Manufacturer
	Very High Permeability at Low Field Strengths	
"Mumetal"	76 Ni, 6 Cu, 1.5 Cr, bal. Fe	Allegheny-Ludlum
"Permafly"	80 Ni, bal. Fe	Acieries de Firmany
"Permalloy"	30–90 Ni, Cr, Mo, bal. Fe	Western Electric
"1040" Alloy	72 Ni, 14 Cu, 3 Mo, bal. Fe	Heraous Vacuumschmelze
	High Permeability for Higher Field Strengths	
"Allegheny" 4750	47 Ni, bal. Fe	Allegheny-Ludlum
"Anhyster" C and D	45–50 Ni, bal. Fe	Acieries de Imphy
"Audiolloy"	48 Ni, bal. Fe	Crucible Steel
"Hipernik"	50 Ni, bal. Fe	Westinghouse Electric
"Hyperm"	50 Ni, bal. Fe	Krupp
"Megaperm" 4510	45 Ni, 10 Mn, bal. Fe	Heraous Vacuumschmelze
"Nicaloi"	49 Ni, bal. Fe	General Electric
"Permenorm"	48 Ni, bal. Fe	Heraous Vacuumschmelze
"Radiometal"	45–50 Ni, bal. Fe	Telcon
"49" Alloy	49 Ni, bal. Fe	Carpenter Steel
"2129" Alloy	45–50 Ni, bal. Fe	Telcon
	Moderately High Permeability Alloys of High Electrical Resistance	
"Anhyster" A and B	35 Ni, bal. Fe	Acieries de Imphy
"Gemma"	35 Ni, bal. Fe	Acieries de Imphy
"Monimax"	35–40 Ni, bal. Fe	Allegheny-Ludlum
"Photometal"	40–45 Ni, 5 Cr, 3 Si, bal. Fe	Telcon
"Sinimax"	35–40 Ni, bal. Fe	Allegheny-Ludlum
	Constant Permeability Over a Wide Range of Flux Densities	
"Coppernik"	50 Ni, bal. Fe	Westinghouse Electric
"Isoperm"	45–50 Ni, bal. Fe	Allgemeine Elektrizitats
"Isoperm" A	36–50 Ni, 9–15 Cu, bal. Fe	Allgemeine Elektrizitats
"Isoperm" B	40–60 Ni, 3–4 Al, bal. Fe	Allegemeine Elektrizitats
"Perminvar"	20–75 Ni, 5–40 Co, Mo, bal. Fe	Western Electric
	Alloys with Permeability Varying with Temperature	
Compensator Alloy	29–32.5 Ni, bal. Fe	Simonds Saw and Steel
N 30	30 Ni, bal. Fe	Carpenter Steel
N.M.H.G.	30 Ni, bal. Fe	Acieries de Imphy
"Thermoperm"	30 Ni, bal. Fe	Krupp

TABLE 89. *Magnetic Properties of Various Alloys*

Material	Initial permeability	Maximum permeability	Hysteresis loss, ergs per cc. per cycle	Residual induction (gauss)	Coercive force (oersteds)	Saturation value (gauss)	Resistivity (microhm per cm^3)	Specific gravity
"Armco" iron	250	7,000	5,000	13,000	1.0	22,000	11	7.9
4% Silicon iron	500	12,000	800	6,000	0.3	19,500	55	7.6
78.5 "Permalloy," quenched	10,000	105,000	200	6,000	0.05	10,700	16	—
45 "Permalloy"	2,700	23,000	1,200	8,000	0.3	16,000	45	—
3.8–78.5 Cr "Permalloy"	12,000	62,000	200	4,500	0.05	8,000	65	—
3.8–78.5 Mo "Permalloy"	20,000	75,000	200	5,000	0.05	8,500	55	—
45–25 "Perminvar" baked	400	2,000	2,500	3,000	1.2	15,500	19	—
7–45–25 Mo "Perminvar"	550	3,700	2,600	4,300	0.65	10,300	80	—
70–7.5 "Perminvar," annealed	750	3,500	—	—	0.8	12,000	16	—
"Wemco" iron (99.95% Fe)	—	100,000	150	9,000	0.05	21,600	10	7.2
"Hipernik"	4,500	100,000	100	8,000	0.03	16,000	45	7.6
"4750"	5,000	32,500	718	5,500	0.1	16,000	45	8.3
"Mumetal"	10–30,000	60–100,000	40–60	—	0.03	6–9,000	42	8.6
"Radiometal"	2,000	10–15,000	350	—	0.4–0.5	15,600	55	8.3
"Anhyster" A and B	1,300	—	—	—	—	9,000	70	—
"Anhyster" C	1,500	—	—	—	—	13,000	59	—
"Anhyster" D	2,200	25,000	330	—	—	15,000	46	—
"1040" Alloy	Up to 50,000	100,000	50	—	—	6,000	56	—
"Permenorm" 4801 *	2,700	19,000	—	—	0.20	14,000	58	—
"Megaperm" 6510	4,800	25,000	—	—	0.08	8,500	58	—
"Rhometal"	850	5,000	420	—	—	4,500	—	—

* Constant permeability of over 2,000 when H is less than 0.06.

cent nickel exhibits unusual magnetic properties. In addition to the low saturation intensity shown, these alloys have a permeability which is very nearly proportional to the temperature.

Furthermore, the magnetic transformation point of these alloys occurs at a low temperature (approximately 130° F.), so that by using the proper composition in the range 28 to 32 per cent nickel, the material will become non-magnetic at a specified temperature; as the reaction is reversible, the material again becomes magnetic as the temperature drops. These last two characteristics make these alloys ideal as compensating metal for temperature changes and are known as *temperature compensator alloys.* The magnetic permeability of iron and iron alloys decreases with temperature, so that accuracy of electrical meters which depend upon the flux produced by a constant voltage supply or by a certain load current, such as watt-hour meters or voltage and current regulators, will change with the temperature unless some method of compensation is used. It is customary to shunt a certain amount of the magnetic flux around the moving part of the meter by means of a temperature compensator alloy so that as the temperature increases the amount of flux shunted around the moving parts will decrease, forcing more of the flux through the moving member. By proper balancing, temperature changes may be completely compensated. Mechanical devices involving bimetal hinges may be used for this same purpose, but iron-nickel alloys are often more convenient.

Iron-Silicon Alloys. As mentioned above, pure iron has low resistivity with consequent high eddy current losses. The addition of silicon increases the resistivity and this reduces the eddy current losses. By decreasing the solubility of carbon in iron and by promoting grain growth, the addition of silicon decreases the hysteresis loss also. As the per cent silicon is increased, the permeability increases, the residual induction, saturation value, coercive force, and magnetizing force to produce saturation decrease, and the alloys become magnetically softer. The hardness and brittleness of the alloys increase, however, so for practical purposes the silicon content is limited to about 4.7 per cent in commercial silicon-iron sheet stock. The 4.7 per cent alloy represents substantially the maximum silicon content that can be sheared and punched with satisfactory results. Above this percentage, the sheet becomes so brittle that the edges are ragged after shearing or punching.

Silicon-iron alloy sheets are normally annealed by the manufacturer as one of the last operations before shipping to the customer or warehouse; thus for grades containing up to about 4 per cent silicon, no additional annealing treatment is necessary after shearing or punching laminations. Above 4 per cent silicon, however, the shearing or punching may introduce sufficient cold-working to affect adversely the permeability, and an annealing treatment is advisable for punched laminations, particularly where they

TABLE 90. *Typical Physical and Magnetic Properties, Silicon-Iron Alloy Sheets*

Approx. Silicon (%)	4.7	4.5	4.0–4.25	3.6–4.0	3.25–3.50	2.75–3.25	2.5–2.75	1.75–1.5	0.50–0.60	0.25–0.30	up to 0.25
Gage	29	29	29	29	26	29	26	24	26	24	24
Thickness (inches)	0.014	0.014	0.014	0.014	0.0185	0.014	0.0185	0.025	0.0185	0.025	0.025
Max. Permeability	8,000	8,000	8,000	6,650	6,000	6,000	5,500	5,500	—	—	—
Hysteresis Loss (watts per lb. at 60 cycles)	0.345	0.385	0.426	0.470	0.646	0.572	0.812	0.777	0.834	0.781	0.839
Guaranteed Max. Core Loss: (watts per lb. at 60 cycles)	0.52	0.58	0.65	0.72	0.94	0.95	1.14	1.70	1.55	2.28	2.65
Residual Induction (gauss)	5,700	5,900	6,300	6,900	7,100	7,000	7,900	7,300	8,300	7,900	8,500
Coercive Force (oersteds)	0.16	0.16	0.20	0.33	0.34	0.35	0.40	0.375	0.43	0.45	0.495
Saturation Value (gauss)	19,500	19,500	19,500	19,800	20,200	20,200	20,500	20,500	21,000	21,000	—
Resistivity (microhms per cm³)	65	60	58	52	50	50	44	44	28	28	20
Maximum Aging—Core Loss	Nil	Nil	Nil	Nil	2%	2%	3%	3%	5%	5%	—
Magnetizing Force (oersteds)	1.48	1.50	1.75	1.98	1.98	2.20	1.90	2.25	1.83	2.00	2.01
Nominal Specific Gravity (A.S.T.M.)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.7	7.7	7.7
Hardness Rockwell 30T	—	71	69	67	66	—	64	46	38	—	—
Tensile strength (psi)	70,000	76,000	72,000	80,000	70,000	—	68,000	50,000	44,000	—	—
Yield strength (psi)	68,000	67,000	60,000	67,000	54,000	—	50,000	31,000	25,000	—	—
Elongation % in 2″	2	5	6	8	12	—	14	22	25	—	—
Erickson Cup Test (mm)	2.5	3.5	4.1	4.3	5.5	—	6.5	7.8	8	—	—
Amsler No. 90° Bends to Fracture	—	4.5	7	10	14	—	18	37	—	—	—

are to be used in critical designs. This annealing operation consists of heating the parts to 1450 to 1475° F. and cooling at a rate of approximately 200° F. per hour to 800° F., and the furnace-cooling from there to room temperature. During this annealing operation, the silicon-iron punchings must be sealed from any air and no air must be admitted until after room temperature has been reached. Conversely, a strongly reducing atmosphere such as hydrogen should not be used because the normal surface oxide obtained on the hot-rolled sheet is desirable in reducing the core loss by increasing the surface resistance of the laminations. The commercial grades of silicon-iron sheet are sold by the sheet manufacturers with a guaranteed maximum core loss for certain sizes in each grade. It is current practice for the sheeet manufacturers to grade the silicon-iron sheets according to this guaranteed core loss, and to vary the silicon content and mill practice to meet these guarantees. For this reason, the silicon content figures shown in Table 90 are only approximate and in general apply only to the thicker sheets.

The trade marks of the principal manufacturers of silicon-iron sheet, shown in Table 91, give a clue to the uses for the different grades. The high-silicon grades (3 to 4.5 per cent) are used in transformers and electrical instruments, while lower-silicon grades (1.25 to 3 per cent) are used as armature and stator punchings for electrical motors and generators. Below 1.25 per cent silicon sheet stock is used for pole-shoe punchings for motors and generators and for armature and stator punchings for non-critical motor and generator designs.

The problem of surface finish and surface resistance has become of increasing importance because of increased demands on the performance of the silicon-iron alloys. The surface finish will affect the final performance of the material, since silicon-iron alloys are always used as laminated stocks or punchings. Non-uniform properties due to variation in the surface finish can be as harmful as non-uniform composition or structure of the material itself. The type of surface finish to be selected must be governed by the performance desired, just as in the selection of the proper silicon-iron alloy for a given design. The character of the normal oxide surface will vary in properties from one supplier to another depending upon individual mill practice. It will also vary within a given lot with respect to surface resistance. The most uniform type of surface finish in all respects is obtained by using one of the core plate materials described below. The surface finish offers resistance to the passage of eddy currents from one lamination to an adjacent lamination, being a poor conductor of electricity. This applies to both normal oxide or core plate. In the following discussion, the term *surface resistance* refers to this resistance to passage of eddy currents.

The silicon-iron alloys may be supplied with a normal surface oxide,

TABLE 91. *Trade Marks of Principal Manufacturers of Silicon-Iron Alloy Sheets*

Armco Steel Co.	Allegheny-Ludlum Steel Company	Carnegie-Illinois Steel Corp.	Empire Steel Corp.	Follansbee Steel Corp.	Newport Rolling Mill Co.	Republic Steel Co.	Wheeling Steel Corp.
Tran-Cor 52		Transformer 52		Transformer 52			
Tran-Cor 58	Transformer A	Transformer 58	Tranelec C	Transformer 58			Portsmouth I
Tran-Cor 65	Transformer B	Transformer 65	Tranelec B	Transformer 65			Portsmouth V
Tran-Cor 72	Transformer C	Transformer 72	Tranelec A	Transformer 72	Transformer	Transformer	Portsmouth V
Intermediate Transformer	Dynamo Special	Dynamo	Dynelec	Special Dynamo	Electrical C	Special Dynamo	Portsmouth V
	Super Dynamo						
Special Electric	Dynamo	Motor	Motelec	Special Motor	Electrical B	Special Motor	Portsmouth V
Electric	Electrical	Electrical	Manelec	Improved Electric	Electrical A	Electrical	Portsmouth I
Armature	Armature	Armature	Armelec	Armature	Armature	Armature	Portsmouth I
Field		Field		Field		Field	Portsmouth I
		Pole					Portsmouth I

Special Radio Grades of Silicon Sheet

Armco Steel Co.	Allegheny-Ludlum Steel Company	Carnegie-Illinois Steel Corp.	Empire Steel Corp.	Follansbee Steel Corp.	Newport Rolling Mill Co.	Republic Steel Co.	Wheeling Steel Corp.
Radio #6	Audio Transformer A		Above designation plus note "For Radio Work"	Radio A-1	No designation for radio grades		Above designation plus note "For Radio Work"
Radio #5	Audio Transformer B			Radio A-2			
Radio #4	Audio Transformer C	Radio Transformer 72		Radio A-3		Radio C	
Radio #3	Radio Transformer	Other grades as above with note "For Radio Work"		Radio B		Radio D	
Radio #2				Radio C		Radio E	
Radio #1				Radio D			

pickle-last (scale-free) or various types of baked varnish known as core plate. The appearance of the normal oxide varies from a gray color to what appears to be a bright finish. This variation is the result of the manufacturing process; that is, sheet that has been hot-rolled will have a gray oxide, whereas sheet that has been cold-reduced will have a bright finish. In service, both types of surface oxide have similar properties and exhibit approximately the same surface resistance, the hot-rolled oxide finish being more resistant than cold-rolled. Cold-reduced silicon-iron sheet has slightly higher permeability than hot-rolled sheet.

Silicon-iron sheet supplied as "pickle-last" has been pickled in acid to remove any scale or surface oxide as the last operation after rolling. This type of material has no surface resistance for all practical purposes, and must be core-plated or annealed in a slightly oxidizing atmosphere before assembly and use. This type of finish is most commonly used for sheet that must be cemented in forming the core stack.

Core plating and a core-plated surface refer to the process of coating silicon-iron electrical sheets, strip, or punchings with a thin covering of varnish, enamel, or similar material which, when baked dry, has good electrical resistance in addition to certain other desirable properties. One type of core plate is oil and heat *resistant* and will withstand the normal operating conditions found in an air-cooled core for motors and generators. This material will be sufficiently hard to withstand any temperature encountered in service, but will not withstand lamination annealing temperatures. Actual operating temperatures with this type of core plate should not exceed 450° F. for continuous operation, as the coating will burn off. Moreover, it should not be used in oil-immersed cores, as continued exposure to oil will result in deterioration of the core plate.

A second type of core plate is heat and oil *proof*. This core plate will withstand temperatures up to 1450° F. and will allow punchings coated with this material to be annealed. It is designed for applications in which the normal operating temperature exceeds 450° F., and may be used in oil-immersed cores, being impervious to oils. A third type of core plate is oil *proof* and heat *resistant* and is designed for punchings to be used in oil-immersed cores. This core plate will not soften or deteriorate at the highest temperature normally encountered in service, but will not withstand annealing temperatures. Like the first type, this is designed for operating temperatures below 450° F. but differs from the first type in that it may be used in oil-immersed cores since it is impervious to oils.

These core plate materials add a certain amount of non-magnetic material to the volume of the core stack, and the thickness must be kept to a minimum value consistant with the desirable performance. The usual method of designating the thickness of a core plate is to specify that the stacking factor for the core stack with core-plated material shall not exceed the stacking factor for the same size core stack with normal oxide finish materials by more than one per cent. This method is used for thickness determination because the extremely thin layer of core plate on each individual sheet makes direct measurement difficult, and also because this type of information is useful in assisting the design engineer to allow for the presence of the core plate. In other words, when core plate is used, the number of laminations in a given stack may have to be increased when the minimum volume of iron required in the stack is critical.

Iron-Aluminum Alloys. Iron-aluminum alloys are similar to iron-silicon alloys in their magnetic characteristics. A higher percentage of aluminum is required for the same results obtained with silicon. To date, iron-aluminum alloys have not assumed the commercial importance of iron-silicon alloys.

Iron-Cobalt Alloys. The iron-cobalt alloys in the magnetically soft group are known as "Permendur," "Perminvar" and "Hiperco." The "Perminvar" alloys are of iron-nickel and cobalt and sometimes contain up to 7 per cent molybdenum for improved magnetic properties. The "Perminvars" are characterized by constant permeability over a range of low flux densities. The usual composition contains 45 per cent nickel, 25 per cent cobalt, balance iron. This alloy sometimes contains 7 per cent molybdenum as stated above. Another composition contains 70 per cent nickel, 7.5 per cent cobalt, balance iron. These alloys are used when a constant inductance or reactance is desired, such as in filter coils for radio circuits or for loading coils in telephone circuits.

"Permendur" is an alloy of 50 per cent cobalt and 50 per cent iron, plus vanadium to improve workability. The principal characteristic of this alloy is the increased saturation value over that of pure iron. The cost virtually prohibits its use for any but very special applications in telephone circuits.

"Hiperco" is essentially an alloy of approximately 30 per cent cobalt, balance iron, with small quantities of other elements added to improve the working properties of the base alloy. It is characterized by a high saturation value and high permeability, and is recommended for the same type of application as the silicon-iron alloys.

Powder Metal Alloys. Pure iron, the "Permalloys," and "Mumetal" have been prepared by powder metal methods. In general, the magnetic properties are reduced from those of the alloys produced by conventional means. The disadvantages inherent in powder metals in general also apply to powder metal magnetic alloys, and as the quality of powder metal compacts improves, the powder metal magnetically soft alloy will undoubtedly find more application. The discontinuities in the powder metal material adversely affect the permeability, and at present this constitutes the greatest obstacle to the wider use of powder metal for electromagnetic purposes.

Permanent Magnet Materials

As in the case of magnetically soft materials, permanent magnetic materials are special-purpose alloys in which the usual physical properties, such as tensile strength, yield strength, elongation, toughness, and ductility, are of secondary importance to the magnetic properties. This leads to special treatment that might be considered unorthodox for any other group of materials. The design of these permanent magnet steels should be such that a minimum of forming or machining is required, because the hardness of these steels as cast is such that annealing may be necessary for fabrication, and any annealing operation should be avoided if possible since the magnetic properties are adversely affected.

The permanent magnet alloys are magnetically "hard"; that is, they retain a large part of the magnetism induced in them. This magnetic hardness is closely associated with physical hardness so that the same alloying elements and treatment which will harden a steel will be desirable for a permanent magnet material. In practice, the alloys most commonly used are carbon-manganese magnet steel, chrome magnet steel, tungsten magnet steel, cobalt magnet steel and more recently, a group of precipitation-hardening alloys known as "Alnico" alloys. Iron-platinum, copper-manganese-aluminum, copper-manganese-tin and copper-manganese alloys (known as "Heusler alloys"), oxide magnets using iron, cobalt, and complex oxides of these two metals, and recent developments, such as "Silmanal," "Colmolloy," etc., all exhibit ferromagnetic properties of a permanent magnet nature.

The permanent magnet alloys are characterized by high residual magnetism and high coercive force, with a correspondingly low permeability. The energy product is the ordinary criterion for evaluating the permanent magnet qualities of a given magnet alloy. This is a measure of the maximum magnetic energy available for use in the material. As the residual magnetism and coercive force are improved by the addition of alloying elements, the energy product is also increased.

Permanent magnets are used in many types of electrical and mechanical devices. They provide sources of magnetic force which require no external source of power, and remain constant if properly protected from demagnetizing influences such as elevated temperatures or jarring shocks and blows.

Uses of permanent magnets falls into three groups, namely:

(1) Production of electrical energy by the mechanical motion of an electrical conductor in the magnetic field. This is the principle on which the magneto generates electrical current. The permanent magnet creates the magnetic field, while the mechanical motion of the electrical conductor in the field induces the electrical current in the conductor.

(2) Production of mechanical energy by the passage of electric current through a conductor in a magnetic field. This is the principle used in certain types of electric motors, in ammeters, in loudspeakers and galvanometers. The passage of the current through the conductor in the magnetic field produces a force tending to move the conductor toward or away from the magnet, depending upon the direction of the current.

(3) Attraction of magnetic material to a magnet. This may be used for holding or lifting as in magnetic chucks or magnetic separators; producing tension as in pressure control instruments; or assisting electrical switches in a quick make or break of an electrical circuit.

Magnet Steels. Table 92 shows the principal commercial types of magnet steels, and also the acceptable heat treatment to obtain the magnetic properties shown. These properties were measured on bar magnets, and allowance should be made for the fact that magnet design will influence the resulting properties in a given magnet. The table also shows the effect of chemical composition on the magnetic properties. The hardened carbon-manganese magnet steel is used for low-cost permanent magnets, where service requirements are not severe. As the alloy content is increased, the quality increases. It will be noted that chromium, tungsten, and cobalt, in that order, have an increasingly beneficial effect on the coercive force and energy product. The cost of the magnets increases in the same order, although this can be offset somewhat by the fact that the size of the magnets can be reduced as the energy product is increased.

As could be expected from the heat treatment, a fine-grained structure is desirable in permanent magnet steels. The quenching treatment is followed by a low-temperature tempering treatment at 300° F. The hardened magnet is then magnetized by being subjected to a magnetizing force in excess of that to be expected with the magnet in order to insure that the saturation point is obtained.

The magnetic properties of the permanent magnet steels are not stable with time, but begin to change spontaneously after hardening and magnetizing. The rate of change is greatest immediately after magnetizing, and the rate decreases rapidly so that in a few days it is low. The rate and amount of change differ with the different kinds of steel. The direction of the change is always for the residual induction to increase and the coercive force to decrease. For this reason, all magnet steels should be given an "aging" treatment so that, although some magnetism is lost, that which remains is practically constant and permanent provided the magnet is not abused or heated to a high temperature. Aging is accomplished by alternately heating the magnet to 212° F., holding for about one hour, and then cooling to 32° F. and holding for about an hour, repeating this process 5 to 10 times. This aging may be accomplished by holding the magnet steel

TABLE 92. *Permanent Magnet Alloys*

Commercial Types of Magnet Steels

Type of steel	Nominal composition						Nominal magnetic properties		Hardening temp. °F.	Quenching medium
	C	Mn	Cr	W	Co	Mo	Residual induction, gauss	Coercive force, oersteds		
1. C-Mn	0.80	0.80					10,000	43	1,450	water
2. Cr	0.60	0.40	0.90				10,000	50	1,450	oil
3. Cr	0.90	0.35	2.25				9,000	58	1,500	water or oil
4. Cr	0.95	.20/.60	3.0/4.0				9,500	63	1,525	oil
5. Cr	1.00	0.35	6.0				9,000	72	1,550	oil
6. Cr-Mo	1.00	0.35	4.0			0.35	9,000	65	1,550	oil
7. W	0.70	0.30	0.20	5.5			10,000	65	1,550	water
8. W-Cr	0.70	0.50	0.50	6.0			9,000	70	1,525	oil
9. Co-Cr-W	0.90	0.35	4.75	1.25	8.5		7,500	120	1,650	oil
10. Co-Cr-W	0.90	.30/.85	3.5/5.75	3.75/7.0	35.0/0.41		9,700	235	1,700	oil
11. Co-Cr-Mo	0.95	0.30	9.0		16.0	1.30	8,000	180	X	air (see Note)
12. Co-W	0.85	0.50	2.0/5.0	8.75	17.0		9,000	165	1,750	oil
13. Co-Cr			10		15		7,700	185	These alloys also are hardened but information on the particular alloy was not available.	
14. W-Co				18	15		11,500	150		
15. Mo-Co					12	19	8,400	300		
16. Cu-Ni-Fe	60 Cu—20 Ni—20 Fe						5,280	460		

X Triple heat treatment, 2,100° F. cool in air, 1,150° F. cool in air, 1,850° F. cool in air.

at 212° F. for long periods, say 24 to 48 hours. Aging may also be accomplished by magnetic methods by subjecting the magnet to a demagnetizing force for a few minutes.

"Alnico" Alloys. The range of possibilities for the design and use of permanent magnet alloys has been greatly extended by the introduction of substantially carbon-free alloys of the precipitation-hardening type. These alloys are marketed under the trade name "Alnico." The data in Table 93 show typical analyses and magnetic properties of the various types available. The magnetic properties of any of the permanent magnet steels can be substantially duplicated by these precipitation-hardening alloys. These alloys offer a higher energy product by virtue of higher coercive force than other types of permanent magnet steels, enabling the designer to use a smaller magnet when it is made from "Alnico" than from other permanent magnet alloys. These alloys have a lower density and cost (when size is considered) than the high-cobalt magnet steels, but have the disadvantage of being neither forgeable, machinable, nor readily ground. Their use is therefore limited to magnet designs which can be cast. After magnetizing, these alloys exhibit strong anisotropic characteristics which limits the shape of the magnets. "C" magnets, for example, are subject to domain alignment entirely in one direction rather than in a mean path through the magnet.

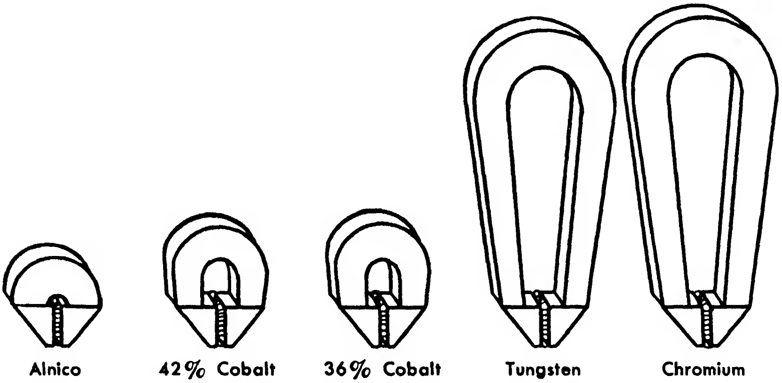


Figure 79. Equivalent magnets made of different kinds of magnet materials, comparing Alnico magnets with those of other materials.

Under proper conditions, these alloys may be used in the cast condition, but in general, a solution heat treatment, followed by a precipitation heat treatment is required for best and most uniform magnetic quality. The aging phenomenon observed in the permanent magnet steels is much less in these alloys and may be entirely absent in some of them, so that no aging treatment of the type used for the permanent magnet steels is necessary.

TABLE 93. *Precipitation-hardening Permanent Magnet Alloys*

Type of alloy	Nominal composition					Nominal magnetic properties		Energy product BH max.
	Ni	Al	Co	Other	Fe	Residual induction, gauss	Coercive force, oersteds	
"Alnico" 1	20	12	5		Bal.	7,300	440	1,400,000
"Alnico" 2	17	10	12.5	6 Cu	Bal.	7,350	560	1,600,000
"Alnico" 3	25	12			Bal.	6,900	475	1,380,000
"Alnico" 4	28	12	5		Bal.	5,300	730	1,300,000
"Alnico" 5 *	14	8	24	3 Cu	Bal.	12,500	550	4,500,000
"Alnico" 12	18	6	3.5	8 Ti	Bal.	5,800	950	1,750,000
"Nipermag"	32	12		.4 Ti	Bal.	5,500	675	1,340,000
New KS Magnet Steel	18	4	27	7 Ti	Bal.	7,150	785	2,030,000

* Heat-treated in a magnetic field.

The solution treatment involves heating the cast alloy to about 2100° F. The exact temperature varies for each grade and the casting is quenched from this temperature in air. The quenching is followed by a precipitation-hardening treatment at approximately 1200° F. In the case of "Alnico" 5, the material must be cooled from this temperature in a strong magnetic field. The alloys are then magnetized in much the same way as ordinary magnet steels, except that very high coercive forces must be used to obtain the maximum properties of the material. Experimental work is still in progress to improve the properties and obtain uniform results from one lot of magnets to the next. "Alnico" 2 is available as a sintered powder, but the lower density results in lower magnetic properties than in the cast alloy.

"Alnico" alloys are now being centrifugally cast. This improves the reproducibility of the magnetic properties; also magnets can be made to closer tolerances than by either conventional casting or by sintered powder methods. This method has been announced only recently and is not in general practice as yet.

Oxide Magnets. Oxide magnets are made from metal oxide powders pressed into desired shapes and subsequently sintered. The residual magnetism is generally low, but coercive forces up to 750 oersteds may be obtained. Magnets containing approximately 16 per cent CuO, 34 per cent Fe_2O_3 and 50 per cent Fe_3O_4 pressed, sintered at 1800° F., magnetized at 570° F., and then allowed to cool to room temperature have residual magnetism values of 3,000 to 5,000 gauss and coercive force values of 600 to 400 oersteds. Chromium, zinc, tungsten, nickel, and copper oxides have been used in oxide magnets, but results have not been of commercial importance to date. The low density of the oxide magnets accounts in part for the low residual magnetism, but the performance in laboratory tests[6] shows an energy product equivalent to 3.4×10^6. Another disadvantage of the oxide magnets is the difficulty in obtaining reproducible results from different lots of supposedly the same compositions. The relatively light weight of these magnets offers interesting possibilities, and research is still progressing to develop a commercially feasible oxide magnet. The General Electric Company has announced an iron and cobalt oxide permanent magnet material which they designate as "Vectolite" 61. This consists of approximately 30 per cent Fe_2O_3, 44 per cent Fe_3O_4 and 26 per cent Co_2O_3. The outstanding features listed for this material are: (1) a specific gravity about half that of other solid magnet materials, (2) high electrical resistivity, and (3) high coercive force. The material is weak mechanically and therefore magnets made from "Vectolite" preferably are sintered to final size. "Vectolite" has been used for rotor magnets in moving magnet instruments such as tachometer indicators, where the light weight of the material can be used to advantage (see Table 94).

TABLE 94. *Oxide Magnets*

Composition	Residual induction (Gauss)	Coercive force (Oersted)	Energy product BH max.
16 CoO; 34 Fe_2O_3; 50 Fe_3O_4	3,500	600	1,030,000
26 Co_2O_3; 30 Fe_2O_3; 44 Fe_3O_4 (Vectolite)	1,600$_2$	900	500,000

MISCELLANEOUS PERMANENT MAGNET MATERIALS

Precious Metal Magnets. The alloys of iron and platinum, iron and platinum-rhodium, cobalt and platinum, iron and neodymium exhibit ferromagnetic properties similar to permanent magnet alloys. These are shown in Table 95. These alloys are principally of academic interest as the cost makes them commercially unfeasible. They are characterized by extremely high coercive force, ranging from 1400 to 2000 oersteds, with a correspondingly high energy product. These alloys with those in the following sections are interesting to the metallurgist because they are the only ferromagnetic materials composed principally of elements which are not themselves ferromagnetic in the pure state.

Special Permanent Magnet Alloys.[8] "Cunife," a permanent magnet alloy of copper, nickel and iron, and "Cunico," a permanent magnet alloy of copper, cobalt, and iron are distinguished by the unusual properties (for permanent magnet materials) of being ductile, malleable, and machinable even in the heat-treated condition. This makes it possible to produce these materials in sheet or wire form, opening new uses for permanent magnet materials. "Cunife" has directional properties, so that magnets of this material must be magnetized in the direction of rolling or drawing to produce the maximum properties. "Cunico," however, does not exhibit strong directional properties; hence magnets made from it can be magnetized in any desired direction. "Silmanal" is an alloy of silver, manganese, and aluminum whose unusual magnetic properties greatly influence magnet design and application. These include a low residual induction ($Br = 600$) and a large area is required to produce appreciable total flux, but it is highly resistant to demagnetizing influences. The coercive force, Hc, for "Silmanal" is 5500 oersteds, so that a demagnetizing force of 6000 oersteds must be applied to demagnetize a "Silmanal" magnet completely. This characteristic requires a high magnetizing force of the order of 20,000 oersteds (40,400 ampere turns per inch of length) to magnetize a "Silmanal" magnet. As this makes it difficult to magnetize long pieces, the typical shape for such a magnet is a thin disc, magnetized across the thickness.

"Vicalloy," a cobalt, vanadium, iron alloy and "Comol" (also referred to as "Remalloy") a cobalt, molybdenum, iron alloy are precipitation-hardening alloys. These can be machined after solution heat treatment and before age-hardening heat treatments. Their properties and applications are similar to those of high-cobalt steel, but since these alloys are dispersion-hardening, they are structurally more stable[18] (see Table 95).

TABLE 95. *Miscellaneous Permanent Magnet Alloys*

Type	Composition per cent	Residual induction (Gauss)	Coercive force (Oersted)	Energy product (BH max.)
Iron-Platinum	77 Pt; 23 Fe	5,830	1,570	3,070,000
Cobalt-Platinum	77 Pt; 23 Co	4,530	2,650	3,770,000
Iron-Neodymium	93 Ne; 7 Fe	low	4,300	——
"Cunife"	60 Cu; 20 Ni, 20 Fe	5,280	460	1,070,000
"Cunico"	50 Cu; 21 Ni, 29 Co	3,400	710	850,000
"Silmanal"	87 Ag; 9 Mn; 4 Al	500	5,500	60,000
"Vicalloy"	32/62 Co; 6/16 V; bal. Fe	9,600	400	2,800,000
"Comol" or "Remalloy"	81 Fe; 12 Co; 17 Mo	10,500	250	1,100,000

"Cunife," "Cunico," and "Silmanal" derive the properties shown by a combination of heat treatment and cold working. The treatment for "Cunife," which is typical of these alloys, consists of prolonged heating at 1900° F., quenching in oil, prolonged heating at 1100° F., cold-rolling, reheating to 1100° F., and cold-rolling again.

Heusler Alloys. In the early part of the present century, Dr. F. Heusler, working at the University of Marburg in Germany, noticed that certain manganese-copper alloys showed decided ferromagnetic qualities. These alloys, with and without additions of aluminum and tin, have received some study by research physicists and metallurgists in an attempt to determine the nature of ferromagnetism. The alloys themselves do not exhibit outstanding ferromagnetic properties, but their study has led to the conclusion that ferromagnetism is a property of body-centered cubic materials,[5] although all body-centered cubic materials are not ferromagnetic. Table 96 shows the typical chemical composition of these alloys.

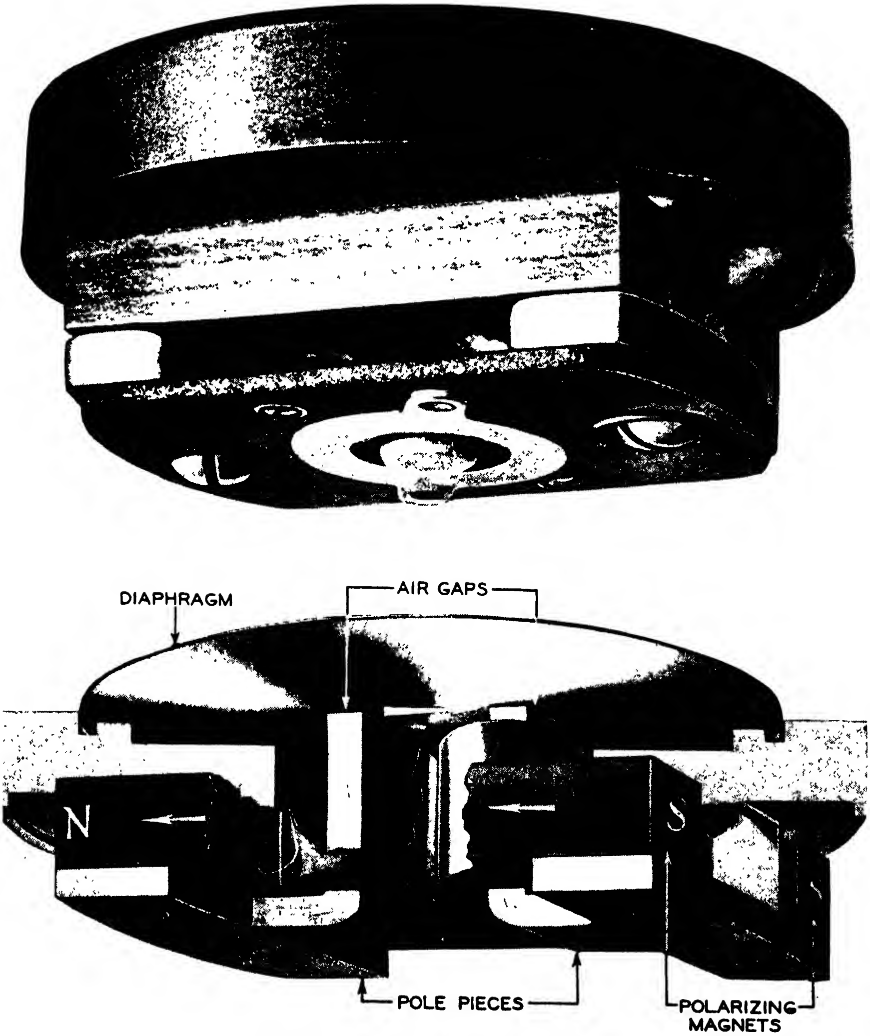
TABLE 96. HEUSLER ALLOYS

Al	Cu	Mn	Pb
11.1	66.5	22.4	—
10	68	18	4
4–15	54–76	16–30	—
13	61	26	—

Testing Magnetic Materials

The design of permanent magnets is beyond the scope of this chapter except that the design of the magnet will influence the resultant properties. In order to test a given magnet alloy for performance, the customary bar magnet, on which residual magnetism and coercive force may be measured, will give only the relative quality of the magnet material and not actual performance figures when a different shape magnet is used. The field of magnet testing has not been standardized, so that at present, the best method of obtaining the desired magnetic material from a supplier is to agree upon some magnet shape which can be readily tested and correlate these tests with actual performance.

Figure 80 shows the application of permanent magnets in telephone

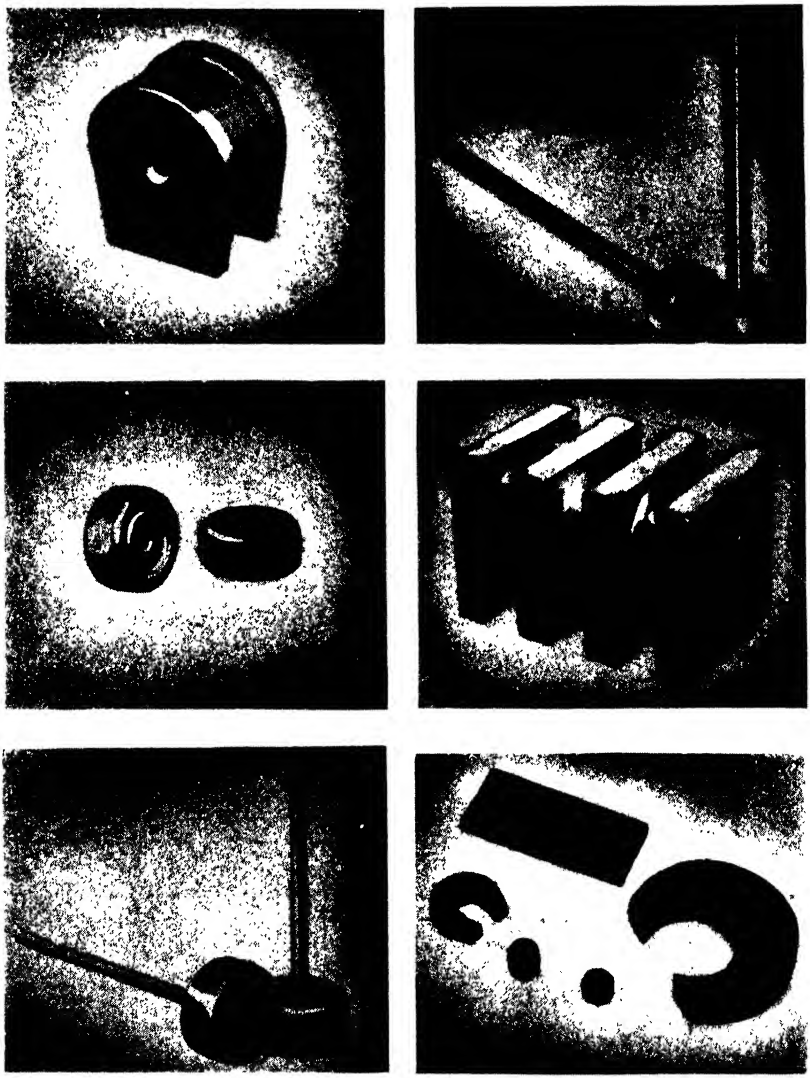


(*Courtesy Bell Telephone Laboratories, New York, N. Y.*)

Figure 80. Telephone receiver.

equipment. The two straight bar permanent magnets are "Remalloy"; the pole pieces are 45-"Permalloy"; and the diaphragm is "Permendur." The magnets are welded to the pole-pieces to form a unit which is mounted on projecting lugs on the die-cast frame.

Figure 81 shows a new standard line of General Electric "Alnico" permanent magnet holding assemblies which combine minimum space require-



(Courtesy General Electric Co., Schenectady, N. Y.)

Figure 81. "Alnico" magnet holding assemblies.

ments with maximum holding power, ranging from a pull of 1½ to 500 pounds.

Figure 82 shows the method of construction of the "Perma-Pulley," a most powerful non-electric magnet pulley used for the separation of magnetic particles from non-magnetic material. Full magnetic action over the total pulley face is obtained by using "Alnico" magnets as "spokes."

Figure 83 shows an installation of the belt drive "Perma-Pulley" at the Arco Die Cast Metal Co. It is being used in a smelting operation for separating steel borings and turnings from the aluminum.

Figure 84 shows a rectangular type magnet attached to the overhead crane. It is used for lifting metals.

Note:

A number of trade marks for magnetic materials have been mentioned throughout this chapter. The manufacturers of these materials are given below:

Allegheny-Ludlum Steel Co.
  "Mumetal"
  "Electric Metal 4750"

Bell Telephone Laboratories and Western Electric Co.
  45 "Permalloy"
  78.5 "Permalloy"
  "Permendur"
  V-"Permendur"
  "Perminvar"
  "Vicalloy"

Carpenter Steel Co.
  "Hymu" 80
  "49 Alloy"

Crucible Steel Co. of America
  "Audiolloy"

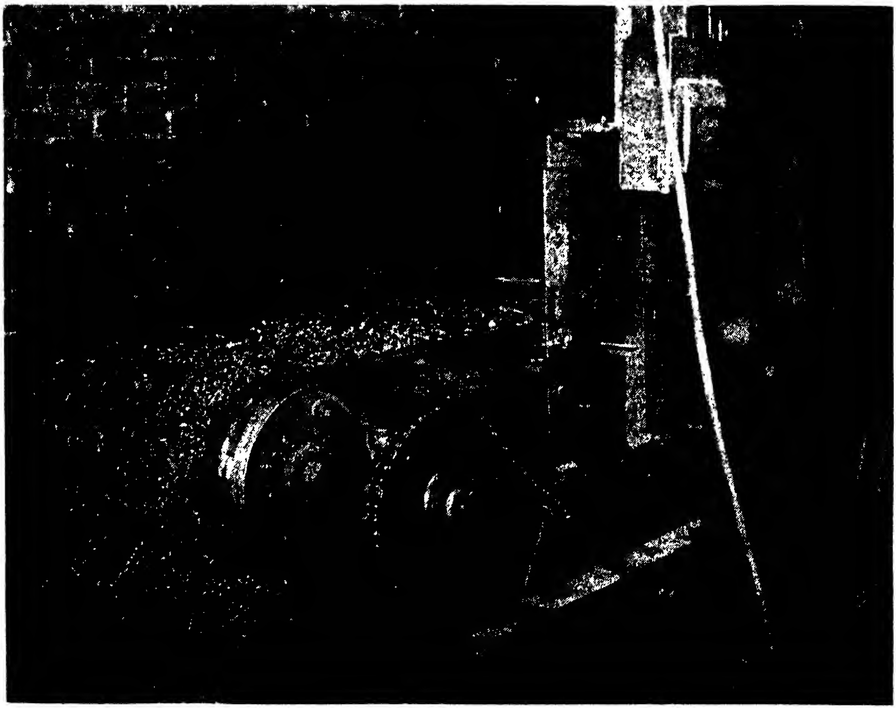
General Electric Co.
  "Alnico" 1, 2, 3, 4, 5, 12
  "Colmolloy"
  "Cunico"
  "Cunife"
  "Nicaloi"
  "Silmanal"
  "Vectolite" 61

Westinghouse Electric Corp.
  "Hiperco"
  "Hipernik"

A number of the above alloys are manufactured by other firms under licensee rights.

Figure 82. Magnetic "Perma-pulley".

(Courtesy Dings Magnetic Separator Co., Milwaukee, Wis.)



(Courtesy Dings Magnetic Separator Co., Milwaukee, Wis.)

Figure 83. Magnetic separator.

(Courtesy Ohio Electric Mfg. Co., Cleveland, Ohio)

Figure 84. Rectangular lifting magnet.

References

1. Elmen, G., "Magnetic Alloys of Iron, Nickel and Cobalt," *J. Franklin Inst.* 207 (May, 1929).
2. Yensen, T., and Ziegler, N., *Trans. A.S.M.*, 33 (1935).
3. Shockley, W., "The Quantum Physics of Solids," *Ibid.*, 18 (1939).
4. Bozorth, R., "The Physical Basis of Ferromagnetism," *Bell Tech. J.*, 19 (1940).
5. Carapella and Hultgren, "The Ferromagnetic Nature of the Beta Phase in the Copper-Manganese-Tin System," AIME Tech. Pub. No. 1405 (1941).
6. Brace, P. H., "Cobalt Magnets," *Product Engineering* (July, 1942).
7. Sanford, R., "Permanent Magnets," Bureau of Standards Circular No. C–448, 1944.
8. General Electric Co. Private Communications, 1945.
9. Bozorth, R., and Dillinger, J. "Heat Treatment of Magnetic Materials in a Magnetic Field," Bell System Monographs B–898 and B–899.

10. Ritter, F., "Introduction to Ferromagnetion," McGraw-Hill Book Co.
11. Woldman, N. and Metzler, R., "Engineering Alloys," American Society for Metals, 1945.
12. "Metals Handbook," American Society for Metals, 1948.
13. Allegheny-Ludlum Steel Corp., Tech. Bull. EM-1.
14. "Armco Electrical Sheet Steel," Armco Steel Co.
15. "American Electrical Steel Sheets," American Sheet and Tin Plate Co.
16. "Follansbee Electrical Sheets," Follansbee Steel Corp.
17. "Iron-Nickel Alloys for Magnetic Purposes," International Nickel Co., Data Sheet No. 2, Section IV.
18. "Electrical Steel Sheets," United States Steel Corp.
19. Chegwidden, R., "A Review of Magnetic Materials Especially for Communication Systems," *Metal Progress* (November, 1948).

Chapter XI

Electrical Contacts

Metallic contacts of some kind are essential in practically every electrical circuit. The electrical energy that performs the multitude of tasks must be controlled, in many cases instantaneously.[10] This is accomplished by small but important pieces of metal upon the dependability of which the operation of the apparatus relies. These contacts, made of special metals or alloys, must have the endurance to withstand the physical and electrical impact of countless operations.

In most applications, electrical contacts are required to perform one or more of the following three functions: (1) make an electrical circuit, (2) carry current, (3) break an electrical circuit. At some time or other most contacts interrupt an electrical circuit. Currents made, interrupted or carried by different contacts[6] vary from millionths of an ampere to many thousands of amperes, with circuit voltages covering a similar wide range. Frequency of operation, ambient temperatures, the medium in which they operate, and the time in which the circuit must be made or broken are other variables.

To meet the wide differences in operating conditions and requirements, an equally great variety of contacts is necessary. The materials employed include carbon and practically all the metals, from platinum, gold and silver to copper and iron. Contacts can be either soldered, brazed, welded, screwed or clamped to their supports. They may be effective with a wiping, sliding, or rolling motion, and can move slowly or with extreme rapidity. Contact forces vary from a few grams to many pounds.

In general, contacts are considered to be "good" when they make and maintain the required electrical circuits without overheating or causing excessive voltage drop, and in addition resist sticking, arcing and mechanical wear. Operational failures due to faulty contact are usually caused by (1) the contacts failing to make a circuit when they close, (2) "burning-out" or oxidizing to such an extent that they will no longer maintain a circuit, (3) failing to break the arc when opened, or (4) welding together and failing to open.

Requirements of Contact Materials

The following properties[5] affect either the life or performance of electrical contacts: (1) high melting point, desirable because it tends to reduce susceptibility to disintegration and roughening under arcing conditions; (2) high specific heat, giving higher thermal capacity and reducing transient temperature rise; (3) high thermal conductivity, which permits rapid transmission of heat from contacts to backing material, reducing the tendency to oxidize (if the material is a base metal); (4) low specific resistance, giving high electrical conductivity; (5) low temperature coefficient of resistance, so that circuit resistance will not change with temperature increase; (6) low expansion coefficient, which results in better alignment and maintenance characteristics; (7) low contact resistance, tending to give better performance at high current densities, and depending on the kind of material, condition, and shape of surfaces and pressure; (8) hardness and toughness, preventing excessive wear, especially under pressure and high frequency of operation; and (9) stability toward oxidation, preventing excessive heating of contact surfaces due to resistance of the oxide film.

The perfect contact material[10] therefore would have the following physical properties: (1) high electrical and thermal conductivity, (2) non-sticking properties, (3) low contact resistance, (4) resistance to electrical erosion, and (5) high strength and hardness. In other words, the ideal contact material would have high melting point, specific heat, thermal conductivity, hardness, toughness, and wear resistance, and would have also low electrical resistance, temperature coefficient of resistance, contact resistance, coefficient of expansion, in addition to non-oxidizing properties and low final cost.

Inasmuch as no metal or alloy combines the optimum of all these desirable properties, there is no universal contact material available. Some materials have high electrical conductivity and little resistance to electrical erosion and sticking. The selection of a contact material therefore necessitates a compromise in order to meet the operating conditions with the material best suited for the purpose.

Contact Materials

Of all the elements which might be used successfully, individually or in combination, as electrical contacts, it has been found that from the practical standpoint of availability, performance, cost and ease of reproduction, only the following need be considered:[4]

Aluminum
Antimony
Beryllium
Bismuth
Boron
Cadmium
Calcium
Carbon
Chromium
Cobalt
Columbium
Copper

Germanium
Gold
Indium
Iridium
Iron
Lead
Lithium
Magnesium
Manganese
Mercury
Molybdenum
Nickel
Osmium
Palladium
Platinum
Rhenium
Rhodium
Ruthenium
Silicon
Silver
Tantalum
Thorium
Tin
Titanium
Tungsten
Vanadium
Zinc
Zirconium

Of these 40 elements the 14 which have been used most actively for contact purposes are:

Carbon
Copper
Gold
Iridium
Mercury
Molybdenum
Nickel
Osmium
Palladium
Platinum
Rhodium
Ruthenium
Silver
Tungsten

However, the most important of these are: carbon, copper, gold, mercury, palladium, platinum, rhodium, silver and tungsten. The remaining elements listed above have proved advantageous only when combined with one or more of the 14 widely used elements. In addition, small amounts of other elements may be added to the above to modify their properties.

Carbon is used for contact parts where a large area is permissible and where bulk is not a disadvantage. The large area is necessary to overcome inherent high resistance. It is normally used in circuit breakers, as the arcing tips on overload switches, etc. The carbon so used is impregnated with contact metals such as copper, nickel and silver to good advantage, and these also aid in reducing mechanical wear. In the form of carbides with tungsten and molybdenum carbon has desirable contact characteristics.

Copper is used in both the pure and alloyed forms. It is alloyed with silver extensively and admixed with pure tungsten or molybdenum and/or their carbides. Copper is also incorporated with graphite. Age-hardening alloys of copper with small amounts of silver, cobalt, chromium, silicon and nickel as hardeners are in service.

Copper contacts have the undesirable characteristic of oxidizing when heated in air (but not in oil). To use them safely, the contact mechanism must provide a relatively great force on the contacts and give some sliding or wiping action between the moving and stationary contact surfaces when they touch or separate from each other. It is necessary to keep the contact surfaces clean even if this means an increase in the mechanical wear.

Improvements have been made in copper-base contact alloys, such as contactor contacts, by such additions as selenium, lead and tellurium. Materials of this class have less tendency to stick or weld together when making large currents.

Copper containing small amounts of cobalt and cadmium possesses arc-resisting properties. This mixture is used in circuit-breaking devices which must interrupt the flow of an electrical current in a short time with a minimum of arc hangover. It also replaces pure copper in many types of circuit-breaker contacts where a material of greater hardness and resistance to wear is required. It can only be cast, as it cannot be hot- or cold-worked.

Gold is used when light pressures and low voltages are encountered, but is unsuited for high voltages or heavy current. It is too soft for most applications and is therefore alloyed or admixed with platinum, silver or nickel. Gold contacts are used for certain types of telephonic, thermostatic and ultra-sensitive applications.

Iridium is seldom used in the pure form, but as an alloying element with platinum, osmium, palladium or rhodium.

Molybdenum is used in pure form for low-current, high-voltage applications, but generally tungsten is preferred. In combination with silver, copper, nickel and graphite, it has marked advantages from the standpoint of non-welding under overload conditions. It is used in the form of carbide with silver and/or copper, and/or nickel and/or graphite.

Molybdenum[9] is used as a contact material in applications where the electrical burden is not sufficiently severe to require tungsten. As it has a low density, it can also be used where the higher density of tungsten may be objectionable for mechanical reasons. Typical physical properties of molybdenum for contacts are 10.2 grams/cc. density, 31 per cent IACS electrical conductivity, 55 Rockwell A hardness and 150,000 psi ultimate strength.

Nickel is occasionally used for contacts, particularly when exposed to fumes of hydrocarbon vapors, and under conditions where highly inductive loadings at low currents are to be controlled. Nickel is used as an admixing and/or alloying element in conjunction with silver, copper, graphite, molybdenum and tungsten, and their carbides. Nickel is an active ingredient in a number of powdered metals and sintered contacts.

Osmium is used as an alloying element with platinum, palladium or rhodium.

Palladium is an excellent contact material both in the pure form and in alloys. For relay contacts palladium is generally used as the pure metal, but it is sometimes alloyed with silver, silver-nickel and silver-copper. It has excellent resistance to oxidation and sulphidation and is standard for all voice current-carrying contacts in the telephone system.

Palladium forms a series of homogeneous solid solutions with silver and with nickel. Of these, the high palladium-silver alloys are most used; such alloys may be used as a substitute for platinum-base materials on both light- and medium-duty relay equipment subjected to chemical fumes or prolonged exposure under adverse atmospheric conditions. Ruthenium hardens palladium effectively, and is added to it where hardness is of major importance. The addition of copper to palladium increases the hardness materially and gives an economical material having most of the desirable characteristics of palladium. The 60 per cent palladium and 40 per cent copper alloy is a valuable contact metal for special applications if considerable shunt capacity is present.

Platinum is used in the pure state for contact purposes, and may be hardened with ruthenium, iridium or palladium. The properties of high melting point, resistance to corrosion and oxidation, and retention of low contact resistance over long periods makes platinum an outstanding high-quality contact material. When platinum[9] is alloyed with other noble metals, such as iridium, ruthenium, rhodium, osmium, and palladium, the hardness and strength are increased without sacrificing the nobility of the platinum. Commercially pure platinum is used extensively for contacts in circuits having low electrical loads and where minimum contact resistance and maximum reliability are essential.

The addition of iridium to platinum (up to 35 per cent) increases the hardness, strength, and resistance to wear. Ruthenium has twice the strengthening effect of iridium on platinum and is used up to 15 per cent. Platinum-ruthenium alloys are generally interchangeable with platinum-iridium alloys, and are used for aircraft magnetos and similar exacting service.

Rhodium may be alloyed with platinum.

Ruthenium is used mainly as a hardener for palladium and platinum.

Silver in the purest form available (fine silver) is an excellent contact material when a fair rate of wear keeps the contact clean. It has the highest electrical and heat conductivity of any metal, but has a relatively low melting point and is somewhat soft. Small amounts of copper, nickel, zinc, cadmium, etc., are often added to silver to improve its hardness, wear resistance, tendency to stick, transfer rate, and arc-resisting qualities, as well as to lower cost. The alloys of silver have increased hardness but lower electrical conductivity.

Fine silver (99.9%) has been extensively used for current-carrying contacts in heavy-duty equipment. Pure silver resists atmospheric oxidation, but is attacked by ozone and sulphur compounds. It can be used in a wide variety of light-duty applications, particularly when contact forces are light, since the surface maintains a lower contact resistance than copper. However, at low currents the resistance increases and becomes variable, so that the effect is undesirable if electrical noise is a factor. A sulphide film on silver causes trouble at low voltages, but it can be broken down at higher voltages and may then be tolerable. Silver shows a tendency to transfer under some operating conditions, and this should be recognized.

Fine silver is an economical and satisfactory contact material for d.c.

and a.c. industrial contactors that are rated up to 50 amperes. The inherent characteristics of silver make it possible to use a minimum contact mass and a smaller force to hold the contacts together than is the case with base metals; but the force is greater than with the more noble metals.

Coin silver is a silver-base alloy containing about 10 per cent copper, and is widely used as a substitute for fine or sterling silver.[6] Coin silver is used when it is necessary to maintain a relatively low contact resistance, but when greater hardness is desired than can be obtained with fine silver. It is recommended if the operating force is high and if mechanical deformation is likely to occur. Sterling silver contains about 7.5 per cent copper and has about the same electrical properties as coin silver.

A silver-base alloy containing copper and nickel is used as a substitute for fine, coin and sterling silver. It is a low-wear resistance alloy which retains its physical properties up to its annealing temperature of 400° C. (752° F.).

A silver-base alloy containing nickel and cadmium exhibits very low material transfer and contact resistance under conditions of high-frequency operation at comparatively low voltage (6–8 volts) and extremely low contact forces. It is an economical substitute for platinum alloys in certain low-voltage, low-current applications. A contact material having low temperature rise and low contact resistance is provided by a silver-base alloy containing copper, cadmium and nickel, in proper proportions. It responds to heat treatment and therefore the material, softened by annealing or brazing, can be improved in physical characteristics.

A silver-cadmium alloy of proper composition or a silver-cadmium oxide mixture can maintain low contact resistance over a long period of time and is suitable for use in electrical switches forming a part of starting, lighting, ignition or voltage-regulation apparatus in automotive and aeronautical equipment.

Platinum additions to silver-base alloys reduce the tendency toward material transfer at relatively low currents without decreasing the critical or limiting current. Palladium has the same effect as platinum on silver-base alloys and is more economical, although the electrical and thermal conductivity is somewhat higher.

A silver-base alloy containing a high percentage of gold and some nickel is characterized by its ability to withstand atmospheric corrosion and operate at low electrical burdens with negligible metal transfer. It operates well in tropical atmospheres in circuits of very low voltage and currents, and can be used as a substitute for platinum-base alloys.

Tungsten in the pure and alloyed forms has many applications as a contact material. Tungsten doped with silicon or boron is considered superior to other tungstens on normal ignition breakers. Tungsten [5] and its alloys are excellent contact materials because of such properties as low vapor pressure at elevated temperatures, high melting point, reasonable conductivity, good resistance to chemical attack, and relatively low cost. Tungsten has a higher contact resistance than silver or platinum, and is not used where a low-pressure contact material is required. Tungsten forms three distinct oxides, one or more of which may form at comparatively low temperatures. The current-interrupting capacity of simple make-and-break tungsten points is thus limited by the possibility of serious oxidation. For circuits similar to automobile ignition systems, the maximum current at the instant of interruption is limited to about five amperes; above this value oxide formation sets in rapidly. Sometimes oxidation also seems to be related to critical voltage.

Tungsten contacts are of the greatest utility in medium- and high-speed make-and-break mechanisms where impact and mechanical stresses require a material of relatively high strength and hardness.

Consideration of chemical purity alone is not sufficient to guarantee maximum performance of tungsten contacts.[9] Electrical erosion starts at the grain boundaries and progresses until the grains themselves are loosened and fall away. Rigid processing control will retard wear and grain erosion because of the resultant interlocking grain structure.

It has been found that certain contact applications respond favorably to one type of tungsten grain structure, while others operate more efficiently with a different type. As a result, several grades of tungsten have been put on the market, as illustrated by one manufacturer's three grades, HA, K and MK, each having the same density (19.3 g/cm), the same electrical conductivity (32% IACS), the same Rockwell A hardness (70), but different tensile strengths (120,000, 200,000 and 300,000 psi, respectively). The difference in the three grades lies in the controlled grain size, the controlled purity of grain boundary material, and the controlled fiber, *i.e.*, whether parallel or transverse to the operating face.

A number of new materials[8] are highly resistant to arc erosion. Some of them are alloys, others combinations of metals which do not alloy with each other. In these latter compositions, refractory metals, such as tungsten and molybdenum, are combined with highly conductive metals, such as silver or copper, by powder metallurgy processes. Other elements are sometimes added. The resulting materials have low contact surface resistance and other desirable properties, coupled with a marked resistance to intense arcing and mechanical wear. Contact materials of this class are being used in aircraft relays and switches to break inductive d.c. loads of hundreds of amperes without arc suppressors. By manipulation of constituent materials, pressing and sintering operations, an almost infinite variety of materials is available.

Sintered Material

One of the first items fabricated by powder metallurgical methods[3] on a commercial scale aside from platinum, tungsten and molybdenum metals was electrical contacts. The reason for making contacts by this process is that the composition of most of these materials is such that they cannot be made by the conventional methods of melting, casting, rolling, drawing, etc.

In general, the electrical contacts[3] fabricated from metal powders fall into two classes, both from the point of view of the method of fabrication and of the chemical composition. One class is composed of silver or copper and a refractory metal, such as tungsten, molybdenum, or compounds thereof, such as carbides; the second class contains a predominant amount of silver and semi-refractory material, such as cadmium oxide, nickel, cobalt, or graphite. Electrical contacts of the first class were developed primarily as facing materials for heavy-duty circuit-interrupting devices. This class unites the high melting point, high boiling point, great resistance to electrical erosion, and refractory characteristics of molybdenum, tungsten, or their carbides with the high thermal and electrical conductivities and low contact resistance properties of silver and copper. The second class of material is used for lighter duty or specialized applications, such as heavy-duty, direct-current aircraft relays.

Sintered alloy contacts are generally furnished in composite form in which a facing is applied to base metal backing, generally copper. In sintered mixtures of two or more materials the individual characteristics of each material are maintained.

Silver-nickel composition is a sintered mixture of silver and nickel powders in which the individual characteristics of the silver and nickel are retained. The hardness and strength of nickel is combined with the high conductivity of silver. The result is a hard, smooth contact surface which does not develop an appreciable oxide film. Galling is eliminated and welding is reduced, but the constant low resistance drop of silver is maintained. "Wilco Agnilite," "Mallory D-50" and "Gibsiloy" are typical sintered silver-nickel contact materials having an electrical conductivity about 75 per cent of that of pure silver and a hardness about 40 Rockwell B.

Silver-graphite composition is a sintered mixture of silver and graphite powders. Non-fluxing and non-welding characteristics are imparted to the high conductivity and non-oxidizing property of silver. "Wilco Agraphite" and "Mallory D-58" are typical of such compositions. The graphite provides refractory characteristics which reduce sticking tendencies. The material is self-lubricating, and therefore reduces scoring or galling.

Silver-molybdenum composition is a sintered mixture of silver and molybdenum metal powders. "Wilco Agmolite" and "Mallory G-17" are such mixtures, which have an electrical conductivity of 45 per cent that of pure silver and a hardness of 70 Rockwell B. These materials have a very high resistance to the erosion of the electric arc, and are used where it is essential that the contacts do not weld when interrupting the circuit.

Silver-tungsten composition is a sintered mixture of silver and tungsten metal powders. In this material the good conductivity and low contact resistance of silver is combined with the non-welding, arc-resistant qualities of tungsten. "Wilco Tungsil" and "Mallory 50-S" are typical of such materials.

Cadmium oxide imparts non-sticking properties and, when compounded with silver, has less effect upon the conductivity than cadmium in solid solution. It is an excellent material for current-carrying and circuit-interrupting contacts at moderate voltage and high currents, as it maintains a low contact resistance and exhibits a low loss of material. "Mallory D-52" and "Mallory D-54" are typical of such contact materials.

Copper-tungsten composition is a sintered mixture of copper and tungsten used for contact facings in heavy-duty circuit-interrupting devices because of its ability to withstand severe electrical erosion and mechanical wear. The stability of tungsten at high temperatures and its fairly high hardness give the material its wear-resistant and arc-resisting qualities, so that welding or sticking of the contacts is minimized; the copper gives the material good electrical and thermal conductivity, so that the contacts do not overheat when carrying heavy currents. The exact properties of the material vary with the proportion of its copper and tungsten content.

Copper-tungsten carbide composition is a sintered mixture of copper and tungsten carbide having higher electrical conductivity and higher hardness than copper-tungsten material; it is used for devices having high impact forces where hardness and electrical conductivity are desired.

Silver-tungsten carbide composition is used on relays and circuit-interrupting devices where the contacts must carry high currents and display good arc-resisting qualities. They show a minimum of material transfer in repeated arcing operations and maintain a low contact resistance.

Classification of Contact Materials

Nearly all the contact materials[11] in use today can be classified under three general headings: Silver-group Metals, Platinum-group Metals, and Tungsten-group Metals. Alloys and combinations of these groups taken in conjunction with certain base metals, particularly copper, cadmium, carbon and nickel, result in a wide variety of contact materials. No contact material is satisfactory for all purposes: each class of service requires its own proper material, size and design. Proper design will depend not only upon the current to be handled, but upon the frequency of operation reliably required, and numerous other factors.

At low frequencies, fine silver can be tentatively considered for current values up to approximately 20 amperes. Silver is relatively cheap and is readily fabricated. It can oxidize, and sulphur reacts quantitatively, producing a film of silver sulphide. However, these films are stable only over a limited temperature range and when sparking occurs, they are usually decomposed at the points of contact because the local temperature may be momentarily quite high. Furthermore, as these films are usually thin and fragile, they are easily destroyed by incorporating in the design of the device some wiping motion between the contacts. The contact resistance of pure silver is very low except at low currents; it remains so if operating conditions cause sufficient wear to destroy such oxide and sulphide films as may form.

Although silver is also classed as a precious metal, its use is so extensive that it is considered separately, since it is frequently used to replace copper. On relays, master switches, limit switches, push buttons and similar devices handling control circuits or currents under 10 amperes, fine silver, coin silver, and other silver alloys are most often used.

Copper[11] is commonly alloyed with silver to harden it. Silver-copper alloys have higher resistivity than fine silver, the contact resistance for a given set of conditions generally being proportional to the amount of copper present. For many applications where considerable mechanical action takes place, the increased life of these alloys due to greater hardness and wearability more than compensates for the slight increase in contact resistance.

Contactors, cam and drum switches or controllers, circuit breakers, rheostats or similar devices, handling currents up to several thousand amperes, usually have contacts of copper, silver, or one of their alloys. If circuits involving appreciable current must be interrupted in a short time with minimum arcing, copper or a copper alloy is indicated. For maintaining a similar circuit closed for long periods of time, with low resistance and little operation, silver is superior to copper.

Copper is subject to oxidation, and when it is oxidized it will have an appreciably higher contact resistance. Trouble due to overheating may result. The oxidation has a time-temperature characteristic. Copper at moderate temperature will oxidize if the time is long; or if the temperature is high, oxidation can occur in a comparatively short time.

Silver does not oxidize at normal temperatures, except where ozone is present, or at temperatures considerably in excess of normal. Silver surfacing of fixed contacts affords an answer to the problem of copper-surface oxidation.

When the product of the frequency and the current interrupted becomes high, erosion and loss of silver becomes excessive as a result of volatilization of the contact metal. An illustration of a high-current, low-frequency application is the air circuit-breaker. For this application sintered mixtures of silver-molybdenum, silver-tungsten, silver-graphite, and silver-nickel are commonly chosen. These combinations, being physical mixtures of elements having little or no mutual solubility, retain the properties of the component metals. Thus the high conductivity of silver is combined with the heat resisting and non-welding properties of the second element.

With an increase in frequency of circuit interruption, the magnitude of current which can be successfully handled becomes much smaller, particularly if the circuit has appreciable inductance. At moderate current and high frequency, the rate at which electrical energy is released as heat energy in the contact gap may become so great that only the most refractory of metals will have a satisfactory life. Automobile ignition points make millions of interruptions in an ordinary day's driving. Even though the current broken is usually less than 5 amperes, only high melting-point materials such as tungsten are satisfactory. Although tungsten develops little loss of material due to volatilization under such severe operating conditions as exist in magneto and automobile ignition systems, it does have a serious limitation due to the formation of tungsten oxides if the peak current exceeds about 5 amperes, or if the pressure is low.

Tungsten contact surfaces, which are quite hard and wear-resisting, oxidize at arcing temperatures to form a high-resistance oxide. They are used where services are very severe and the contacts are made with an impact or wipe sufficient to break the oxide film.

The platinum family of contacts usually comprises platinum, platinum-iridium, platinum-ruthenium, palladium, rhodium or some alloy of these metals. They are so expensive that the tip is usually a thin sheet. As the metals are valuable, it may pay to use clad material in which the precious metal is welded to a base-metal backing. Contacts made of these materials are used when the voltage is low, current is very small, contact force is light, or where corrosive atmospheres require them. They are also used when a reliable noise-free contact is essential, or when lower wear than provided by silver is required.

The virtues of the platinum group metals for electrical contact purposes have long been recognized.[11] Their freedom from objectionable oxide and sulphide films, and their low rate of volatilization under severe operating conditions make them admirably suited for nearly all low and moderate applications, regardless of frequency. In applications where the utmost reliability is required, the platinum metals and their alloys are unsurpassed. For room thermostats an alloy of 85 per cent platinum, 15 per cent iridium is often used. A few grams' pressure is sufficient to establish a definite low resistance contact. For higher frequencies of operation at greater current values, particularly in inductive circuits, platinum alloys with higher iridium content are recommended. Modern magnetos and similar services use either a 10 per cent ruthenium-platinum or a 25 per cent iridium-platinum alloy.

An alloy containing 67 per cent osmium and 33 per cent rhodium has a melting point even greater than that of the platinum-iridium alloys, and is a superior alloy for low-current vibrating contacts where the utmost in dependability and service life is required.

Typical applications of various contact materials may be given briefly:

Molybdenum: mercury switch electrodes, calculating machines, selector contacts for card sorters, pattern needles for moving electric signs, etc.

Tungsten: automotive ignitions, aviation and marine magnetos, voltage regulators, cash registers, electric clocks, radio vibrators, etc.

Silver compositions: make-and-break contacts for light-duty circuit breakers, main current-carrying contacts for multi-stage circuit breakers, heavy-duty line starters and commercial relays, etc.

Copper-tungsten and copper-tungsten carbide: Oil-immersed circuit breakers, voltage tap regulators, air circuit breakers, arcing contacts.

Silver-tungsten and silver-tungsten carbide: heavy duty air-type circuit breakers (arcing tip), oil-type circuit breakers, heavy-duty industrial controls, aircraft relays, and multi-breakers.

Platinum alloys: magneto ignition systems, telephone relays, household thermostats, fire alarm indicators, recording instruments, etc.

Palladium alloys: telephone relays, recording and indicating meters, control relays, signaling relays, sensitive low voltage relays, etc.

Silver (fine): coin-operated devices, domestic appliances, limit switches, motor controls, general and sensitive relays, thermostatic controls, etc.

Properties of Contact Materials

The properties of contact materials vary with the composition and the processing. Typical properties of these materials are best illustrated by the tables published by the P. R. Mallory Company for their particular grades as shown in Table 97.

Typical properties of the silver and copper sintered compositions are illustrated by the properties given by the P. R. Mallory Company[9] for their products in Table 98.

Factors in Contact Operation

Successful operation[10] of the contacts in a simple contact device depends upon a number of factors, the most important of which are: (1) contact resistance, (2) contact force in the closed position, (3) voltage, and (4)

TABLE 97. *Typical Properties of Contact Materials*

Material	Principal components	Electrical conductivity % I.A.C.S.	Hardness Rockwell 15T scale	Ultimate tensile strength (psi)	Elongation (% in 2 in.)
Fine silver	Ag	107	(a) 30	25,000	55
			(c) 75	45,000	5
Coin silver	Ag—Cu	85	(a) 70	40,000	32
			(c) 83	75,000	4
"Elkonium" 1	Ag—Cu—Ni	68	(a) 75	45,000	32
			(c) 85	80,000	4
"Elkonium" 17	Ag—Cd—Ni	30	(a) 50	35,000	55
			(c) 85	68,000	4
"Elkonium" 18	Ag—Cd—Ni—Cu	43	(a) 65	40,000	43
			(c) 87	75,000	3
"Elkonium" 23	Ag—Cu	97	(a) 50	30,000	37
			(c) 80	50,000	3
"Elkonium" 217	Ag—Cd	35	(a) 42	28,000	55
			(c) 83	63,000	3
"Elkonium" 36	Ag—Pt	45	(a) 45	25,000	37
			(b) 77	41,000	4
"Elkonium" 45	Ag—Pd	58	(a) 45	27,000	37
			(b) 77	40,000	5
"Elkonium" 44	Ag—Pd	27	(a) 63	34,000	31
			(b) 80	46,000	5
"Elkonium" 70	Au—Ag—Ni	14	(a) 61	33,000	34
			(b) 81	50,000	5
"Elkonium" 71	Ag—Au	40	(a) 57	27,000	28
			(b) 75	44,000	5
"Elkonium" 30	Pt	15	(a) 60	20,000	35
			(b) 75	33,000	5
"Elkonium" 31	Pt—Ir	7	(a) 67	55,000	20
			(b) 89	90,000	5
"Elkonium" 301	Pt—Ir	6	(a) 91	75,000	15
			(b) 92	120,000	5
"Elkonium" 32	Pt—Ir	5.5	(a) 82	100,000	12
			(b) 91	145,000	5
"Elkonium" 38	Pt—Ir	5.5	(a) 92	125,000	10
			(b) 97	170,000	5
"Elkonium" 35	Pt—Ir	4	(a) 80 *	170,000	3
"Elkonium" 34	Pt—Ru	4	(a) 84	70,000	15
			(b) 92	120,000	5
"Elkonium" 33	Pt—Ru	4	(a) 90	100,000	12
			(b) 96	145,000	5
"Elkonium" 37	Pt—Ru	4	(a) 74 *	170,000	3
"Elkonium" 323	Pt—Pd	8	(a) 77	50,000	26
			(b) 83	70,000	5

(a) = Annealed
(b) = 2 nos. Hard
(c) = 4 nos. Hard
* = Rockwell 15 N Scale

TABLE 98. *Silver and Copper Compositions*

Material	Principal composition	Electrical conductivity % I.A.C.S.	Hardness Rockwell "F"	Tensile strength psi
D-50	Ag—Ni	70	(a) 35-50 (b) 70-85	25,000 30,000
D-51	Ag—Ni	45	(a) 55-65 (b) 83-93	25,000 36,000
D-52	Ag—CdO	90	(a) 15-25 (b) 65-75	16,000 25,000
D-54	Ag—CdO	80	(a) 35-45 (b) 75-85	16,000 26,000
D-58	Ag—C	55	(a) 0-10 (b) 15-36	6,000 9,000
20-S	Ag—W	43-48	92-99 Rb	70,000
50-S	Ag—W	60-65	60-65 Rb	35,000
G-17	Ag—Mo	45-50	80-90 Rb	60,000
G-18	Ag—Mo	50-55	70-80 Rb	45,000
G-12	Silver-Tungsten Carbide	50-60	50-65 Rb	35,000
G-14	Silver—Tungsten Carbide	30-40	95-105 Rb	55,000
1W3	Cu—W	35-42	72-82 Rb	63,000
3W3	Cu—W	31-38	85-92 Rb	75,000
TC-5	Copper—Tungsten Carbide	45-50	90-98 Rb	70,000

(a) = Annealed (b) = Full Hard

current. Besides the primary factors, others may affect the contact reactions, such as (1) frequency of operation, (2) type of load, (3) type of current (alternating or direct), (4) speed of contact separation, (5) atmosphere in which contacts operate, and (6) size and method of fabrication.

The primary function of most contacts is to carry an electric current. It is desirable, therefore, that they offer as little resistance as possible to the flow of current. Such resistance is made up of two separate resistances: (1) that of the contact material itself, and (2) that arising at the junction between one contact and its mating contact.

Contact performance[8] is affected by the material used in the contacting surfaces. A material with a relatively high specific heat will have a large thermal capacity, which helps to limit the temperature rise of the contact surfaces. A material having high thermal conductivity will provide rapid transfer of heat from the contact surfaces to the supporting members, thus minimizing the temperature rise of the contact surface, as well as the possibility or degree of oxidation.

In most cases the surface resistance [11] is of a much greater magnitude than the actual resistance of the contacts themselves. The primary reason for high surface resistance is the very small area which is in sufficiently good contact for current to flow. No matter how carefully contact surfaces are prepared, there will be minute high spots which will be the actual points of contact. Films of gas, oil, dirt, and oxide will further reduce the effective contact area.

As the contacts open by the force applied, the potential drop between them rapidly increases and soon reaches the full potential difference of the circuit. If the force to close the contacts is relatively large or is applied a great number of times, it is apparent that the contact material must have sufficient strength to withstand mechanical wear.

With low potential differences and light forces, a contact material must be used that will interpose the least resistance in the circuit. Low surface resistance will therefore be required, as well as resistance to oxidation and to atmospheric tarnishing, which would tend to increase surface resistance. (The contact resistance due to films, etc., is usually the more important factor.) If heavy currents [11] are to be carried for appreciable periods of time, the material must have not only a low contact resistance, but also a low specific resistance. Moreover, it must have a high thermal conductivity and a design that will permit rapid radiation of heat, so that the contacts will maintain a sufficiently low temperature.

To open the circuit successfully, the contacts must be resistant to sticking or welding, particularly when only light forces are available to separate them. In circuits where an arc is formed at opening, the contact should be of such composition that the high temperature and eroding effect of the arc will not seriously damage the surface. A high melting point for a contact material minimizes the possibility of welding or cohering. It also reduces the transfer of contact material during the arcing that occurs on closing or opening a circuit. Relatively high hardness provides resistance to mechanical wear. The outstanding material from a non-sticking standpoint is carbon.

Such contact materials as copper, silver and gold have the best thermal and current-conducting characteristics, but usually have a comparatively low tensile strength, hardness and melting point. The last two metals are subject to considerable transfer in use. However, elements such as tungsten, molybdenum, platinum, and platinum-iridium have a high melting point and hardness. These, of course, are more expensive than the first group. The specific resistance is high, but the contact resistance is low and constant. Every practical contactor or relay contact design is generally a compromise between the characteristics desired and those that can be obtained economically.

In general, metals which are resistant to tarnish may be used at low contact forces, while those subject to oxidation or tarnish require higher forces. The higher force tends to break through the tarnish film or oxides.

It is generally assumed[2] that a metal or alloy of high conductivity will be inherently low in contact surface resistance. This is not necessarily true. Copper is an excellent conductor, but a poor contact material where low pressures and low voltages are encountered. However, it is the most widely used contact material. Tungsten and platinum are only fair conductors, but excellent contact materials in the different services for which they are intended. Silver is one of the best conductors, and is second only to copper in the extent of its use as a contact material. The effectiveness of a contact material, as far as surface resistance is concerned, is determined not by its inherent conductivity, but by its ability to retain a surface of low resistivity after prolonged use.

Important current characteristics in contact selection are: (1) amount and type of current, (2) frequency of operation, (3) voltage to be interrupted, (4) speed of opening and closing, (5) contact pressure, (6) ambient temperature, and (7) atmosphere in which the contacts operate. Circuit characteristics—inductive, restrictive, or capacitative—should be considered, as well as the methods used for closing contacts, whether gravity, mechanical, or magnetic.

Electrical contact materials employed in circuit-breaker applications have been known to weld or "freeze" when heavy overcurrents or current surges are passed between two contacts held together by a static force. It is the function of circuit-breaker contacts to carry short-circuit currents and heavy current surges without welding, so that the contacts may be parted by the supporting mechanism when the trip device operates.

Welding of circuit-breaker contacts has been known to occur in the short interval between the start of an abnormally high current and the operation of the circuit-breaker mechanism moving as quickly as possible against the inertia of its parts. However, welding is most probable in circuit breakers when a time delay device, such as a bimetal strip, is employed to provide an interval between the initiation of a current surge and the operation of the circuit-breaker trip device.

The useful life of electrical contacts is determined to a great extent by the degree of arcing that occurs when the contacts close or open a circuit.

The principal cause of arcing[8] when contacts close to energize a circuit is the rebound or bouncing of the moving contact off the stationary contact. Also, a wiping or sliding action between the moving and stationary contact surfaces produces some arcing, as the point of contact is transferred from one point to another. Because the magnitude of the contact bounce or wiping action is directly determined by the mechanical design of the contact-operating mechanism, careful consideration must be given to the mechanical design of contactors.

In general, the moving contacts of electromagnetically operated relays and contactors shift extremely rapidly from one position to another. During the closing operation, the kinetic energy of the moving contact assembly often produces contact bounce. Sometimes this can be reduced by making the moving contact assembly as light as possible, by utilizing a relatively high initial contact force, or by decreasing the contact velocity to a minimum practical value. Fortunately, there is usually some friction in the moving contact assembly which helps to reduce the magnitude of the rebound and to damp the contact oscillation.

Failures

Practically all failures[2] come under one of the following classifications:

(a) Contacts fail to open.
(b) Contacts close, but fail to conduct current.
(c) Contacts overheat.
(d) Abnormal or excessive contact voltage drop.
(e) Abnormal or excessive wear or disintegration.
(f) Abnormal transfer of metal from one contact to the other.

There are two common causes of failure to open: either the contacts actually weld, or they stick together mechanically because of excessive transfer of material. When contacts stick suddenly with no preceding marked increase in resistance, so that a force of several ounces is required to separate them, the cause is actual welding. This can be prevented by (1) using a non-welding contact material, if possible, such as tungsten, graphite, or one of the refractory powdered metal compositions; (2) using larger contacts of the same material; (3) altering the design of the device; (4) increasing the break forces; and (5) altering the circuit.

In most cases[2] where contacts fail to open, it will be found that they have stuck together mechanically because of pitting or transfer. Migration or transfer of contact material involves the development of a pit in one contact and a cone or pyramid of corresponding shape and size on the face of the mating contact. This situation is most common in d.c. circuits and seldom occurs in a.c. circuits. The direction of transfer sometimes can be altered by reversing the current or by changing the circuit constants. Transfer can in many cases be reduced or entirely eliminated in d.c. circuits by using dissimilar contact materials.

The appearance of the metal transferred from one contact to the other will vary over a wide range. It is possible, however, to classify transfer generally into two types: dome and needle. Dome transfer, as the name implies, appears as a small mound of metal added to the contact face; a corresponding depression or crater exists in the mating contact. Needle transfer consists of a long thin spike; the crater in the mating contact often looks as if a small hole had been drilled in the contact face. In some cases a combination of both types of transfer may occur. Dome and needle types of transfer are shown schematically in Figures 85 and 86.

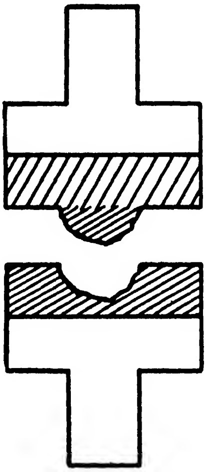


Figure 85. Dome type transfer.

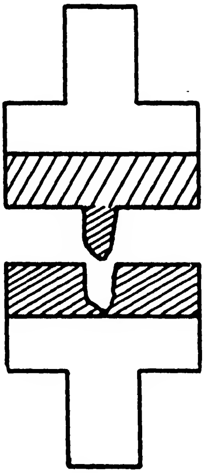


Figure 86. Needle type transfer.

Transfer[2] to the negative contact is frequently attributed to the action of the electron stream in the contact spark, where the length of the contact opening is less than the main face path of the electrons. The cathode (negative contact) remains relatively cool because it is bombarded by only a few positive ions, whereas the anode (positive contact) is heated by the electron bombardment. As a result, the anode tends to vaporize at various local hot zones. The positive metal ions thus formed are then transferred by the intense electrical field between the open contacts to the cathode.

Figures 87 and 88 illustrate a severe type of negative transfer on punched tungsten contacts. Figure 88 shows the transfer, somewhat of a dome type; in addition, a small needle portion exists in the area in the upper left. Figure 87 shows a section of the crater in the mating contact. It will be noted that the electrical conditions have been severe enough to tear the grains of tungsten away from the adjacent metal.

Transfer to the positive contact is commonly explained[8] as occurring when the length of the spark or arc is greater than the primary electrons near the free path, so that the electrons emitting from the cathode strike and ionize or excite the gas molecules in the gap. Then if current and voltage are sufficient, an arc is formed. As a result, the cathode is bombarded by the positive ions and it begins to vaporize more than the anode, with resultant migration of material toward the anode.

If the nature of the failure is abnormal transfer, the cause may be (1) improper contact material; (2) faulty circuit design, requiring a change in inductive, resistive or capacitative values, or even the use of short leads in the arc quenching circuit; (3) mechanical, where the speed of contact separation or contact pressure must be changed; and (4) electrical, necessitating the use of larger contacts or different contact material.

Transfer of contact material may be overcome (1) by using dissimilar materials, (2) using greater break force, (3) changing the inductive, resistive or capacitative value in the circuit, (4) more careful alignment of contacts.

When contacts close, but fail to establish a circuit, the cause may be insufficient pressure, oxidation or corrosion. By using greater closing force, tension failure due to insufficient pressure can be overcome. Oxidation is usually caused by arc action and can be overcome by employing a wiping or rubbing action as the contacts close. A hammering action, which tends to break up oxide, serves to keep the contacting surfaces clean. Oxidation can also be remedied by using non-oxidizing materials, or by quenching the arc by means of a condenser or resistor in the circuit.

Foreign material on the contacting surfaces will also cause failure to establish a circuit, and can be eliminated by operating the contacts with the surfaces in a vertical plane or by properly enclosing the contacts or the entire device. When contacts close, but fail to conduct current due to corrosion on the surfaces, it is advisable to use a more corrosion-resistant material or to protect the contacts by enclosing them.

Overheating of contacts is caused by high contact surface resistance, by improper contact, or by faulty assembly. The resistance may be at the contact surface or caused by loose assembly. Contacts which operate at excessive temperatures tend to arc more severely and thus to transfer and weld more readily. If there is high contact surface resistance, the remedy is to use larger contacts or dissimilar contact materials. Overheating due to improper contact can also be corrected by this means. However, if it is due to improper assembly, the method of assembly must be improved or larger backings used.

Sometimes high contact surface resistance is due to failure to dissipate heat generated by the arc. This trouble is often overcome by increasing the thickness of either the contact itself or the backing. Or it can be corrected by assembling the contacts by welding or soldering, rather than by riveting or using lock nuts with screw-type contacts.

(*Courtesy P. R. Mallory & Co., Indianapolis, Ind.*)

Figure 87. Crater in mating contact to that shown in Figure 88.

Abnormal voltage[2] drop is associated with contact surface resistance. It may be due to incorrect contact material, to circuit conditions or to mechanical conditions. Insufficient or too great arc quenching can cause this difficulty. Bad mechanical conditions that also tend to increase contact voltage drop are insufficient pressure, chattering, and lack of rubbing or wiping action.

Abnormal wear may be purely mechanical, or it may be erosion caused by arcing. Mechanical wear can be reduced by less pressure, less rubbing or wiping, or less hammering action. Changing to a harder contact material is sometimes necessary. If wear is due to a circuit condition, it is wise to reduce arcing or change the speed of make and break. If the contact material is improper, arc-resisting or more wear-resistant material should be used.

(Courtesy P. R. Mallory & Co., Indianapolis, Ind.)

Figure 88. Negative transfer on tungsten contacts (100X magnification).

Design

The engineer designing circuit-interrupting equipment[10] is interested in obtaining electrical contacts that will give maximum performance at minimum cost. These objectives can be best attained if consideration is given to the shapes, tolerances, and physical characteristics of contacts that can be produced by standardized manufacturing procedures, before the final design of the device is completed.

The principal factors to be considered in contact design are: (1) Electrical and mechanical factors of the equipment, and (2) physical characteristics of the contact material that may govern the construction and method of fabrication.

From the variation in physical properties previously indicated, it is evident that different designs are required for different materials. Soft, ductile materials, such as silver, most silver alloys, palladium and platinum, can be cold-headed into many sizes and shapes. Rivets headed from wire can be riveted or spun to the contact support. If the size of the rivet required is large, a composite construction in which a disc of the contact material is attached to a base-metal backing may be more economical. Such base-metal backings in common use are steel, brass, bronze, copper, "Monel" and nickel. Brass and steel adequately serve most applications.

In situations where pure platinum is too soft for contact uses, it can be hardened by alloying with iridium, ruthenium, or palladium. Palladium, generally unalloyed, is suitable for most applications at and below one ampere. Composite designs are generally used for economy.

As pure tungsten is quite hard and somewhat brittle, composite designs are used for practically all applications. Though tungsten contacts usually employ a steel backing, nickel is sometimes preferred.

The ductility of the pressed powder compositions, such as silver-tungsten and silver-molybdenum, is low, again generally calling for the use of composite designs. The contact facing may be brazed to backing materials, such as copper, steel, nickel, brass and bronze. The pressed powder compositions are generally used where high currents are involved. Since copper and copper alloys afford maximum electrical and thermal conductivities, they are generally used for supports.

Make-and-break contact devices[10] are fabricated in a variety of forms for widely different purposes. They may be small switches or relays actuated by light forces and carrying low currents, or they may be extremely large units requiring greater force to actuate. Likewise, the contacts used in such devices vary from small rivets of pinhead size to relatively massive contactors requiring several pounds of material. Depending on the services, the material used may range from relatively soft fine silver to extremely hard tungsten.

Although contacts of many shapes and sizes are in use, the majority may be found in one of the following groups:

(1) Rivet type
    (a) solid rivet
    (b) composite rivet
(2) Screw type
(3) Button or projection welding type
(4) Special shapes

Silver is furnished in the form of solid silver rivets, silver-steel laminated buttons for projection welding, composite (silver-faced) rivets, and inlay and overlay strip.

Silver-steel laminated buttons have become one of the most extensively used types of contacts. Steel-back contacts were developed to provide contacts which could be welded to their supporting members by means of projections formed on the steel back. The laminated construction offers economy in the use of silver. The silver facing consists of solid, hard-rolled silver bonded to steel. "Monel" or nickel-silver may be used in place of steel in the backing material where preferred to avoid rusting, and so forth.

Screws provide a means of easy adjustment and assembly of contacts in many electrical devices. The contact facing material is usually silver, but may be tungsten, platinum and their alloys.

Silver inlaid or overlaid on a base metal provides an economical and ideal contact material for many devices. Economy is afforded by limiting the use of silver only to the amount necessary for successful bonding to the base metal. Mechanical strength, spring properties, corrosion resistance, ability to withstand high temperatures, and other desirable physical properties can be secured by the selection of the appropriate base metal.

Table 99 gives a tabulation of sizes of silver contact rivets which have been found generally satisfactory for various current ranges.

TABLE 99. *Sizes of Silver Contact Rivets*

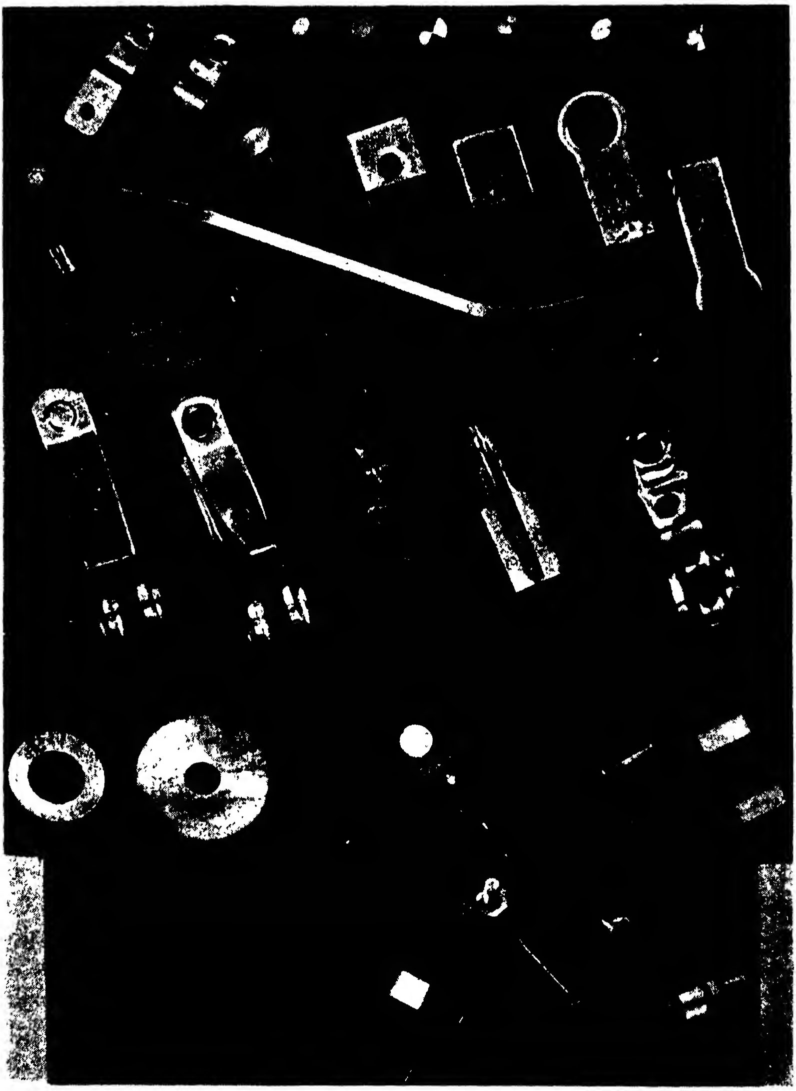
Maximum amperes	Diameters	Thickness
Under 1	0.078″–0.125″	0.018″–0.031″
1–5	0.125″–0.250″	0.025″–0.047″
5–10	0.187″–0.312″	0.050″–0.062″
10–20	0.312″–0.500″	0.062″–0.093″

Selection[9] of contacts to make and break an electrical circuit involves two fundamental factors: the choice of a material and the choice of a design. The former depends upon the electrical and mechanical characteristics of the apparatus. The design of the contacts is determined in general by the size and shape of the circuit-interrupting portion of the device.

The many factors involved in selecting a contact material make it difficult to offer specific recommendations for general applications. The choice of a material and a design can best be made by balancing the physical and electrical and mechanical characteristics of a given apparatus.

The design of the complete contact member is of fundamental importance. The material from which the contact arm is fabricated, its design and the method of assembly all directly affect the life and efficiency of the contacts.

There is always the possibility of using combinations of materials to accomplish intermediate results. For example, tungsten may be used successfully against fine silver, and platinum-ruthenium may be used against tungsten. Such combinations give the net effect of one low-contact resistance material operating against another which is resistant to welding. For further pairing of contacts of dissimilar materials there are silver with molybdenum and silver with silver-tungsten composition.

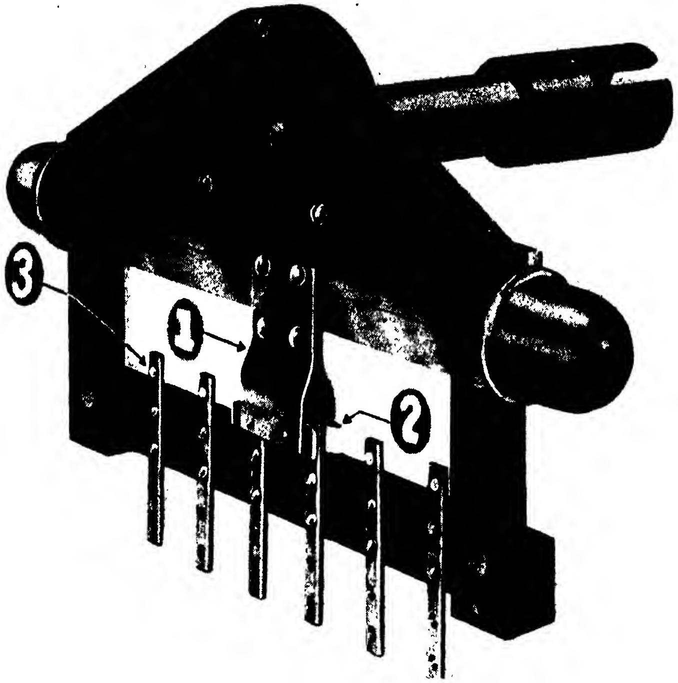


(Courtesy P. R. Mallory & Co., Indianapolis, Ind.)

Figure 89. Different contact designs.

Contact members[2] can be made in various styles, shapes and sizes to achieve certain desired results. Operating movements can be made slow or fast, and contact pressure controlled to suit circuit conditions. A wiping, rubbing, or hammering action can be employed to remove oxidation and keep surfaces clean. A rolling or hinge action can be used to minimize danger of sticking or welding. Protection against arc erosion can be obtained by the use of arc-quenching devices such as condensers or resistors, or by proper balance of the circuit.

Figure 89 shows examples of many designs of electrical contacts for a large number of types and sizes of electrical apparatus using contacts.



(Courtesy Gibson Electric Co., Pittsburgh, Pa.)

Figure 90. Transformer tap changer.

Figure 90 shows a straight-line transformer tap changer on which the steel springs (1) maintain a heavy unit contact pressure between "Gibsiloy"-faced contact sliders (2) and "Gibsiloy" contact buttons (3).

A number of registered trade-mark alloys are mentioned in this section. The manufacturers of these alloys are as follows:

Gibson Electric Co., Pittsburgh, Pa.
"Gibsiloy"

P. R. Mallory & Co., Indianapolis, Indiana.
1W3
3W3
20S
50S
D-50
D-51
D-52
D-54
D-58
G-12
G-14
G-17
G-18
HA
K
MK
TC5
"Elkonium" 1
" 17
" 18
" 23
" 30
" 31
" 32
" 33
" 34
" 35
"Elkonium" 36
" 37
" 38
" 44
" 45
" 70
" 71
" 217
" 301
" 323

H. A. Wilson Co., Newark, N. J.
"Agmolite" "Agraphite"
"Agnilite" "Tungsil"

References

1. Hensel, F., and Larsen, E., "Tungsten-Copper for Electrical Contacts," *Metals and Alloys* (May, 1941).
2. Kleis, J., "Design of Electrical Contacts for Trouble-free Service," *Product Engineering* (November, 1943).
3. Larsen, E., "Electrical Contacts Manufactured from Metal Powders," *Metal Tech.* (January, 1945).
4. Gwyn, C., "Electrical Contacts," *Metals and Alloys* (May, 1945).
5. Anon., "Properties of Contact Alloys," *Aviation* (August, 1945).
6. Bloodsworth, W., "Electrical Contacts," *Factory Management and Maintenance* (June, 1946).
7. Swazy, E., and Heil, V., "Cadmium-Oxide-Silver Materials for Difficult Contact Jobs," *Electrical Mfg.* (September, 1946).
8. Immel, R., "Some Design Considerations for Electrical Contact Operation," *Product Engineering* (February, 1947).
9. "Contact and Contact Material," P. R. Mallory & Co., bulletin.
10. "Electrical Contact Data Book," P. R. Mallory & Co.
11. "Electrical Contacts," H. A. Wilson Co., bulletins.
12. Jones, B., and Zickrick, L., "Characteristics of Silver and Copper for Use as Electrical Contacts," *Product Engineering* (November, 1947).

Chapter XII

Thermostat Metals

Thermostat metal is defined as "a composite metal usually in the form of sheet, strip, rod or wire, comprising two or more metals which by virtue of the differing expansivities of its components, tends to change its curvature when subjected to a uniformly distributed change in temperature." A thermostat metal comprising only two metal components is called a bimetal. Most thermostat metals produced today are bimetals.

As the name implies, bimetal is a composite metal half of whose cross-section is composed of a high temperature coefficient of expansion metal, and half of a low temperature coefficient of expansion metal. This difference in expansion is responsible for the unique property of moving, or more properly bending, of the composite material with a temperature change. One layer tends to expand or contract more than the other when the temperature of the composite is changed, and forces are set up which cause the strip to bend.

The two metals are permanently welded together throughout their entire surface of contact by a direct high-temperature, high-pressure process without any bonding material. This joint is very important, since a uniformly good weld is necessary to resist the shearing stresses which exist in the joining plane when the composite is warmed or cooled in service operation.

The composite plate of bimetal, after welding, is either rolled into sheet or strip, or sheared and drawn into rod or wire. The material may also be cut, trimmed and shaped into various forms.

The function of a thermostat metal is to convert heat energy or electrical energy directly to mechanical movement. Therefore, differential expansion offers a basis for indicating and controlling temperature over a wide, useful range in an accurate and inexpensive manner.

When the bimetal[1] is heated, a warping action is produced. This change in curvature, or the force developed by restraining this deflection, provides a simple, reliable and compact means of transforming heat into mechanical movement. The heating may be the result of electrical heating by induction or resistance, or by conduction, convection or radiation.

Thermostat metal forms the temperature-sensitive element in devices where protection from overheating or controlled temperature is necessary, or where the device is a measuring unit and automatic compensation for changes in temperature is required.

Basic Principles

When an element of thermostat metal is heated, the component with a high coefficient of expansion will expand a certain amount, while the other component having a low coefficient of expansion will expand relatively little. In the same manner, when the element is cooled, the component with a high coefficient will contract a certain amount while the other component having a low coefficient will contract very little. The result of this difference in the expansion or contraction of the bonded metals is a bending action.

Thus, if a strip of thermostat metal is flat at some given temperature, on heating it will bend to the arc of a circle with the high-expansion metal convex. On return to its original temperature, the strip will again be flat. If the strip of thermostat metal is cooled below the given temperature, it will bend to the arc of a circle, but with the high expansion side concave, again becoming flat on returning to its original temperature. This differential thermal expansion is schematically illustrated in Figure 91.

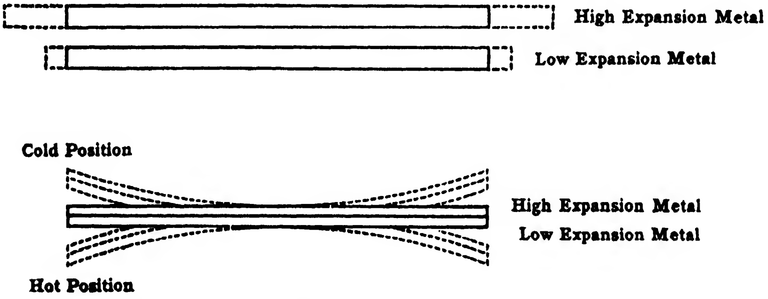


Figure 91. Differential thermal expansion.

This change in the radius of curvature depends on the thickness of the thermostat metal, the difference in the coefficients of expansion of the components, and the magnitude of the temperature change. This basic characteristic is called "flexibility," and is defined by the following formula:

$$F = \frac{\left(\frac{1}{R_2} - \frac{1}{R_1}\right)t}{T_2 - T_1}$$

where

F = flexibility or the change in curvature per unit temperature change for unit thickness

R = radius of curvature in inches

t = thickness in inches

$T_2 - T_1$ = temperature change in ° F

Curvature change, R, of a narrow bimetal strip of thickness t on heating $T_2 - T_1$ degrees, when the difference in mean expansivity of the components over the temperature range chosen is A, is given by the equation $R = \frac{3A(T_2 - T_1)}{2t}$. It is evident that the change in curvature, other things being the same, is inversely proportional to the thickness of the bimetal: the thinner the strip, the more it should move when heated.

Bimetal is often used as a cantilever; that is, a strip is held rigid at one end and does useful work such as tripping a latch at the other end. This is the simplest form of mounting and one well adapted to illustration.[1] A narrow bimetal strip so mounted is shown in Figure 92. Deflection x at the free end may be calculated from the curvature change on heating, and the active length L by means of the relation $x = 1/2L^2R$ when the change in curvature is very small. Combining with the previous equation, we have $x = \frac{3L^2AR}{4t}$.

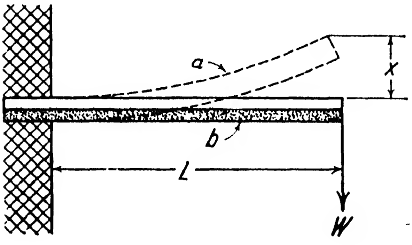


Figure 92. A bimetal strip mounted as a cantilever beam *b* would rise to a position *a* if the motion were not prevented by an imposed load, as *W*.

Thus it is seen that a given bimetal strip, heated over a specified temperature range, will deflect an amount directly proportional to the square of the length and inversely proportional to the thickness. Hence for maximum sensitivity it should be as long and thin as possible.

A bimetal is often required to exert considerable pressure at the free end in order to actuate a mechanism. This means that a certain amount of thermal deflection must be annulled. The efficiency of bimetal for this type of service may therefore be measured by the load, W, at the free end required to annul unit thermal deflection. This property is often called "activity."

From elementary mechanics it may be stated that the deflection of a cantilever loaded at the free end is inversely proportional to the elastic modulus of the beam. Hence the activity of a bimetal is proportional both to the difference in expansivity of its components and to the effective elastic modulus of the combination. One may therefore improve the activity by increasing either the difference in expansivity between its components or their mean modulus of elasticity. Little can be accomplished by the latter alternative, however, because the elastic modulus of metals responds only slightly to alloying.

The significance of the foregoing observations can be better appreciated if the magnitude of the operating stresses is calculated. It has been shown that the stress distribution at an elevated temperature in a bimetal free from stress at room temperature is that shown in Figure 92, when the components have the same elastic modulus. The stress at the joint between the components is twice as great, and of opposite sign from that at the outer surface of the same component. The value of the maximum stress, p, is given in terms of the modulus, E, by the equation $p = 1/2EAT$. Thus a strong, uniform joint is necessary.

Derivation of Thermometal Formulas[5]

A mathematical analysis will show that a straight narrow strip of thermometal will bend to an arc of a circle. The radius of this arc can be expressed:

$$\frac{l}{R} = \frac{6fT(t_1 + t_2)t_1t_2E_1E_2}{3\,(t_1t_2)^2t_1t_2E_1E_2 + (t_1E_1 + t_2E_2)\,(t_1^3E_1 + t_2^3E_2)}$$

Where
R = radius of curvature
$T = T_2 - T_1$ = temperature change
$f = f_1 - f_2$ = difference in coefficient of expansion
t_1 = thickness of element (1)
t_2 = thickness of element (2)
E_1 = elastic modulus of element (1)
E_2 = elastic modulus of element (2)

This is the fundamental relation between the properties of the two elements of a bimetal and its behavior with a temperature change.

Differences in the elastic moduli of the elements now being used in thermometals affect the rate of curvature only slightly, and when the moduli are equal the formula reduces to

$$\frac{l}{R} = \frac{6fTt_1t_2}{(t_1 + t_2)^3}$$

The curvature is greatest when the thickness of the two elements are equal, so if the total thickness $t = 2t_1 = 2t_2$

$$\frac{l}{R} = \frac{3fT}{2t}$$

Neither the rates of thermal expansion nor the elastic moduli of most materials are uniform over wide temperature ranges, but in the practical application of thermometals there is a temperature range where the curvature can be expressed by the equation:

$$\frac{l}{R} = \frac{2kT}{t}$$

where k is a constant for each thermometal which depends on the difference in thermal expansion and the ratio of the elastic moduli of the two elements.

If we have a straight strip fastened at one end and free to move at the other then d, the distance moved by the free end, will be approximately $\frac{l^2}{2R}$, where l is the effective length of the strip, so that

$$d = k\frac{TL^2}{t}$$

This is the form of the equation generally used for estimating the behavior of straight strips.

Many thermometal parts are in the form of helices and spirals. Neglecting the relatively small change in length of the strip, it can be shown that the angular rotation between the end of a coil is

$$\Delta = \frac{360}{\pi}k\frac{TL}{t} = 114.6k\frac{TL}{t}$$

where $\triangle$ is the angular rotation in degrees.

When the temperature of a piece of thermometal is changed, a force is required to keep it from moving. We can consider this force to be that which would be required to restore the strip to its original position after it had deflected freely. Then, by combining the temperature-deflection formulas above with the more common load-deflection formulas of beams and coil springs, we arrive at formulas expressing the relation between temperature and force for thermometals. For a straight strip fastened at one end and touching a stop at the other end,

$$P = \frac{kE}{4}\frac{Twt^2}{l}$$

where P is force exerted at the end of a straight strip of uniform width w. For coils

$$M = \frac{kE}{6}Twt^2$$

where M is the torque of coil.

In many applications thermometal must do work. If it is already supporting a load and must merely move this load, the amount of movement for a given temperature change will be the same as when the strip carries no load. If the strip must pick up a load and also move it, the total temperature change required will be larger and can be divided into two parts. One part is required to produce a force equivalent to the load and the remaining part to produce the movement. An expression of the ability of a thermometal to do work is reached by combining the formulas for temperature-deflection and force. With one half of the temperature change producing force and the other half producing movement, we have for a strip of uniform width fastened at one end,

$$Pd = \frac{k^2ET^2}{16}wtl$$

The work which a piece of thermometal can do is proportional to its volume, modulus of elasticity, the square of the constant *k*, and the square of the temperature change.

Relatively high stresses are set up in thermometals by temperature change alone, and the value and distribution of these stresses are changed when the thermometal is not free to deflect, or if it carries a load. In a freely deflecting strip with elements of equal thickness and elastic moduli it can be shown that the change in stress *S* will be:

$$Sa = \frac{fET}{4} = \frac{kET}{3}$$

Tension in high expanding side and compression in low expanding side at outer fiber.

$$Sb = \frac{fET}{2} = \frac{2kET}{3}$$

Compression in high expanding side and tension in low expanding side at junction.

If the strip is fastened at one end and bears against a stop at the other end the change in stress at the fastened end would be:

$$Sc = \frac{7fET}{8} = \frac{7kET}{6}$$

Compression in high expanding side and tension in low expanding side at outer fiber.

This is almost twice the maximum stress introduced in a piece which is free to deflect. It is evident that a thermometal should not be strained over a large temperature change.

Knowing the maximum stress which may be applied to the elements and the temperature-deflection characteristics of a given thermometal, one can approximate the temperature range over which it will operate without taking a set.

The distribution of stress in a thermometal depends on its history. Proper treatment of a piece of thermometal would place low stresses at the dangerous section at some intermediate temperature in the range of operation, so that the stresses will be compressive at one limiting temperature and tensile at the other.

Computed stresses should be used with care in any attempt to reach a limited load condition. Generally, observations on the performance of a thermostat should be made after the assembly has been held at temperatures below the minimum and above the maximum it will reach in service.

The derived formulas given in the foregoing apply strictly to narrow strips, as only the longitudinal expansion and contraction were considered. Actually the elements change dimensions in all directions and the transverse expansion or contraction causes a strip to bend across its width as well as along its length. In some applications the effect of this cross bending is appreciable, particularly in short, wide strips and in curved strips, where the width approaches the radius of curvature of the strip. No general formulas can be given to cover the variables of shape and dimensions, but those given above, with the constants, serve as a useful guide in determining approximate dimensions for the most common forms.

Thermostat Material

Alloys having the proper physical properties, including widely differing expansion coefficients, are the most suitable materials for thermostat purposes. The selection is also dependent upon the properties required in the thermostat metal, *i.e.*, high deflection, high torque, electrical resistivity graduated for various electrical applications, and combinations of the above.

In general, single-phase (solid solution) alloys[3] are preferable to alloys containing intermetallic compounds or those which are characterized by a changing solubility of one of their constituents with changes in temperature. The expansion rate must be reversible, not only in the temperature range in which the thermostat is intended to function, but also in any range to which it could be subjected.

The commercial applications of bimetal began after a low-expansion alloy, such as "Invar" (34–36 per cent nickel, balance iron), became available. This alloy had an expansivity very close to zero at room temperature. It also had the necessary strength and endurance for high-temperature applications.

Brass-"Invar"[1] bimetal has an exceptionally high sensitivity at room temperature, as does also silicon bronze-"Invar." These two combinations are widely used, but they are not satisfactory where temperatures much above 100° C. (212° F.) are encountered. "Invar" was used for the low-expansive side, and various copper alloys for the high-expansive side.

Bimetals having better stability and ability to survive overheating are desired. An austenitic corrosion-resistant steel can replace the brass or silicon bronze in these. Sensitivity is sacrificed here to obtain the improved characteristics. If an austenitic nickel-manganese steel is used as the high-expansion component, the stability of a ferrous alloy, as well as the high sensitivity of brass-"Invar," can be secured. These bimetals can withstand overheating to 150° C. (302° F.) and still retain high sensitivity.

When applications for the use of bimetal at temperatures around 300° C. (572° F.) arose, and where high sensitivity and stability were also required, a 42 per cent nickel-iron alloy was used in place of the 36 per cent nickel alloy ("Invar"). The expansivity of the 42 per cent nickel alloy is higher at room temperature than that of "Invar." However, at and above 150° C. (302° F.) "Invar" expands rapidly, whereas the 42 per cent alloy has a range of low expansivity extending from 150 to 300° C. Consequently bimetals employing the 42 per cent nickel alloy have a high sensitivity at their operating temperature and a low sensitivity at room temperature.

One component used with the 42 per cent nickel alloy is "Monel" metal containing about 67 per cent nickel and 30 per cent copper. The main advantage of using "Monel" is ease of fabrication. "Monel" is closer to the low-expansion nickel alloy in physical properties, other than expansion, than any other useful component. The chief disadvantage of "Monel" bimetal is low sensitivity—about two-thirds that of brass-"Invar." Greater sensitivity has been attained in high-temperature bimetal by using austenitic steels in place of "Monel," but fabrication difficulties are encountered because of the difference in hardness.

A high-manganese alloy, containing 75 per cent manganese, 15 per cent nickel, and 10 per cent copper, has been used as a material for the high-expansion side of a thermostatic metal. Chace No. 772 Alloy, containing 72 per cent manganese, 18 per cent copper and 10 per cent nickel, is another high-manganese alloy used for the high-expansion side.

In addition to bimetals, recent needs have also brought about the manufacture of trimetals.[4] In many cases it was necessary to improve the current-carrying capacity of thermostatic bimetals, and a layer of cadmium-copper between the "Invar" and the brass has solved this problem.

To meet all present demands for dependable bimetal, thermometals are available in many types, the more common of which are marketed under the manufacturers' respective trade marks. In most cases the compositions of the low- and high-expansive side of each proprietary thermometal are not given, since they are not generally disclosed. However, the wide selection of thermometals, covering a broad temperature range, enables the user to select a metal exactly suited to the user or product.

Two well known commercial bimetals[5] known as "Highflex" and "Highflex 45" have both the following compositions:

"Highflex": High-expansive side (18 Ni, 11 Cr, 0.25 C, bal. Fe)
Low-expansive side (36 Ni, 0.12 C, bal. Fe)
"Highflex 45": High-expansive side (19 Ni, 0.9 Mn, 2 Cr, 0.5 C, bal. Fe)
Low-expansive side (36 Ni, 0.12 C, bal. Fe)

Table 100 shows some typical bimetals with the average ratio of thermal expansion of their component elements and also the maximum temperature for active deflection; Table 101 shows some typical bimetals with their corresponding useful temperature ranges.

TABLE 100. *Typical Bimetals, Their Ratio of Thermal Expansion and Maximum Temperature for Active Deflection*[2]

Bimetal element		Average ratio of thermal expansion of component elements at 100° F.	Maximum temperature for active deflection (° F.)
Low-expansive side (% Ni-Fe)	High-expansive side		
36	Iron	1:6.5	400
36	Nickel	1:8	430
36	67% Ni—23% Cu	1:8.5	460
36	Copper	1:10	400
36	22% Ni—8% Cr-Fe	1:10.5	480
36	Brass	1:12.5	300
40	Brass	1:5.5	300
40	67% Ni—23% Cu	1:4	550
42	67% Ni—23% Cu	1:2.5	600
42	22% Ni—8% Cr-Fe	1:3	750

TABLE 101. *Typical Bimetals and Their Useful Range*

Bimetal element		Useful temperature range	
Low-expansion side	High-expansion side	(° C.)	(° F)
"Invar" (36 Ni, Fe)	27 Ni, 5 Mo, bal. Fe	25–190	77–374
42 Ni, bal. Fe	27 Ni, 5 Mo, bal. Fe	60–500	140–932
"Invar" (36 Ni, Fe)	Nickel	60–190	140–374
42 Ni, bal. Fe	Nickel	20–350	68–662
42 Ni, bal. Fe	42 Ni, 5 Mo, bal. Fe	130–400	266–752
"Invar" (36 Ni, Fe)	42 Ni, bal. Fe	250–340	482–644

Properties. Since bimetal is composed of layers of metal, its physical properties are determined by its components, its fundamental property being able to change curvature with change in temperature. On these components depend such properties of bimetal as permanence of calibration, maximum allowable temperature, operation temperature, rate of deflection with temperature change, mechanical stiffness and strength, workability, electrical and magnetic properties, and size and shape of the bimetal unit which must be used for a given application.

In addition, the useful properties of thermostatic metal, such as deflection and force exerted due to temperature change, depend on the strength

TABLE 102. *Type No. 365 Standard*

Material: "Invar" and 60–40 brass.
Operating Range: 0–300° F.
Heat Treatment: 350° F. for one hour.
Electrical Resistance: 68 ohms/sq. mil ft.; 84 ohms/circ. mil ft.
Modulus of Elasticity: 17,500,000 psi.

Straight Strips

$$\text{Deflection (inches)} = \frac{0.0000080TL^2}{t}$$

$$\text{Pull (ounces)} = \frac{560TWt^2}{L}$$

$$\text{Pull (ounces)} = \frac{70{,}000{,}000dWt^3}{L^3}$$

Coils and Helices

$$\text{Angular Rotation (degrees)} = \frac{0.00096TL}{t}$$

$$\text{Pull (ounces)} = \frac{380Wt^2T}{r}$$

$$\text{Pull (ounces)} = \frac{400{,}000Wt^3A}{Lr}$$

Type No. 360 Medium

Material: "Invar" and 22 per cent nickel, 3 per cent chromium steel.
Operating Range: 0–400° F.
Heat Treatment: 450° F. for one hour.
Electrical Resistance: 410 ohms/sq. mil ft.; 520 ohms/circ. mil ft.
Modulus of Elasticity: 25,000,000 psi.

Straight Strips

$$\text{Deflection (inches)} = \frac{0.0000070TL^2}{t}$$

$$\text{Pull (ounces)} = \frac{700TWt}{L}$$

$$\text{Pull (ounces)} = \frac{100{,}000{,}000Wt^3}{L^3}$$

Coils and Helices

$$\text{Angular Rotation (degrees)} = \frac{0.00084TL}{t}$$

$$\text{Pull (ounces)} = \frac{480TWt^2}{r}$$

$$\text{Pull (ounces)} = \frac{571{,}000Wt^3A}{Lr}$$

Type No. 425 High Temperature

Material: 42 per cent nickel steel and 22 per cent nickel, 3 per cent chromium steel.
Operating Range: 0–600° F.
Heat Treatment: 650° F. for one hour.
Electrical Resistance: 349 ohms/sq. mil ft.; 436 ohms/ circ. mil ft.
Modulus of Elasticity: 23,000,000 psi.

Straight Strips

$$\text{Deflection (inches)} = \frac{0.0000069TL^2}{t}$$

$$\text{Pull (ounces)} = \frac{635TWt^2}{L}$$

$$\text{Pull (ounces)} = \frac{92{,}000{,}000dwt^3}{L^3}$$

Coils and Helices

$$\text{Angular Rotation (degrees)} = \frac{0.00079TL}{t}$$

$$\text{Pull (ounces)} = \frac{423TWt^3}{r}$$

$$\text{Pull (ounces)} = \frac{535{,}000wt^3A}{Lr}$$

Key to Formulas

T = Temperature change in ° F.
L = Length in inches
t = Thickness in inches
W = Width in inches
d = Deflection in inches
r = Radius
A = Angular rotation in degrees

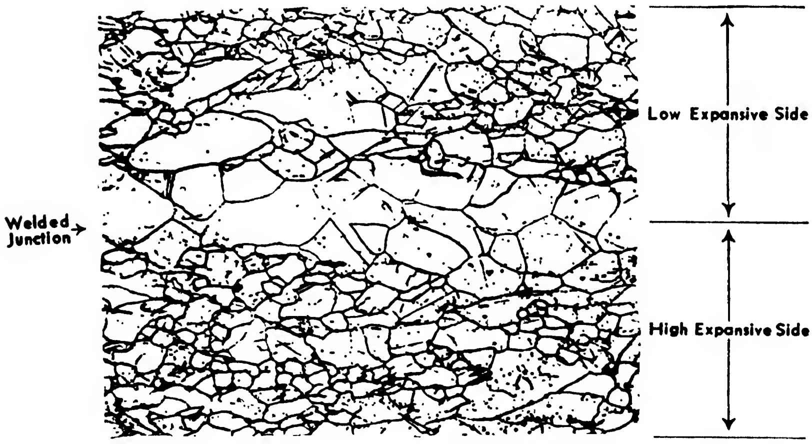
and uniformity of the bond between the metals, the method and uniformity of treatment in manufacture, and the physical properties of the metal components.

Four new alloys were recently developed for bimetal use. Their trade names and compositions are shown below:

	Ni	Ti	Cr	Mn	Si	Al	Fe
"Ni-Span Lo" 42	40.5–42.5	2.2–2.6	—	0.4	0.5	0.6	bal.
"Ni-Span Lo" 45	44.5–46.5	2.2–2.6	—	.4	.5	.6	bal.
"Ni-Span Lo" 52	51–53	2.2–2.6	—	.4	.5	.6	bal.
"Ni-Span Hi"	28–30	2.2–2.6	8–9	.4	.5	.6	bal.

"Ni-Span Lo" alloys have low coefficients of thermal expansion and high strength, while "Ni-Span Hi" is a high thermal expansion alloy. Each of the four alloys can be used as one element of a bimetal in thermostat controls. These alloys respond to precipitation-hardening which results in added strength and improved properties at elevated temperatures.

Figure 93 is a photomicrograph of a cross-section of Chase Thermostatic Bimetal showing the perfect welded bond between the low-expansive and the high-expansive sides. From the grain outline it is observed that there is no seam.



(*Courtesy W. M. Chace Co., Detroit, Mich.*)

Figure 93. Photomicrograph of cross-section of Chace thermostatic bimetal.

The characteristics of some typical bimetal materials (supplied by Baker and Company) are given in Table 102.

To illustrate typical properties of thermometals there are shown in Table 103 the properties of the "Wilco" thermometals.[5] These materials can all be classified in general as follows:

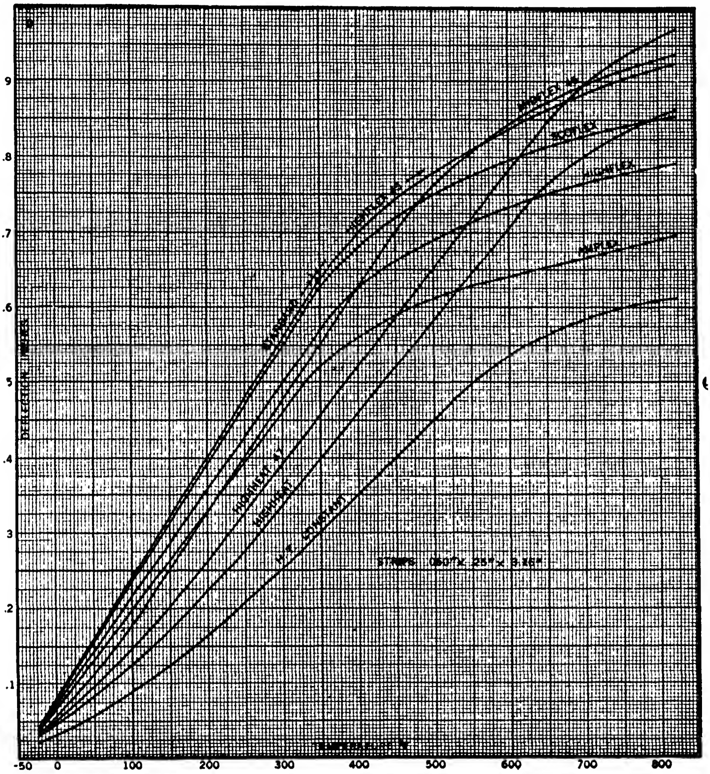
All steel to steel	**Brass to steel**	**Steel to manganese alloy**
"Highflex"	Standard	"Morflex"
"Highflex 45"		
"Midflex"		
"Midflex 46"		
"Highheat"		
"Highheat 47"		
"Saflex"		
"Loflex"		
"Muflex"		
"Ruflex"		
"Coflex"		
"Cirflex"		

TABLE 103. *Properties of "Wilco" Thermometals*

Thermometal	Temperature range (° F.)		Electrical resistivity in ohms						Standard heat treatment one hour at
	Useful deflection	Maximum sensitivity	(square mil ft.)			(circular mil ft.)			
			70° F.	300° F.	500° F.	70° F.	300° F.	500° F.	
Standard	−100 to 300	50 to 300	68	82		87	104		350° F.
"Highflex"	−100 to 700	50 to 300	375	427		477	544		650° F.
"Highflex 45"	−100 to 700	50 to 300	372	427		474	544		650° F.
"Morflex"	−100 to 500	50 to 350	530	623		675	793		650° F.
"Midflex"	−100 to 700	150 to 450	355	437		452	556		650° F.
"Midflex 46"	−100 to 900	150 to 450	350	421		446	536		650° F.
"Highheat"	−100 to 1,000	300 to 600	325	396		414	504		650° F.
"Highheat 47"	−100 to 800	300 to 600	320	400		407	509		650° F.
"Saflex"	+400 to 900	500 to 800	310	395		395	503		1,000° F.
H. T. Special	−100 to 500	50 to 300	280	309		357	393		650° F.
H. T. Constant	−100 to 700	300 to 600	260	302		331	385		650° F.
"Loflex"	−100 to 600	50 to 600	440	492		560	626		650° F.
"Muflex"	−100 to 500	50 to 300	95	158		121	201		650° F.
"Ruflex"	−100 to 500	50 to 300	400	439		509	559		650° F.
"Coflex"	−100 to 500	50 to 300	400	439		509	559		650° F.
"Cirflex"	−100 to 500	50 to 300	87	135		111	172		650° F.
R-24	−100 to 300	50 to 300	24	31		31	39		350° F.
R-39	−100 to 700	50 to 300	39	43	54	50	55	69	650° F.
R-56	−100 to 700	50 to 300	56	76	93	71	97	118	650° F.
R-70	−100 to 700	50 to 300	70	93	111	89	118	141	650° F.
R-97	−100 to 700	50 to 300	97	123	146	124	157	186	650° F.
R-118	−100 to 700	50 to 300	118	181	240	150	230	306	650° F.
R-157	−100 to 700	50 to 300	157	225	285	200	286	363	650° F.
R-203	−100 to 700	50 to 300	203	273	335	258	348	427	650° F.
R-245	−100 to 700	50 to 300	245	316	377	312	402	480	650° F.
R-310	−100 to 700	50 to 300	310	361	405	395	460	516	650° F.
R-372	−100 to 700	50 to 300	372	427	475	474	544	605	650° F.
R-440	−100 to 700	50 to 300	440	488	519	560	621	661	650° F.
R-530	−100 to 500	50 to 350	530	623	634	675	793	807	650° F.

Figure 94 shows temperature deflection curves of a number of "Wilco" thermostatic bimetals for strips 0.050" × 0.25" × 3.16".

In Figure 95 are curves showing relative deflection characteristics of three commonly used bimetals:[2] "Invar"-brass, "Invar"-nickel, 42% Ni-Fe and 22% Ni-8% Cr-Fe alloy.



(*Courtesy H. A. Wilson Co., Newark, N. J.*)

Figure 94. Temperature deflection curves.

Heat Treatment

Thermostatic bimetal, to have proper resiliency and strength, receives a certain amount of cold-rolling in manufacture. Internal stresses are set up which should be removed by heat treatment before putting the parts into service. In fact, all thermometals should be heat-treated[5] to insure consistent and unchanging operation in service. This should relieve stresses due to working or forming and should so condition the metal that repeated cycles of operation result in no change in behavior. In all cases the finished thermometal piece should be given a treatment above the highest and below the

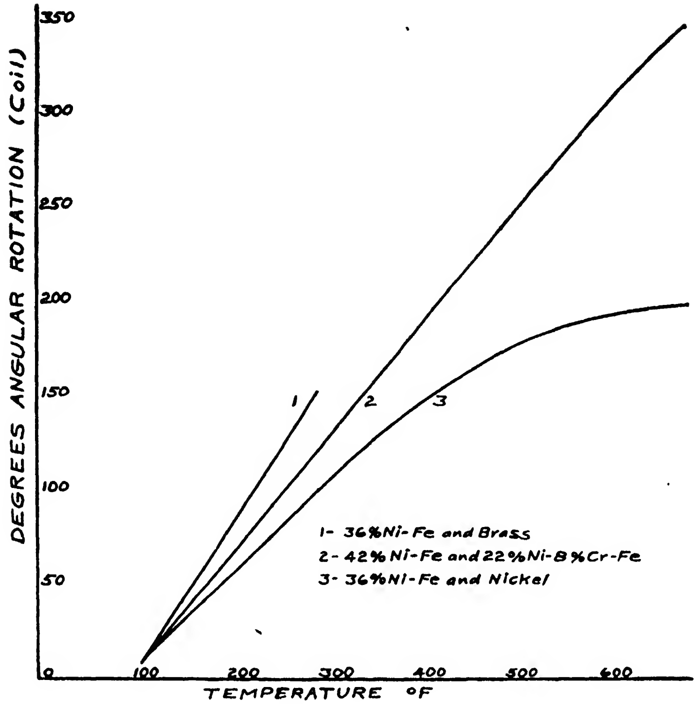


Figure 95. Curves showing relative deflection characteristics of three commonly used bimetals.

lowest temperature it will reach in service. Rapid changes in temperature should be avoided and the pieces should be free to deflect during treatment. Heating in an oven and cooling in air produces satisfactory results.

The data sheets prepared by the manufacturers on the different types of metal describe the heat treatments required.

It should be borne in mind that the thermometal is not the only part of a thermostat assembly which may need heat treatment. Any metal which has been machined or deformed may change shape, due to relief of stresses over a period of time or at elevated temperatures. For accurate thermostats it is recommended that, after mounting the thermometal but before final adjustment, the assembled thermostat be given several cycles over the maximum temperature range, heating and cooling between the minimum and maximum temperature, and under conditions similar to those to which it will be exposed in service.

In addition to changing the distribution of stresses, the heat treatment changes the properties of the thermometal. Increasing the temperature of the treatment causes a permanent decrease in the rate of deflection at lower temperatures. As the temperature of the treatment is increased above

800° F. there is a progressive annealing or softening, with a corresponding decrease in the load-carrying ability of the thermometal. High-temperature treatments should be used only when the metal will be exposed to such temperatures in service.

One manufacturer[5] of thermometals recommends the following treatments for their products: All Standard thermometal pieces should be held for one hour at 350° F., even though the thermostat will be exposed to nothing higher than atmospheric temperatures. "Highflex," "Highflex 45," "Midflex," "Midflex 46," "H. T. Constant," "Highheat" and "Highheat 47" should be held for one hour at a minimum temperature of 600° F. If in service they will be exposed to temperatures above 550° F., then, instead of the 600° F. treatment, they should be held for one hour at a temperature 50° F. higher than the maximum they will reach in service.

Characteristics

There is no well-defined classification of thermostat metals. The general division[8] is into "low-temperature" and "high-temperature" types. The low-temperature group includes "Invar" in combination with brass or bronze, as previously indicated. This material is used only in applications in which the maximum operating temperature is lower than that at which the physical properties of the non-ferrous alloy components are adversely affected. The high-temperature metals include all those which can be used at higher temperature than are recommended for brass or bronze. Into this group fall materials which are primarily intended to control at low temperatures, but which can be heated to elevated temperatures without change in their physical properties.

When a bimetal is subjected to heating or cooling the induced self-bending of the composite by the differential expansion or contraction of the two materials is used to advantage for a multitude of temperature-control applications; moreover it may be put to work in a number of ways, such as bending of straight strips, rotation of spirals and helices, opening or closing of U-shapes, and dishing of washers and discs.

Thermal deflection may be either linear, rotary or endwise. In other words, the action caused by the bending of the bimetal unit can be converted into an up-and-down movement, or a right-and-left movement, or a twisting and turning movement. The shape of the finished bimetal unit determines the kind of movement. The forces developed may be used to produce changes in torque, tension or compression. The size and the type of metal, as well as the varying degrees of temperature changes, determine the force of the movement and its extent or distance. Parts can be designed to give a maximum output of work for a given temperature change and to occupy a minimum space for certain conditions.

The deflection of a bimetal strip with one end fixed, measuring the movement of the free end at right angles from the cold position, varies with the square of the length, inversely with the thickness, and for practical purposes is directly proportional to the temperature change up to a predetermined temperature limit. For example, a piece eight inches long would have four times the deflection of a four-inch length. Reducing the thickness one-half doubles the deflection, and doubling the thickness reduces the deflection by one-half.

The force exerted by the free end of a straight strip, assuming it to be under restraint due to a change in temperature, varies directly with the width of the strip, the cube of the thickness and inversely with the cube of the length. This applies at normal temperature, and allowance must be made for elevated temperatures, as under such conditions the strength of the material is greatly reduced. In the formulas given for calculating the torque of either spirals or helices, expressed in pound-inches, the radius may be selected as the distance from the center to the point at which the load is applied.

The angular deflection of a spiral or helix varies directly with the length of the strip, inversely as the thickness of the material, and directly proportional to the temperature change. Neither the number of turns nor the diameter of either element materially affects the deflection. As far as angular movement is concerned, with the same size of strip, there is no appreciable advantage whether the coil is in the form of a spiral or helix. Coils may be formed either to wind up or unwind with increase of temperature.

The formula estimating the maximum stress in a helix or spiral is the same for both arrangements, so that any limitations mentioned regarding the strength of a straight strip also apply to spirals and helices. At elevated temperatures the strength is reduced.

The deflection of thermostatic metal is produced by stresses in the metal, and the application of a load changes the amount and distribution of these stresses. For any given temperature and for each metal there is a safe limiting stress. Stresses below this value will not produce a set or permanent change in the shape or condition of the metal.

The temperature change over which the metals may be restrained and the load which they will carry without introducing a permanent set depend on the form and temperature of the metals, and the temperature at which they have been heat-treated. It is not possible to present accurate figures for these limits. However, it may be stated that at temperatures above 1200° F. the strength of the metals decreases rapidly; hence very little load should be applied.

It will be noted[2] that the temperature change is directly proportional to the deflection for all the bimetal shapes. This is true only for a specified range of temperature for any specific type of bimetal. Fortunately, most of the available bimetals on the market have a reasonably wide working temperature range with uniform bending. Many controls are calibrated from − 50° F. to + 600° F. At higher temperatures the rate of deflection is greatly reduced. The physical properties of the alloys used as well as methods of fabrication determine the practical operating range of the product.

It may be well to point out that a tabulation of the important characteristics of bimetal elements must include such factors as accuracy, sensitivity, uniformity and endurance.

Selection of Elements

In general, the shape of a bimetal element depends on whether a straight-line motion or a rotary motion is required. For simple thermostats, as in ordinary electric irons, a straight strip is sufficient. For room-temperature controls requiring sensitivity within one degree, the element may have several turns at the stationary end in order to have sufficient length within a reasonable mounting space. For indicating thermometers or oven controls requiring a graduated dial, either a helix or spiral coil can be used.

In order to provide as great sensitivity as possible for a definite working range, several types of thermostatic bimetal are available. High- or low-temperature applications can best be met by selecting a type that gives the greatest sensitivity within the desired working temperature. In other words, the working temperature and the maximum temperature to which the bimetal element will be subjected determine whether high- or low-temperature types will be suitable.

In general, the most sensitive type within the required range is selected, as it reduces the size of the piece to a minimum. When a wide range of adjustment is desired in a small space, a less sensitive metal may be best. By referring to the deflection curves, a comparison of the different types can readily be worked out.

In selecting the metals involved in bimetal fabrication, it is desirable to select materials that have a maximum difference in their thermal expansion, as this insures the greatest movement of the completed element under a given temperature change, and reduces the size of the piece to a minimum, which is, of course, economical from the standpoint of installation.

In circuit-breaking devices,[5] a variety of bimetals is used. In most applications a bimetal is required to produce movement and power when subjected to change in ambient temperature alone; its electrical resistivity is of secondary importance. However, in many types of electric circuit-breakers, deflection and power are developed by heat generated within the thermometal by an electric current passing through it; the heating is proportional to the square of the current and resistance of the path.

Bimetals with definite electrical resistance have been developed to meet such requirements. These thermometals are widely used in industrial circuit-breakers for the protection of motors and other machinery subjected to overloading. The suitability of thermal cutouts activated by a bimetal is apparent. They give broad protection because their operation depends upon the period of overloading combined with the percentage of overload. Furthermore, they produce savings by eliminating fuses, which otherwise must be replaced when overload conditions occur.

The necessity for corrosion-resisting thermometals for use in a variety of applications resulted in the development of special combinations. Such thermometals are adaptable to steam traps, mixing valves and other uses where corrosive conditions prevail.

Design

In designing bimetal parts, after the material type has been selected, factors which must be considered are size, fabricating problems, and properties developed. There are three ways in which the bending of a bimetal with changes in temperature can be utilized.

(1) The part may move freely, actuating a free-moving dial hand, etc.
(2) The part may build up force without moving.
(3) A combination of (1) and (2).

If a bimetal part is required to move a certain distance and pick up a certain load in a given temperature interval, the lightest piece can be used when half the temperature interval is employed to produce movement and half to produce force. This is not always practical. For instance, where the force to be picked up is variable or frictional, the bimetal used should be capable of building force at a greater rate, so that variations in load will cause less variation in temperature intervals.

Since a bimetal deflects across its width as well as its length, the shape of a heated piece approaches a spherical surface. This cross-bending has little effect on narrow strips, but shows itself in non-uniformity of action by strips which are less than three times as long as they are wide. Bimetal used in rod form has the advantage of infinite adjustment by rotation of the rod. This changes the one component of the deflection which is used. Temperature deflection increases with length and decreases with the thickness of the bimetal.

The ability to do work increases with the weight of the part. Straight strips and U-shapes are used for small deflections; for large or angular deflection, spirals and helices are used. The helical coil offers a large exposed surface and the spiral coil maximum compactness.

U-shapes have parallel legs at only one temperature, unless the shapes are mounted so that the legs remain parallel. In this case no deflection with temperature change will be produced. The temperature-deflection rate of an equal-leg U-shape (very small U-radius) equals twice the deflection rate of each leg, and is only one-half the deflection of a straight strip of the same length.

The temperature-deflection rate of coils (spiral and helical) is independent of width if cross-bending is not considered. However, for certain limited temperature ranges, a wide coil has a greater rate than a narrow coil; hence for extremely narrow or extremely wide strips special formulas are necessary for calculations. A spiral is usually wound with the high-expansivity metal on the outside, so that an increase in temperature causes a small decrease in the diameter of the spiral. Likewise, a helix is formed with the high-expanding metal on the outside so that increase in temperature causes a small decrease in axial length. The pitch of a helix must be such that the turns do not bind.

If a coil or helix is called upon to do work, the temperature-deflection rate should be one angular degree per ° F. High-temperature torque rates are obtained only with the use of wide or thick metal (weight) so that rates are limited by available space. Where no work is required, the deflection rates may approach 3 angular degrees per ° F. The inside radius of a helix or coil should be at least 5 times the strip thickness to aid in winding.

Bimetal discs and washers are applied where little deflection and great stiffness are required. If the discs and washers are dished too deeply no deflection is possible; the depth of dish largely determines their rate of deflection.

It is desirable that sufficient room be allowed between turns of a spiral or helix so that under extreme temperature conditions there is opportunity for air circulation as well as mechanical clearance to avoid any friction or binding of the turns. For this reason it is recommended that coils be made to unwind with increase of temperature. The turns may be wound either right-hand or left-hand for helices to give the desired rotation. A helix unwinding with increase of temperature has also a slight elongation. It is necessary that this be taken into consideration so that no friction is introduced by the end thrust of the coil. Parts may be stampings, formed elements, spiral or helical coils, and may be spot-welded or silver solder-brazed to brackets or shafts, or carry welded or brazed flexible cables, terminals or contacts.

Since the fundamental property of a thermostatic bimetal is to change heat into mechanical energy, the problem resolves itself into the best shape to apply the available force.[6] One of the most important factors is the design of a proper mounting to hold the thermostatic bimetal element. In general, the mechanical loading of a bimetal must be within the elastic limits of the material, and sufficient temperature change must be provided to produce the necessary thermal deflection to do the work.

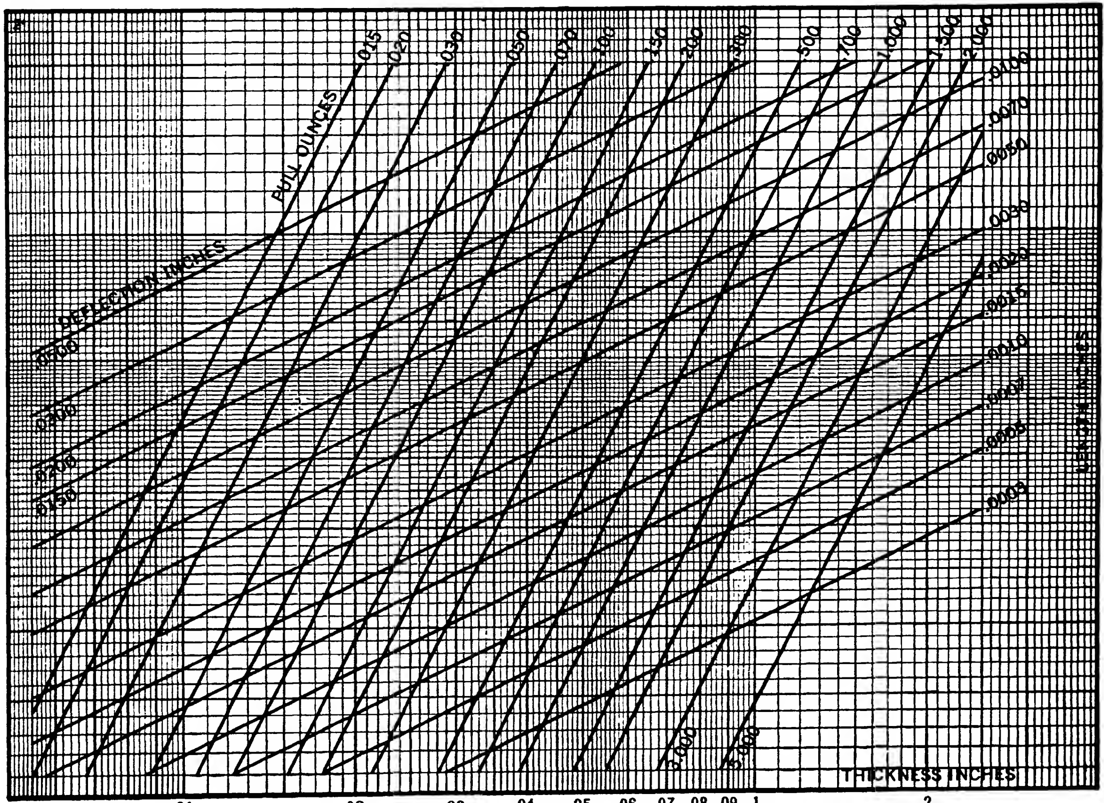
Reverse-welded bimetal consists of at least two lengths of strip in which the high-expansion side of one strip is welded to the low-expansion side of the other. This is useful for ambient temperature compensation or for lateral motion.

The relationships[5] existing between the deflection, force characteristics and dimensions of thermometal strips are shown graphically for types of "Wilco" thermometals in Figures 96 and 97. On one hand, these charts permit convenient determination of the approximate size of a strip to meet specified conditions of deflection and pull; on the other hand they indicate the deflection and pull characteristics of strips the sizes of which are given.

It should be noted that these charts apply only in the case of flat strips fixed at one end, the force and deflection being measured at the other end. Their use is very simple once the significance of the different parallel sets of lines is understood. There are four such sets: a vertical and a horizontal set forming the coordinates, and two sets of heavier lines, one set running at a slant from left to right, the other set at a slant from the bottom to the top. The faint horizontal lines represent strips of a length indicated on the right edge of the chart; thus the bottom line represents strips one inch long and the top line strips 25 inches long. In a similar way the vertical lines represent strips of a thickness indicated by the figures at the lower edge of the chart; the vertical line marked .01 represents strips .010″ thick, the next line to the right from this represents strips .011″ thick, etc. The point of intersection of a horizontal and a vertical line represents a strip of the length indicated by the horizontal line and of a thickness indicated by the vertical line. For example, the point of intersection of the horizontal line marked 3, and the vertical line marked .02 designates a strip 3 inches long and .020″ thick. Thus every point within the chart is made to represent a strip of a length indicated by the horizontal line (actually drawn or imagined) passing through it, and of a thickness indicated by the vertical line (actual or implied) passing through it.

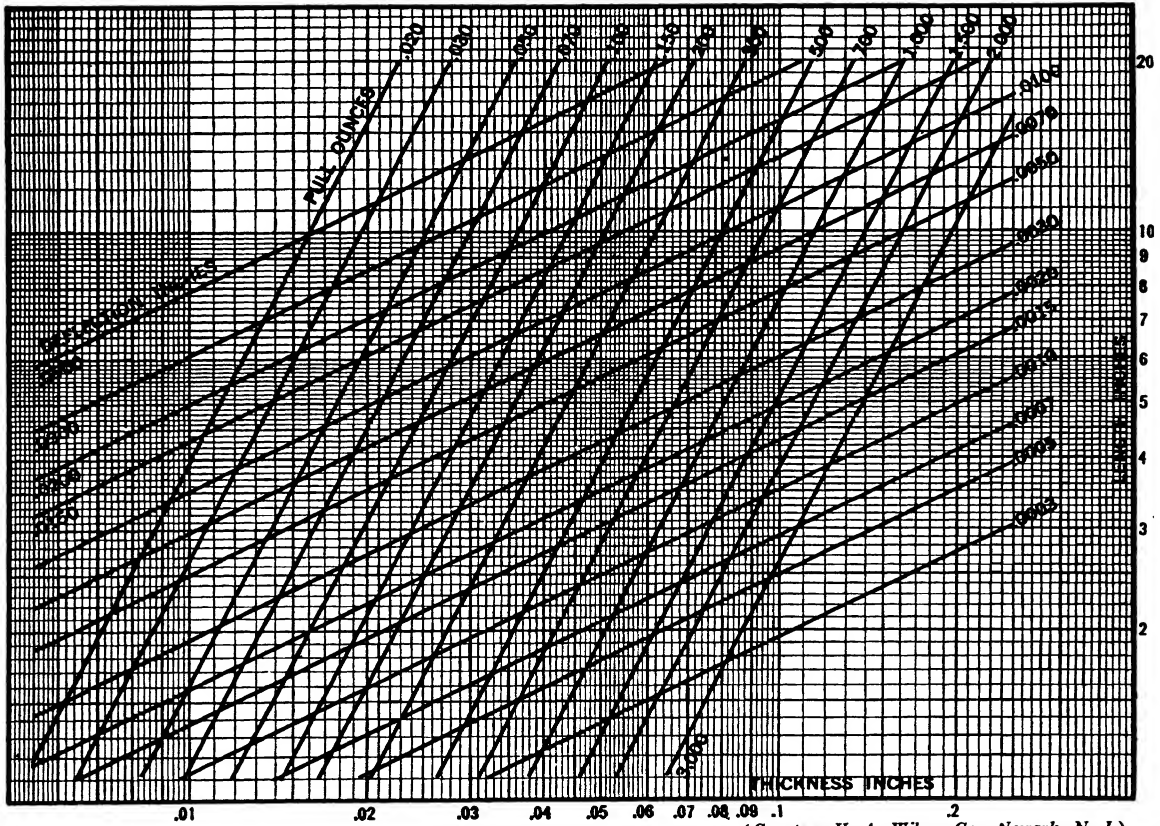
The heavy lines running at a slant from left to right represent strips possessing a deflection per ° F., indicated by the figures appearing at the left or right terminals of these lines. For example, the second line from the top represents strips having a deflection of .030° F. Since any point on this .030 line also corresponds to a strip of definite length and thickness (as explained before), the line serves to give the dimensions of all possible strips (within the limits of the chart) having a deflection of .030″ per ° F.

The other set of heavy lines, running at a slant from the bottom part of the chart upward, represents strips exerting a force (pull or push) per inch width and per ° F., indicated by the figures appearing at the terminals of



(*Courtesy H. A. Wilson Co., Newark, N. J.*)

Figure 96. "Wilco" Thermometal "Highflex." Deflection and pull of straight strips, 1 inch wide, for temperature change of 1° F. in the temperature range of 0° F. to 350° F.



(*Courtesy H. A. Wilson Co., Newark, N. J.*)

igure 97. "Wilco" Thermometal "Highflex 45." Deflection and pull of straight strips, 1 inch wide, for temperature change of 1° F. in the temperature range of 0° F. to 350° F.

these lines. For example, the third line from the left, marked .020, represents strips exerting a force of .020 oz. per inch width of the strips and per ° F.

Generally, then, every point on the charts represents a strip of:

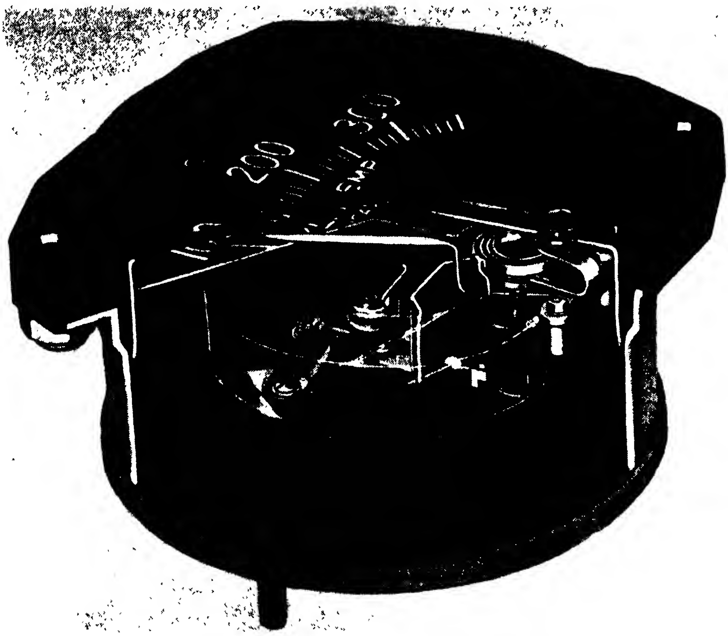
(1) a length indicated by the horizontal line that has been or can be drawn through it;

(2) a thickness indicated by the vertical line that has been or can be drawn through it;

(3) a deflection per ° F. as indicated by the slanting line, actual or imagined, passing through it from left to right;

(4) a force per unit width and per ° F. as indicated by the slanting line (actual or implied) passing through it from below upward.

Selecting a point corresponding to a strip of given length and thickness, one can read at once the deflection and force characteristics of this strip. On choosing a point corresponding to a strip of given thickness and deflection, the necessary length of the strip and its force characteristics become known. Similarly, for given length and deflection the required thickness and resulting pull are indicated, and for given deflection and pull, the required thickness and length. In all cases the effective length of the strip is under con-



(Courtesy Weston Electrical Instrument Corp., Newark, N. J.)

Figure 98. Cylinder temperature indicator.

sideration. The part of a strip which is clamped to a mounting does not give useful deflection.

Figure 98 shows the bimetal strip used as a spiral spring to shift the pointer position on a cylinder temperature indicator. In this use, the spring serves as a cold and compensating device for thermocouple temperature devices. The pointer position is shifted in terms of the ambient temperature change. The bimetal spiral spring is made of a brass and "Invar" combination and is accurately calibrated to fit the cylinder temperature dial graduations.

The proprietary alloys mentioned in this chapter are registered trade marks of the following manufacturers:

Baker and Company
- "Type No. 365 Standard"
- "Type No. 360 Medium"
- "Type No. 425 High Temperature"

W. M. Chace Co.
- "No. 772 Alloy"

International Nickel Co.
- "Monel"
- "Ni-Span Hi"
- "Ni-Span Lo" 42
- "Ni-Span Lo" 45
- "Ni-Span Lo" 52

H. A. Wilson Co.
- "Highflex"
- "Highflex 45"
- "Highheat"
- "Highheat 47"
- "H. T. Constant"
- "H. T. Special"
- "Cirflex"
- "Coflex"
- "Loflex"
- "Midflex 46"
- "Morflex"
- "Muflex"
- "Ruflex"
- "Saflex"
- "Standard"
- "R-24"
- "R-39"
- "R-56"
- "R-70"
- "R-97"
- "R-118"
- "R-157"
- "R-203"
- "R-245"
- "R-310"
- "R-372"
- "R-440"
- "R-530"

References

1. Scott, H., "Thermostatic Metal," *Metal Progress* (November, 1932).
2. Mathews, H., "Mechanical Design of Thermostatic Bimetal Elements," *Product Engineering* (November, 1933).
3. Hood, S., "Thermostat Metal," ASTM Standards on Electrical-Heating and Resistance Alloys" (October, 1942).
4. Hensel, F., "Special Metals in Electrical Industry," *Electrical Engineering* (July, 1943).
5. "Thermometals," H. A. Wilson Co., bulletins, Newark, N. J.
6. "Thermostatic Bimetal," W. M. Chace Co., bulletins, Detroit, Mich.
7. "Thermostat Metals," General Plate Company, bulletins, Attleboro, Mass.

Chapter XIII

Electrical Resistance Alloys

General Characteristics and Properties

The application of electrical energy[4] to industrial heating has so many advantages that the field for electrical heating apparatus includes the entire industrial world, there being scarcely a manufacturing plant that does not require accurate and automatically controlled heating equipment, which means electric heat.*

The modern home, where convenience and refinement are the prime considerations, also requires high-grade electrical cooking and heating appliances. It is therefore necessary to provide a resistor material that will endure the high temperatures necessary for the satisfactory operation of electric furnaces, ovens, heaters, ranges, instruments and special appliances. There are also many applications for such materials in technical apparatus and instruments, such as rheostats and resistance units, because of their combination of high electrical resistance and temperature coefficient of resistance.

The essential part of most heating units and electrical appliances is the heating element, which consists primarily of a high-alloy wire or ribbon. The lasting qualities of these elements depend greatly upon their controlled composition and physical structure. The addition of some other substances such as sulphur and oxides in the alloy lowers resistance to oxidation.

The life of the element will depend upon the temperature at which it operates, providing there is no corrosion. The temperature of the surface of the element is a function of the watts per square inch of the element surface. For an element of a given size and length, the temperature will vary with the dissipation of watt imput, since the surface area remains the same. The design of an element is also important, since convection as well as radiation may affect the temperature of the surface.

The physical principle on which all calculations for resistors as heating elements are made is Ohm's Law: Resistance in ohms, *R*, equals voltage, *E*,

---

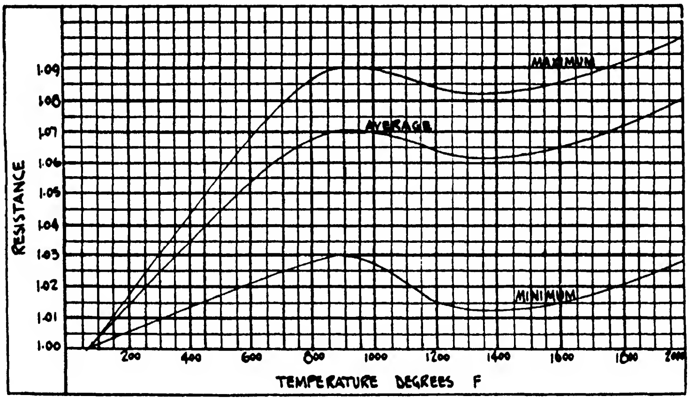
* With permission of the Driver-Harris Co., much of the information on resistor alloys was taken from their latest bulletin.

divided by the current, I; that is, R equals $\frac{E}{I}$. The amount of power in watts, W, equals IE or I^2R or $\frac{E^2}{R}$. The alloys used as heating-element materials always have a greater resistance when hot than at room temperature, although in many cases this difference is small. Therefore the value of R in the above formulas is the resistance at the operating temperature. The amount of change in resistance at various temperatures is normally stated in manufacturers' catalogues.

In any electrical conductor, the resistance is: (a) directly proportional to its length; (b) inversely proportional to its cross-sectional area; or (c) directly proportional to its resistivity.

With the aid of data supplied by the manufacturer for each alloy it is possible to calculate the amount of resistance wire required for a certain electrical appliance or furnace capacity at different temperatures.

Resistance material is produced to have a certain resistivity (ohms per circular mil foot) at room temperature. The user, however, must know that this resistance is going to increase with heat. The curves in Figure 99 represent the maximum and minimum relations between resistance and temperature.[4] The minimum curve is determined by using the standard ASTM method for taking the temperature coefficient of resistance. In this test the wire is cooled slowly from 1832° F. The maximum curve represents the temperature coefficient of wire which has been quenched. The average curve is based upon the average increase in resistance to be expected from wire as shipped, but does not follow either the maximum or minimum curve, because of the method of annealing.



(*Courtesy Driver-Harris Co., Harrison, N. J.*)

Figure 99. Temperature resistance chart for "Nichrome" V.

Since very small wires cool very quickly and heavy wires rather slowly, smaller wires tend to follow the maximum curve, whereas heavy wires tend to follow the minimum curve. Therefore, the "hot" and "cold" resistances are useful to anyone concerned with close specifications or extreme accuracy. The average curve may be used for most design purposes, since it more nearly represents the values of the commonly used sizes as produced.

The "cold" resistance of a wire refers to the resistance at room temperature of wire just as it is when taken off the spool, and therefore never subjected to heat. The "hot" resistance is the resistance of the wire when it is in operation as a heating element. The "hot" resistance is higher than the "cold" resistance by an amount which varies in terms of percentage rise in all resistance tables.

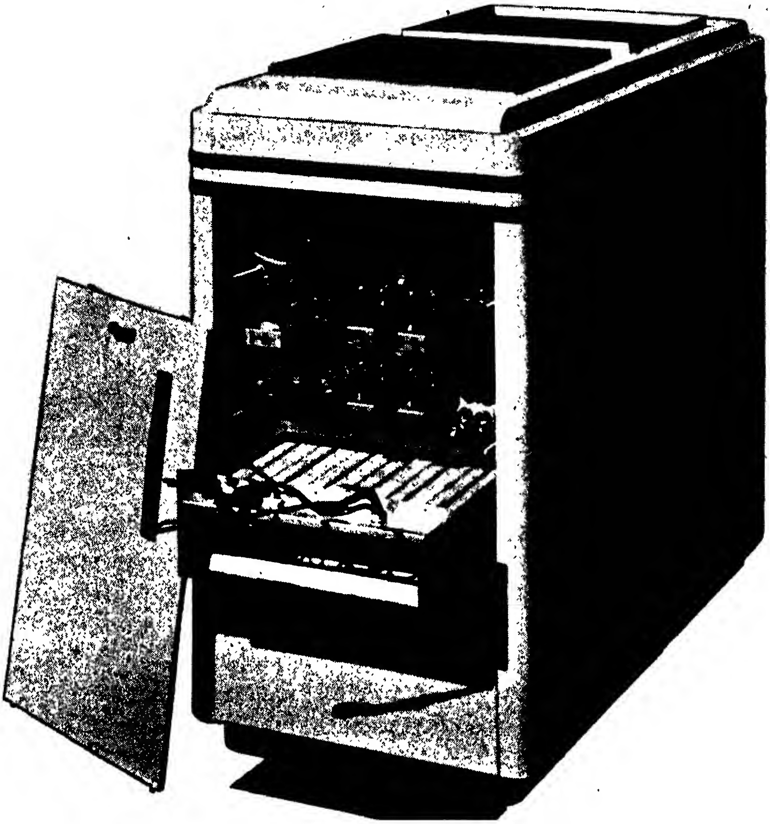
Such factors as the construction of the furnace, kind of current available, voltage, etc., must be taken into consideration. The following circumstances should be considered when determining the dimension of resistance elements.

The higher the temperature at which the furnace is to work, the heavier the material of the resistance elements should be in order to increase their life and to avoid deformation, which may lead to ruptures and short circuit.

On the other hand, the resistance material should not be so heavy as to involve the risk of overheating. The flat heating elements have a greater ratio of surface area to cross section than the round ones, and the watts per square inch is the controlling factor. On these grounds strip seems to be preferable to wire for furnace temperatures higher than 2100° F. (1149° C.). Resistors of spiralled wire have the advantage of being easier to handle and can be replaced with greater ease. They can be conducted through a furnace wall with smaller loss of efficiency and less risk of local overheating.

Commercial electric resistor alloys may be divided into three general classes: namely, (1) alloys of nickel and chromium with or without substantial percentages of iron, which is the major heating alloy; (2) alloys of the iron-chromium-aluminum group, some of which also contain small amounts of cobalt; and (3) alloys that contain copper as the major constituent. There are other special alloys of different compositions adapted to particular fields of application. Pure metals of high melting point and good resistance to oxidation are also used, and in addition nonmetallic resistors, such as the "Globar," for use in air, and carbon and graphite for use in oxygen-free atmospheres.

Pure nickel has a melting point of approximately 2643° F. (1450° C.), but at working temperatures of 1832° F. (1000° C.) or higher it oxidizes rapidly. By combining pure chromium with nickel, alloys are obtained that



(Courtesy Electromode Corp. and Driver-Harris Co.)

Figure 100. Electric Furnace.

resist oxidation at extremely high temperatures better than any other combination of base metals. Wire and ribbon made of these alloys will withstand temperatures of about 2100° F. (1150° C.) for a considerable time, without appreciable oxidation, and do not become brittle with repeated heating and cooling.

Nickel-chromium and nickel-chromium-iron alloys have important qualifications for service as electrical heating elements. They have remarkable hot strength, excellent resistance to oxidation at high temperatures, high electrical resistivity and good mechanical properties. For these reasons they are used in most heating applications. Iron-chromium-aluminum alloys possess higher ohmic resistance and possibly better resistance to high-temperature oxidation than nickel-chromium and nickel-chromium-iron.[1] However, the elevated-temperature mechanical properties of ferritic iron-chromium-aluminum alloys are relatively poor, particularly the creep. They are also subject to considerable growth at their operating temperatures and become brittle when cold. Because of their high melting point they are said to be capable of operating at temperatures around 2462° F. (1350° C.). However, most heating applications do not require temperatures above 2000° F.

The ideal resistor alloy should combine the electrical resistivity and oxidation resistance of iron-chromium-aluminum alloys with the elevated-temperature mechanical properties, resistance to growth and distortion, and the relative ease of manufacturing of nickel-chromium and nickel-chromium-iron. Alloys containing copper as the major constituent are limited to operating temperatures not exceeding 752° F. (400° C.). Such alloys oxidize too readily above this temperature.

These high-resistance alloys used extensively as electrical resistance elements are generally of the solid-solution type. They are combinations of metals in such amounts as not to exceed the solid-solution range. Nickel-chromium and nickel-chromium-iron alloys are austenitic (face-centered cubic) in structure and have good elevated-temperature mechanical properties. They are also characterized by good resistance to growth, creep and distortion at their operating temperatures.

Austenitic ferrous alloys containing more than 10 per cent chromium and more than 25 per cent nickel have electrical resistance characteristics which make them suitable for electrical resistor heating elements, although the high-iron alloys tend to scale rather rapidly on heating and cooling.

Class I Alloys

(1) 80 per cent nickel, 20 per cent chromium type alloy is the most highly resistant to oxidation or corrosion of the nickel-chromium series. It is nonmagnetic and has about the lowest temperature coefficient of resistivity of the high-resistance alloys. It combines the high electrical resistance and low temperature coefficient of electrical resistivity with oxidation resistance of a high order. This type of alloy is suitable for operation at temperatures up to 1150° C. (2100° F.) and retains its strength well at high temperatures. It is essential for resistor elements in the higher-temperature applications and for resistances in technical applications due to its combination of desirable properties. It is used for industrial furnace elements, heating appliances, radiant-type heating elements, volt-meter resistors, and precision electrical instruments.

The alloy is marketed under a variety of proprietary trade names, such as "Alray" A, "Chromel" A, "Jelliff" A, "Nichrome" V, and "Tophet" A.

(2) 60–65 per cent nickel, 14–16 per cent chromium, 20–26 per cent iron type alloy has the highest electrical resistivity of the nickel-chromium-iron

series. Next to (1) it has the highest resistance to oxidation or corrosion. It is recommended for heating elements operating at temperatures not over 925° C. (1700° F.). It is used for domestic appliances, electric toasters, room heaters, flat irons, potentiometers, radio rheostats and resistors. "Nichrome," analyzing 61 per cent nickel, 16 per cent chromium, balance iron, and "Chromel" C, analyzing 60 per cent nickel, 16 per cent chromium, balance iron, are alloys of this type. "Tophet" C and "Alray" C are similar alloys.

(3) 30–35 per cent nickel, 15–20 per cent chromium, 45–55 per cent iron type alloy, known as "Tophet" D, "Chromax," and "Alloy 502," were developed to meet the demand for a more inexpensive alloy for electrical heating where the conditions did not dictate the use of (1) and (2). While it has a lower cold resistance, it has a higher temperature coefficient of resistance than the other two types and can be substituted in many cases size for size in the temperature range 760 to 870° C. (1400 to 1600° F.). In general, it is not recommended for use at operating temperatures exceeding 1400° F. The increased resistance at this temperature is 20 per cent, and is an important factor in designing heating elements.

(4) 30 per cent nickel, 5 per cent chromium, 65 per cent iron type alloy is a lower-priced high-resistance alloy. It resists oxidation at lower temperatures and has a maximum operating temperature of 705° C. (1300° F.). However, it rusts when exposed to moisture. It is used for heavy rheostats, car heaters and heaters operating below red heat, that is, from low to medium temperatures. "Chromin" D, "Comet" and "Chromel" D are typical alloys of this type.

Class II Alloys

(1) 80 per cent iron, 15 per cent chromium, 5 per cent alumium type alloy has a specific resistance at 20° C. of approximately 167 microhm cm. (800 ohms per circular mil foot) and a temperature coefficient of resistance of −0.00035 through a temperature range of 20–500° C. The addition of aluminum to the iron-chromium alloy increases the electrical and heat resistance. It is claimed by the manufacturers that it can be used up to 1350° C. (2460° F.), owing to its high melting point. A series of iron-base alloys[8] containing chromium and 5 to 10 per cent aluminum has a specific resistance approximately that of standard nickel-chromium alloys. The materials have a higher melting point than nickel-chromium alloys and they can be used for higher temperature ranges.

The fact that an alloy has a higher melting point does not necessarily mean that it can be used for higher temperature ranges. For example, pure iron or pure nickel could be specified, but the condition of the atmosphere surrounding the element must also be considered.

Iron-chromium-aluminum alloys do have certain disadvantages, particularly low creep strength at high temperatures and low corrosion resistance, if used in the form of fine wires. In addition, in regard to straight oxidation resistance at high temperature, this will actually depend on how fast the alloy loses its alloying elements, such as aluminum or chromium, which are known to migrate to the surface.

The commercial alloys of the 80 per cent iron, 15 per cent chromium, 5 per cent aluminum type are "Radiohm" and "Ohmaloy." They are used for radio resistors and high resistances. Another alloy of this type, known as "Alchrome," contains 14 to 20 per cent chromium, 3 to 6 per cent aluminum and remainder iron.

A series of iron-chromium-aluminum alloys containing about 23 to 24 per cent chromium, 4 to 6 per cent aluminum, 2 per cent cobalt, balance iron, have a resistivity 25 to 35 per cent higher than pure nickel-chromium alloys and a specific gravity about 15 per cent lower. This makes it possible to design and build electric heating units which are considerably more compact and of higher capacity. They may be used in sulphurous atmospheres, in which nickel-chromium alloys are readily attacked. However, when these alloy heating elements have been used for some time they will be quite brittle when cold, and if they are to be removed from the furnace for any reason, they should be handled carefully to prevent breakage. In addition, they must be well supported to avoid deformation in use. Several of them are marketed under the name "Kanthal."

The iron-chromium-aluminum-cobalt alloys[5] have a maximum element temperature of 1150 to 1350° C. (2100 to 2460° F.), and a specific resistance of 812 to 872 ohms per circular mil foot. The higher their aluminum content the higher the maximum element temperature and the higher the specific resistance. The manufacturers of these alloys claim that the scaling temperature lies above 1400° C. (2550° F.), giving a high margin of safety and a high resistance to oxidation at the recommended operating temperatures. However, life tests made at 2150° F. by certain laboratories showed that scaling occurred much below 2550° F.

Class III Alloys

(1) 55 per cent copper, 45 per cent nickel type alloy has practically zero temperature coefficient of resistivity, low coefficient of electrical resistance, and a high thermal electromotive force against copper. It has a maximum operating temperature of 510° C. (950° F.), and is used for precision rheostats, voltmeter resistors, low-temperature heaters, heating-pad elements, thermocouples, motor control rheostats, resistance coils particularly with alternating current, and also for heavy resistors operating at low temperatures, including motor speed controllers, etc. Its principal use is in the

construction of electrical instruments in which the temperature coefficient of resistance must be very low. Its corrosion resistance and unvarying resistance with changing temperatures over practical ranges have caused its selection for these precision purposes. Its high electrical resistivity, great ductility and corrosion resistance make it particularly useful for winding heavy-duty industrial rheostats. In general it has excellent mechanical and electrical properties. Several of these commercial alloys are known as "Constantan," "Advance," "Copel," "Cupron" and "Excelsior."

(2) 30 per cent copper, 70 per cent nickel type alloy is intended principally for use in electrical heating devices in which the resistance element does not reach a temperature higher than about 595° C. (1100° F.). It will not become brittle on repeated heating and cooling, and oxidation and internal deterioration are negligible if the temperature does not exceed 595° C. (1100° F.). Typical commercial alloys of this type are "Monel," "Lucero" and "Jelliff" 70.

(3) To meet the requirement for a series of copper-nickel alloys[4] graduated downward as to specific resistance, other alloys of decreasing nickel content have been developed, such as a 23 per cent nickel, 77 per cent copper alloy, with a specific resistance of 30 microhms cm., a 11 per cent nickel, 89 per cent copper alloy with a specific resistance of 15 microhms cm., a 6 per cent nickel, 94 per cent copper alloy with a specific resistance of 10 microhms cm., and a 2.25 per cent nickel, 97.75 per cent copper alloy with a specific resistance of 5 microhms cm. These are used for relay coils and radio resistors.

No. 180 alloy contains 78 per cent copper and 22 per cent nickel, No. 90 alloy 88 per cent copper and 12 per cent nickel, No. 60 alloy 94 per cent copper and 6 per cent nickel, and No. 30 alloy 98 per cent copper and 2 per cent nickel.

Special Alloys

(1) 86 per cent copper, 10 per cent manganese, 4 per cent nickel type alloy in the form of wire has the high resistivity of 180 ohms per circular mil foot. The thermal electromotive force against copper is so small (0.003 per ° C.) that temperature differences in the assembled circuit cause no troublesome parasitic e.m.f.'s. This is important in low-voltage D. C. devices, but not in A.C. equipment. The temperature coefficient of resistance is low over the usual room temperature range of 15–35° C. (59–95° F.), the highest resistance being at 25° C. (770° F.) (decreasing as the temperature rises or falls); hence the maximum change in resistance due to thermal differences is less than 0.02 per cent. This material is very stable in resistance and is not subject to change with ageing. It is necessary, however, for the user to remove strains caused by the winding operation by heating the completed spools to 120° C. (248° F.) for 24 hours.

This alloy is suitable for all types of apparatus requiring assembled resistance spools, coils or slide wires, such as bridges, potentiometers, and resistance boxes; it is also used for instrument resistors and shunts. In general it is used in standard resistances of high precision.

(2) 87 per cent copper, 13 per cent manganese type alloy is known commercially as "Manganin"[4] and is used for resistors in many types of precision direct current apparatus. It has a resistivity of 48.2 microhms cm. (290 ohms per circular mil foot). In the form of wire, it increases very slightly in resistance from 15 to approximately 25° C. and then decreases until the resistance at 35° C. is about the same as at 15° C. Artificial ageing of assembled coils has been found necessary to avoid a slow decrease in resistance with time. This is commonly done by baking at a temperature between 120 and 140° C. (248–284° F.) for a period of 24 to 48 hours. The high-manganese alloys are rather difficult to solder, and therefore oxidation during heat treatment must be avoided.

All of these high manganese-copper alloys are subject to selective oxidation of manganese even at room temperature. This leaves more copper, or a copper-rich material, which will affect both the specific resistance and the temperature coefficient of the alloy. Of course, this concerns only those cases where extreme accuracy and uniformity of resistance with time are important.

(3) 70 per cent nickel, 30 per cent iron type alloy is characterized chiefly by its high temperature coefficient of electrical resistance (about 0.0022° F. between 70 and 212° F.). Its resistivity is 120 ohms per circular mil foot annealed and 140 ohms per circular mil foot hard at 70° F.

While this alloy has practically the same temperature coefficient of resistance as pure nickel, its specific resistance is twice as great. It therefore lends itself advantageously to uses requiring self-regulation by temperature, such as immersion heaters and heater pads.

"Hytemco," analyzing 72 per cent nickel and 28 per cent iron, is a commercial alloy of this type.

(4) A series of manganese-base alloys containing over 50 per cent manganese, the remainder being nickel and copper, give extremely high resistivity values. They are not corrosion-resistant, however, and will deteriorate after contact with perspiration. Some of the larger sizes have been used successfully, but they are not usually applied for sizes under 20 B.&S. gage. They are recommended for fixed or variable resistors but are not intended for heating elements.

A number of silver-base alloys have also been developed recently, such as silver-manganese-tin (80 per cent silver, 17 per cent manganese, 3 per cent tin). Here again the temperature coefficient of resistivity varies with the composition and heat treatment. Alloys of this type approach a zero temperature coefficient over a range of 0–200° C. (32–392° F.), and, for alloys containing 10 per cent manganese, 10 per cent tin, and the remainder silver, it is possible to produce a negative temperature coefficient which is desirable for compensating resistances.

Many pure metals such as copper, molybdenum, nickel, platinum, silver and tungsten find application as electrical resistance materials because of their high melting points and specific resistance. For work at very high temperature pure molybdenum is used. In this case it is necessary to have a protective atmosphere, such as hydrogen. A molybdenum wire coated with beryllium oxide and a special refractory outer coating can be used as a heating element operating in air; but for practical purposes, either pure platinum or 10 to 20 per cent rhodium-platinum alloys are used for high-temperature furnaces operating in air above the limit of the chromium-nickel alloys.

"Mangrid" and "Gridnic" E are alloys containing 4–5 per cent manganese, balance nickel. They have a resistivity at 20° C. of 110 ohms per circular mil foot and a temperature coefficient of 0.0031 between 20 and 100° C. They are used for grid wire and for radio tubes. "Mangrid" E, an alloy containing 2–3 per cent manganese, balance nickel, has a resistivity at 20° C. of 84 ohms per circular mil foot and a temperature coefficient of 0.0038 between 20 and 100° C. It is used for furnace lead wire.

Properties

Some of the typical properties of the pure metals for electrical resistance material are shown in Table 104.

TABLE 104. *Pure Metals for Electrical Resistance*

	Copper	Nickel	Silver
Specific resistance (microhm cm.) (20° C.)	1.724	10	1.629
Temperature coef. resist. (20° C.)	0.0039	0.005	0.0038
Specific heat (gram cal.)	0.0921	0.130	0.0559
Thermal conductivity (watts./cm./° C.)	3.88	0.615	4.19
Melting point (° C.)	1083	1450	960
Coef. linear exp. (20° C.)	0.0000166	0.000015	0.0000189
Specific gravity	8.92	8.9	10.5

	Molybdenum	Tungsten	Platinum
Specific resistance (microhm cm.) (20° C.)	5.7	5.523	10.61
Temperature coef. resist. (20° C.)	0.0033	0.0045	0.003
Specific heat (gram cal.)	0.0647	0.0336	0.0324
Thermal conductivity (watts/cm./° C.)	1.46	1.60	0.695
Melting point (° C.)	2625	3410	1773
Coef. linear exp. (20° C.)	0.000005	0.000004	0.000009
Specific gravity	10.2	19.3	21.45

Some of the typical physical properties of the Class I alloys are given in Table 105.

TABLE 105. *Physical Properties of Class I Alloys*

	80 Ni, 20 Cr	65 Ni, 15 Cr, 20 Fe	35 Ni, 18 Cr, 45 Fe	30 Ni, 5 Cr, 65 Fe
Specific resist. (microhm cm.)	108	112	100	95
Temp. coef. resist. (20–500° C.)	0.00013	0.00017	0.00031	0.00088
Specific heat (gram cal.)	0.104	0.107	0.110	0.114
Thermal cond. (watts/cm./° C.)	0.136	0.132	0.130	0.135
Melting point (approx. ° C.)	1400	1350	1380	1480
Coef. linear expansion (20–500° C.)	0.000017	0.000017	0.0000158	0.000015
Specific gravity	8.41	8.25	7.95	8.15

Some of the typical physical properties of the Class II alloys are given in Table 106.

TABLE 106. *Physical Properties of Class II Alloys*

	80 Fe, 15 Cr, 5 Al	24 Cr, 5 Al, 2 Co, bal. Fe
Specific resist. (microhm cm.)	112 750 ohms (c.m.f.)	130–160
Temp. coef. resist. (20–500° C.)	0.00016	
Specific heat (gram cal.)	0.172	
Thermal cond. (watts/cm./° C.)	0.02	
Melting point (approx. ° C.)	1480	1660
Coef. linear exp. (20–100° C.)	0.0000114	0.0000118– 0.0000139
Specific gravity	7.31	7.1–7.25

Some of the typical properties of the Class III alloys are given in Table 107.

TABLE 107. *Physical Properties of Class III Alloys*

	55 Cu, 45 Ni	30 Cu, 70 Ni	94 Cu, 6 Ni
Specific resist. (microhm cm.)	49	48.2	10
Temp. coef. resist. (20–100° C.)	±0.00002	0.0010	0.00071
Specific heat (gram cal.)	0.094	0.127	0.092
Thermal cond. (watts/cm./° C.)	0.218	0.250	——
Melting point (approx. ° C.)	1210	1350	1100
Coef. linear expansion (20–100° C.)	0.0000149	0.0000125	0.000018
Specific gravity	8.9	8.9	8.9

Some of the typical properties of the special alloys are given in Table 108.

TABLE 108. *Properties of Special Alloys*

	4 Ni, 10 Mn, 86 Cu	13 Mn, 87 Cu	70 Ni, 30 Fe
Specific resist. (microhm cm.)	49	48.2	20
Temp. coef. resist. (20–500° C.)	0.00004	±0.000015	0.0045
Specific heat (gram cal.)	——	——	0.125
Thermal cond. (watts/cm./° C.)	——	——	0.289
Melting point (approx. ° C.)	1020	1020	1425
Coef. linear exp. (20–500° C.)	0.0000187	0.0000187	0.000015
Specific gravity	8.19	8.19	8.46

The life of a resistance material is directly dependent on the working conditions, *i.e.*, furnace atmosphere, ceramic supports, temperature, radiation possibilities, surface load, frequency of switching, and the design of the heating element.

Figure 101 * shows the effect of temperature on the useful life of various resistance wires, as determined by intermittent life tests [3] with the Bash and Harsch testing apparatus. It is claimed by the manufacturer that the iron-chromium-aluminum-cobalt series of alloys ("Kanthal") has a longer useful life at higher temperatures than the other alloys.

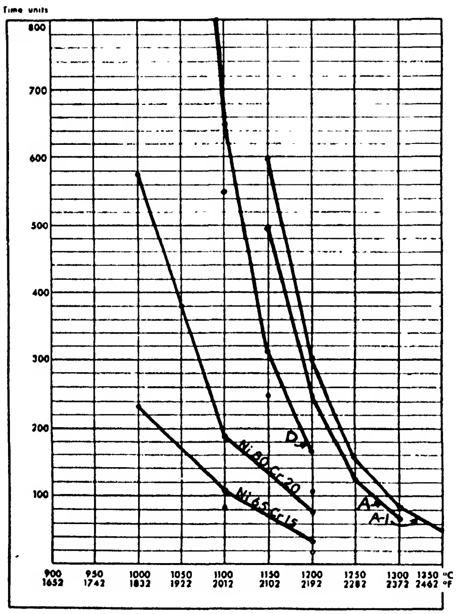


Figure 101. Comparative life diagram of "Kanthal" and nickel-chromium alloys. "Kanthal" alloys grades A, A–1 and D. Mean values obtained with Bash and Harsch testing apparatus.

(*Courtesy C. O. Jelliff Mfg. Corp., Southport, Conn.*)

The American Society for Testing Materials defines "useful life" as the time required for the element to increase 10 per cent in resistance. The expe-

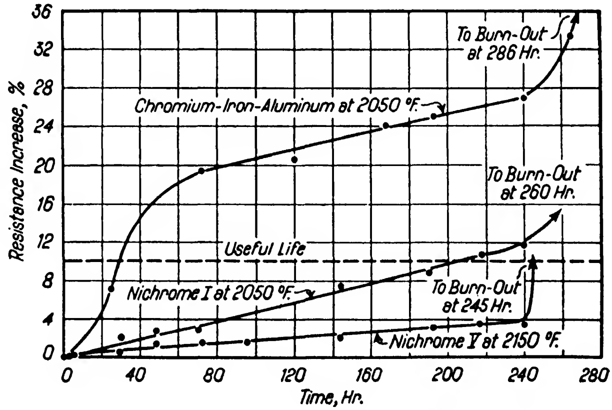
---

* These curves were published by the manufacturers of "Kanthal" alloys.

rience of other manufacturers has been that the iron-chromium-aluminum-cobalt alloys have exceptionally long total life, because the resistance increases so rapidly that on a constant voltage the temperature falls off to a point where the wire lasts almost indefinitely. "Nichrome" V or standard "Nichrome" would probably last for six months instead of 200 to 300 hours on a total life test. Since the elements are purchased on the basis of useful life, the data on total life may be misinterpreted and misleading.

In a life test made in the laboratories of a commercial manufacturer to show how the resistance increases on a standard A.S.T.M. constant-voltage life test for "Nichrome" V and "Kanthal" A, both tested at 2150° F., the latter burned out at 305 hours, but had a useful life of only about 13 hours, whereas "Nichrome" V burned out in 328 hours and had a useful life of approximately 322 hours. The resistance of "Nichrome" V held to a 6 per cent increase up to almost the time of burn-out, while that of "Kanthal" A increased 13 per cent at the end of the first 24 hours' operation. In addition to resistance increase the "Kanthal" wire increased in length over 2 inches, or approximately 12 per cent during the test. Even if completely supported, it will grow. In a constant-temperature life test in which 0.081 inch diameter wire was mounted in a U shape and maintained at 2200° F. with photoelectric cells, "Kanthal" A-1 had a useful life of 98 hours as compared with 136 hours for "Nichrome" V.

In Figure 102 are plotted the time-resistance curves of "Nichrome" V, "Nichrome" and a chromium-iron-aluminum alloy sold for similar applications. These were taken from standard life tests for 0.025-inch diameter wire. Here is to be noted the meaning of and the difference between useful



(*Acknowledgments to J. M. Lohr*)

Figure 102. Typical life test curves for 0.025-in. wire.

TABLE 109. *Current-Temperature Characteristics of "Nichrome" V (Straight Wire)*

B. & S.	Dia. in Ins.	Temp. F. 400 Temp. C. 204	600 315	800 427	1,000 538	1,200 649	1,400 760	1,600 871	1,800 982	2,000° F. 1,093° C.
1	.289	78.2	109	140	177	219	268	322	378	434
2	.258	65.1	92.6	118	149	185	227	272	319	366
3	.229	54.9	77.0	99.0	125	156	190	228	268	307
4	.204	45.8	64.9	83.0	104	130	160	191	224	258
5	.182	39.1	55.2	71.0	88.8	110	135	161	189	217
6	.162	32.5	45.8	59.0	74.2	92.0	112	135	158	182
7	.144	27.4	38.5	53.4	62.2	77.1	95.5	114	134	153
8	.128	22.4	32.2	41.0	52.2	64.9	79.1	94.8	111	128
9	.114	18.8	27.0	34.6	43.9	54.6	66.9	80.0	94.0	108
10	.102	16.3	23.4	29.2	37.7	46.2	56.5	68.0	80.0	92.3
11	.091	13.8	19.1	24.8	31.3	39.1	47.7	57.5	67.1	77.8
12	.081	11.6	16.1	20.8	26.7	33.5	40.8	48.5	56.6	65.5
13	.072	9.76	13.6	17.7	22.5	28.1	34.3	41.0	48.0	55.5
14	.064	8.43	11.7	15.0	18.9	23.5	28.9	34.7	40.5	46.2
15	.057	7.21	10.0	12.85	16.1	20.0	24.5	29.4	34.2	39.2
16	.051	6.39	8.66	10.94	13.7	17.0	20.9	25.1	29.4	33.6
17	.045	5.53	7.48	9.51	11.8	14.5	17.6	21.1	24.6	28.1
18	.040	4.82	6.53	8.23	10.1	12.2	14.8	17.7	20.7	23.7
19	.036	4.26	5.84	7.21	8.77	10.6	12.8	15.2	17.9	20.4
20	.032	3.80	5.07	6.30	7.59	9.13	10.9	13.0	15.2	17.4
21	.0285	3.34	4.33	5.32	6.48	7.84	9.37	11.0	12.9	14.8
22	.0253	2.93	3.77	4.53	5.58	6.81	8.15	9.57	11.0	12.6
23	.0226	2.58	3.34	4.04	4.87	5.89	7.09	8.17	9.60	10.9
24	.020	2.21	2.88	3.46	4.18	5.06	6.04	7.10	8.12	9.40
25	.0179	1.92	2.52	3.02	3.58	4.32	5.18	6.10	7.25	8.04
26	.0159	1.67	2.15	2.61	3.16	3.79	4.49	5.25	6.06	6.95
27	.0142	1.44	1.84	2.25	2.75	3.29	3.92	4.58	5.28	5.96
28	.0126	1.25	1.61	1.96	2.39	2.86	3.23	3.94	4.51	5.11
29	.0113	1.08	1.39	1.74	2.10	2.51	2.96	3.44	3.94	4.44
30	.010	.92	1.18	1.48	1.79	2.14	2.53	2.93	3.33	3.75
31	.0089	.77	1.02	1.30	1.58	1.85	2.18	2.51	2.85	3.19
32	.008	.68	.90	1.13	1.38	1.62	1.90	2.18	2.47	2.76
33	.0071	.58	.78	.98	1.18	1.40	1.62	1.87	2.12	2.35
34	.0063	.49	.67	.83	1.01	1.17	1.42	1.61	1.80	1.99
35	.0056	.42	.57	.72	.87	1.03	1.22	1.38	1.54	1.71
36	.005	.37	.52	.63	.77	.89	1.05	1.17	1.28	1.49
37	.0045	.34	.46	.57	.68	.79	.90	1.06	1.18	1.29
38	.004	.29	.41	.50	.60	.69	.78	.88	.98	1.09
39	.0035	.26	.36	.43	.50	.57	.66	.75	.83	.92
40	.0031	.24	.31	.37	.43	.50	.57	.64	.71	.79

life and total life to "burn-out." The graph therefore shows typical life-test curves.

Table 109 shows the approximate amperes necessary to produce a given temperature in straight wires of "Nichrome" V stretched horizontally in free air.[2]

A number of registered trade mark alloys are mentioned in this section. The manufacturers of these alloys are listed below:

Driver-Harris Co.
- "Advance"
- "Chromax"
- "Gridnic" E
- "Lucero"
- "Manganin"
- "Nichrome"
- "Nichrome" V
- "Radiohm"
- "Hytemco"

Alloy Metal Wire Co.
- "Alray" A
- "Alray" C
- "Excelsior"

International Nickel Co.
- "Monel"

C. O. Jelliff Mfg. Co.
- "Jelliff" A
- "Jelliff" 70
- "Kanthal"

Hoskins Mfg. Co.
- "Chromel" A
- "Chromel" D
- "Chromel" C
- "Copel"

Wilbur B. Driver Co.
- "Alchrome"
- "Cupron"
- "Mangrid"
- "Mangrid" E
- "Ohmaloy"
- "Tophet" A
- "Tophet" C
- "Tophet" D
- No. 30
- No. 60
- No. 90
- No. 180

References

1. Sanford, A., "The Effects of Substantial Additions of Aluminum, Cobalt, Titantium and Columbium, on the Properties of 80 Nickel, 20 Chromium Alloy," *Trans. A.S.M.* (June, 1939).
2. Hansel, F., "Special Metals in the Electrical Industry," *Electrical Engineering* (July, 1943).
3. "Kanthal," C. O. Jelliff Co., bulletin.
4. "Nichrome and Other High Nickel Alloys," Driver-Harris Co., bulletin.
5. "Resistance Alloys," C. O. Jelliff Co., bulletin.
6. "Resistor Alloys," Hoskins Mfg. Co., bulletin.
7. "Resistor Alloys," Wilbur B. Driver Co., bulletin.
8. Bash, F. E., "Life Expectancy of Electrical Heating Elements," *Metal Progress* (January, 1940).

Section IV

Materials for Special and Severe Service

Chapter XIV

Corrosion and Its Prevention

Corrosion may be considered as the gradual decomposition of a metal by some chemical means, or the destructive alteration of a metal resulting from contact with a liquid or gaseous medium. In other words, corrosion[4] is a phenomenon involving chemical reactions of metals with the non-metallic elements of their environments, forming chemical compounds which are either oxides or salts. The nature of these compounds, particularly their solubilities in the surrounding medium, and the position with respect to the metal surface, where they may be precipitated in solid form, has considerable influence upon the process and may determine whether it will continue to the destruction of the metal or become stifled; if the latter, corrosion resistance has been imparted to the metal surface.

The problem of corrosion is continuous and occurs wherever metals and their alloys are employed. The extent to which it takes place and the rate at which it proceeds depend upon the composition of the material employed, the combination of metals and alloys in contact with each other, the combination of metals and alloys in contact with non-metallic materials, and the nature of the environment encountered in service.

Corrosion is very widespread. Rusting and tarnishing are everyday examples of progressive and self-protecting atmospheric corrosion, respectively; more complicated forms occur with rain, dew, salt spray, sun, and active gases from atmospheric pollution. Perspiration and humidity are eternally at work attacking, deteriorating and destroying valuable materials, which must be protected against these natural forces. The annual loss due to corrosion of equipment in the United States is in excess of two billion dollars.

A knowledge of the fundamentals of corrosion, the nature of attack, and the resulting products and effects is necessary in order to recommend intelligently the best materials for manufacturing and for service application. Frequently, a material which is satisfactory metallurgically but not sufficiently corrosion-resistant can be made so by suitable surface treatment. A working knowledge of such surface treatments is advantageous. Familiarity with the special alloys which have been developed to resist specific media at room and elevated temperatures is also desirable.

Corrosion Reactions

Corrosion can manifest itself in a number of different forms, though they are fundamentally the same. Corrosion reactions are usually classified either as direct atmospheric chemical attack or as an electrochemical mechanism. Although broad distinction is sometimes made between direct chemical corrosion and electrochemical corrosion, it is difficult to maintain scientifically in view of the electrochemical features of so many surface reactions. However, in practice, the distinction is made according to whether measurable currents in a definite circuit are absent or present, and also whether the corrosion is occurring at elevated temperatures in the absence of moisture.

The dry or direct-combination process is exemplified by oxidation and tarnishing reactions. The oxidation of iron and steel at elevated temperatures, the oxidation of aluminum and magnesium, and the tarnishing of copper by the atmosphere illustrate corrosion by direct chemical or atmospheric attack. The staining of nickel and silver by sulphurous gases in the atmosphere is another example of corrosion by direct chemical attack of the metal by another substance. Atmospheric corrosion can be due to the action of sulphur dioxide and hydrogen sulphide, which are present in industrial atmospheres. Under conditions of high temperature, the presence of CO_2 may convert the material to the carbonate.

Electrochemical attack occurs when a metal surface is corroded by a chemical compound, such as an acid or alkaline solution, to form the compound of the reactant and the metal. The reaction on the whole surface of the metal will be fairly uniform and will proceed at a uniform rate. The surface of a metal subjected to such attack will be smooth, but visibly etched. An example of this type of attack is the effect of hydrochloric acid on iron; the reaction tends to form iron chloride, with liberation of hydrogen gas. As long as the hydrogen escapes or is removed by some means, the reaction will continue, the iron being evenly dissolved away.

The electrochemical mechanism, which is the type of corrosion usually encountered when metals are corroded in service, takes place when other metals or hydrogen are displaced by more active metals in solutions of electrolytes. In electrochemical corrosion the process is essentially electrolytic in character and involves the electrochemical reactions. The basis for the interpretation of this type of corrosion is the electromotive force series, an arrangement of the elements in order of their dissolution tendencies in solution of their own ions of corresponding concentrations.

The Electromotive Series

When two dissimilar metals are in contact with each other or otherwise or voltage is set up between the metal and the solution. The magnitude of this potential is determined by the nature of the metal surface exposed, the composition of the liquid, and by other factors such as temperature, degree of agitation, gas pressure, etc.

The tendency for pure metals to corrode by displacing hydrogen ions from solution is indicated in a general way by their position in the electromotive series[8] shown in Table 110. It should be noted that the potential values given in this table apply only to the conditions in which the metal is in contact with a solution in which the activity of the ion indicated is one mole per 1000 grams of water. In any other solution different values for the potentials would be developed.

TABLE 110. *The Electromotive Series*

Metals electrode potential at 77° F. (25° C.)

Metal	Ion	Voltage
Magnesium	Mg^{++}	−2.34
Aluminum	Al^{+++}	−1.67
Zinc	Zn^{++}	−0.76
Chromium	Cr^{+++}	−0.71
Iron	Fe^{++}	−0.44
Cadmium	Cd^{++}	−0.40
Nickel	Ni^{++}	−0.25
Tin	Sn^{++}	−0.14
Lead	Pb^{++}	−0.13
Hydrogen	H^{+}	Arbitrary zero point
Copper	Cu^{++}	+0.34
Silver	Ag^{+}	+0.80
Palladium	Pd^{++}	+0.83
Mercury	Hg^{++}	+0.85
Platinum	Pt^{++}	+1.2
Gold	Au^{+++}	+1.42

Metals above hydrogen in this series displace hydrogen more readily than do those below it; a decrease in hydrogen ion concentration (acidity) tends to move hydrogen up relative to the metals, while an increase in the metal ion concentration tends to move the metals down relative to hydrogen. Whether or not hydrogen evolution will occur in any case is determined by several other factors in addition to the concentrations of hydrogen and metallic ions. These include the phenomenon of hydrogen overvoltage. In this series the metals at the top of the list are very prone to go into solution, whereas those at the bottom of the list have little tendency to corrode.

The Galvanic Series

When two dissimilar metals are in contact with each other or otherwise electrically connected and exposed to a corrosive liquid or conductive solution, a potential is set up between them, and a current flows. In many cases the corrosion of one metal is accelerated and that of the other metal decreased, compared to the corrosion behavior of the same metals when not in contact. Because of the electric currents and dissimilar metals involved, this form of corrosion is called galvanic corrosion.

The electromotive force series, as far as galvanic corrosion is concerned, gives an indication of the potential that should exist if two of the metals are in contact in a given electrolyte. In addition it indicates that the metal higher up in the series will probably corrode and the lower one will be protected. The farther apart the metals are in the series, the greater the potential and the greater the likelihood of galvanic attack. For example, aluminum and copper represent a bad combination, since galvanic corrosion would probably occur, and the corrosion of the aluminum be greatly accelerated.

The galvanic series[8] for metals and alloys (Table 111) is based upon actual experience with corrosion in practice and laboratory measurements. Voltage figures are not given because they vary with every new corrosive condition. The series as it stands is accurate for common dilute water solutions such as sea water, weak acids, and alkalies. The metals at the top of the list are anodic, those at the bottom cathodic. "Anodic" means that the pole at which the current is flowing from the metal to the solution is the anode and that the metal goes into the solution as positive charged ions; "cathodic" means that the pole at which the current is flowing from the solution to the metal is the cathode, and that positive charged ions are attracted to it from the solution and plate out. For example, a piece of zinc and a piece of copper immersed in a solution of 5 per cent sulphuric acid but not in intimate contact will produce no noticeable action. If the two metals are connected externally by means of a piece of wire, bubbles of gas will begin to collect on the copper and the zinc will gradually be dissolved away. The following reaction takes place:

$$\text{At the zinc (anode): } Zn^0 = Zn^{++} + 2e$$
$$\text{At the copper (cathode): } H_2SO_4 = 2H^+ + SO_4^{--}$$
$$2H^+ + 2e = H_2$$

In other words, the zinc loses two electrons (e), thus becoming positively charged and going into solution. The copper in turn gains two electrons, which give it a negative charge. These electrons on the copper, however, are immediately taken up by the positive charged hydrogen ions in solution, formed by ionization of the sulphuric acid, and become neutral hydrogen atoms which combine in pairs to form hydrogen molecules (gas) which collect on the copper electrode.

In this galvanic series the metals close together have little tendency to form galvanic cells with appreciable flow of current. However, if two metals widely separated in this series are connected and immersed in a solution, the metal higher up on the list will corrode and go into solution. This con-

TABLE 111. *Galvanic Series**

ANODIC END

Magnesium
Magnesium alloys
Zinc
Aluminum 2S
Cadmium
Aluminum 24ST
Carbon steel
Copper steel
Cast iron
4–6% Cr steel

X	12–14% Cr steel	Active
	16–18% Cr steel	
	23–30% Cr steel	

Ni-Resist

Y	7Ni–17 Cr steel	Active
	8Ni–18 Cr steel	
	14Ni–23 Cr steel	
	20Ni–25 Cr steel	
	12Ni–18 Cr–3 Mo steel	

Lead-tin solder
Lead
Tin

(Series continued at right)

Z	Nickel	Active
	60 Ni–15 Cr	
	Inconel	
	80 Ni–20 Cr	

Brasses
Copper
Bronzes
Nickel silver
Copper nickel
"Monel"

Z	Nickel	Passive
	60 Ni–15 Cr	
	"Inconel"	
	80 Ni–20 Cr	

X and Y	12–14 Cr steel	Passive
	16–18 Cr steel	
	7 Ni–17 Cr steel	
	8 Ni–18 Cr steel	
	14 Ni–23 Cr steel	
	23–30 Cr steel	
	20 Ni–25 Cr steel	
	12 Ni–18 Cr–3 Mo steel	

Silver
Graphite
Gold
Platinum
CATHOTIC END

dition existing between two metals causes a flow of current which can be measured by means of an ammeter. The current generated determines the rate of solution of the anodic metal or the rate of corrosion.

It should be understood that the series shown above does not hold true in all cases. The position of any metal in the series can change with conditions and environment; hence under specific conditions one metal may be either anodic or cathodic to another. It is important, therefore, that the prevailing condition be taken into consideration.

Corrosion, therefore, is a complex phenomenon[8] which may take one or more of several forms. The fundamental reaction involves a transfer of electrons in which some positively charged ions in the corroding solution, usually hydrogen ions, lose electrical charges. The complete corrosion reaction is divided into an anodic portion and a cathodic portion, which occur simultaneously at discrete points on metallic surfaces. The anodic reaction

---

* Some metals and alloys can become passive in certain environments and conditions. These active-passive materials are designated in three groups, X, Y and Z, which under certain conditions become passive and are then lower on the list.

(oxidation) represents the acquisition of charges by the corroding metal, while the cathodic reaction (reduction) represents the loss of charges by the hydrogen ions, which are discharged. The flow of electricity between the anodic and the cathodic areas may be generated by local cells set up either on a single metallic surface or between dissimilar metals. Sometimes an electric current may be applied from some external source, either accidentally or deliberately.

It is not always necessary to have dissimilar metals in contact; it is possible to form a galvanic cell with the accompanying flow of galvanic current within a piece of apparently homogeneous metal. In an apparently uniform piece of metal, any portion which has been subjected to strain or stress of some kind will be less noble than an unstrained portion of the same metal. Similarly, small grains are less noble than large grains; moreover, minute inclusions of more noble impurities are often found in a relatively pure piece of metal. These differences permit local galvanic cells to be set up, and corrosion of the baser (anodic) regions will occur slowly in the presence of air or moisture and more rapidly in the presence of stronger electrolytes.

The local galvanic cell can be caused by any of the following conditions (the galvanic cell will result in a difference of potential between the metal and the interface of the non-homogeneous portion):

Conditions for localized attack:

(1) Presence of metallic or non-metallic impurities.

(2) Grain boundaries. The potentials at the grain boundaries are different from those in the center of the grains.

(3) Differential orientation of the grains.

(4) Differential grain size. Fine grains have higher internal energy than coarse grains.

(5) Differential thermal treatment.

(6) Differential mechanical treatment.

(7) Differential strain.

(8) Surface roughness.

(9) Local scratches or abrasions.

(10) Differential pre-exposure to air or oxygen.

(11) Differential concentration or composition of the corroding solution.

(12) Differential aeration.

(13) Differential heating. This may give rise to corrosion currents.

(14) Externally applied potentials.

Such variations in a metal and environment occur very often in practice, thus corrosion of a metal can take place very easily if a liquid is present which can act as an electrolyte. The electrolyte may be only moisture from the air which has condensed on the surface of the metal, even though it be only a very thin film.

Rate of Corrosion

The rate of corrosion of any metal is proportional to the flow of current per unit area. Several factors influence the corrosion rate in any of the mechanisms described above, and they are important enough to warrant brief consideration. One of the most important retarding factors is polarization of the electrodes, *i.e.*, formation on the surface of the metal of a film which resists the flow of current. Polarization is usually caused by a film of hydrogen gas on the cathode, although corrosion products on the cathode may also cause it. This is known as *cathodic polarization.* The formation of a film of oxygen on the anode, called *anodic polarization,* also tends to retard the rate of corrosion, though to a somewhat lesser degree than cathodic polarization. Generally, anodic polarization is the result of the accumulation of anodic corrosion products, either in solution or as films, on anodic surfaces. Any action which removes the polarization effect, whether it be agitation, chemical combination or solution, will of course permit corrosion to proceed at its normal rate.

A second factor affecting the corrosion rate is the difference in potential between local anodic and cathodic areas. The greater the difference between the two, the faster corrosion proceeds, since there is a greater driving force.

Another important factor is the acidity of the electrolyte. The more acid the environment, the more rapid the rate of corrosion, for the number of hydrogen ions in a solution increases with increase in acidity. This is easily understandable, for we have already seen that hydrogen ions act as a metal and tend to be replaced by a metal.

Temperature also exerts a tremendous influence on corrosion rate. As in any chemical reaction, the speed of the reaction increases with increase in temperature. In corrosion mechanisms, elevated temperatures neutralize the beneficial effect of polarization because of the decreasing solubility of gases with increasing temperatures. The decrease in solubility of oxygen counteracts the promoting effect of temperature on corrosion by reducing the extent of cathodic depolarization and thus acting as a brake on the corrosion process. Higher temperatures also increase the solubility of corrosion products, thus removing them from metal surfaces and pushing the reaction even further toward completion.

Other factors which may effect corrosion rate are the degree of aeration or circulation of the electrolyte, the presence of inhibiting agents, such as chromates, dichromates or silicates, and dissolved oxygen in the electrolyte, which tends to prevent cathodic polarization by combination with the hydrogen.

In a particular galvanic combination, the relative areas of the two materials forming the couple have a very important bearing on the extent of corrosion. Under most conditions the extent of galvanic corrosion for any metallic couple will be very nearly proportional to the ratio of the area of the cathodic metal to the area of the anodic metal. Thus, if a piece of aluminum having a surface area of 2 square inches is coupled to a piece of steel with a surface area of 100 square inches, the galvanic corrosion is roughly 50 times faster than it would be if the same piece of aluminum were coupled to a piece of steel having a surface area of 2 square inches. For this reason, it is wise to avoid galvanic couples where the exposed area of a metal lower in the galvanic series is much greater than that of a metal higher in the series. The higher metal will suffer accelerated corrosion to an extent determined by the corrosiveness of the environment, the area of the more noble metal, and the resistance of the galvanic circuit.

The corrosion rate can be decreased by the addition of inhibitors to the environment of a metal or alloy. These may be divided into two classes, depending on whether they impede the anodic or the cathodic reaction. A further division may be made into inorganic and organic inhibitors.

In almost all cases, inhibitors reduce corrosion by forming films. In general, anodic inhibitors thinly coat on the anodic areas, thus impeding the anodic reaction; cathodic inhibitors retard the cathodic reaction in an analogous manner. Often the use of ions, such as Ca^{++}, Mg^{++} or Zn^{++}, will decrease the rate of attack on partly submerged steel structures. The precipitation of magnesium or zinc hydroxide on the cathodic areas provides the inhibitor action by preventing or reducing oxygen diffusion to the surface.

Some typical anodic inhibitors are chromates, silicates and phosphates. Organic oxidizing agents (benzoyl peroxide) are also effective. Cathodic inhibitors, which include a wide variety of organic compounds and are more generally used than anodic inhibitors, are represented by aliphatic and aromatic amines and their derivatives, heterocyclic nitrogen compounds such as pyridine, and sulphur compounds such as thiourea, sulphides and mercaptans. The important factors in organic inhibitors are the presence of a polar or ionizable group.

Galvanic couples do not always result in corrosion attack of the anodic metal, as indicated by the relative positions of the two metals in the galvanic series. The condition that prevents the expected attack is called *passivation.* This is a relative term, because a metal or an alloy may be passive to one environment and yet react violently to another corrosive medium.

The phenomenon of passivation is one of the reasons why metals behave differently from what their positions in the galvanic series would indicate. Passive surfaces on metals show more noble characteristics, that is, better corrosion resistance. The most widely accepted theory postulates the formation of a tenacious oxide, such as chromium oxide in stainless steel, on the surface of the metal.

Alloys containing chromium are most pronounced in the passivity, which accounts for the wide use of chromium in corrosion-resistant and stainless steels. The corrosion behavior of a metal can be markedly changed because of numerous surface reaction possibilities, such as oxide formation, the presence of physically or chemically adsorbed gases, or adherent corrosion products. Passivity depends, therefore, on the nature of the solution: if it is one that destroys passivity, the alloy is then said to become active and will be attacked.

What is more important than the rate of corrosion in many cases is the pattern of attack. For example, the rate in terms of weight loss of metal per unit time may be low; but if this loss is concentrated at points or small areas, the damage may be many times greater than the rate would indicate. Thus the pitting type of corrosion may cause leak in a tank, or intergranular attack in a highly stressed part may lead to destruction, though the actual loss of metal may be negligible. Intergranular corrosion can prove quite serious under internal and applied stresses, particularly cyclic stresses approaching the fatigue limits of metals and alloys in corrosive atmospheres or environments.

Other Types of Electrochemical Corrosion

The corrosion mechanisms explained so far are of a simpler type. The other types frequently met with in practice are (1) concentration or solution cell, which is a galvanic cell created by the presence of the same metal in different concentrations of the same electrolyte or of the same metal in different electrolytes; (2) dezincification, which is the dissolution (by electrochemical mechanisms) of one constituent in an alloy, leaving the other constituents intact (usually encountered in high-zinc brasses). This action appears to be much more complex and involves redeposition of copper after previous solution of the alloy as a whole or one of its phases; (3) stress corrosion, and corrosion fatigue, which are the results of accelerated corrosion in the metal because of internal stresses or fatigue stresses; (4) oxygen concentration cell, which occurs on metal surfaces at which the oxygen concentration (in the presence of an electrolyte) at one area is higher than at another.

Stress corrosion is corrosion accelerated by internal stresses or externally applied stresses. Internal or residual stresses (locked-up stresses) are often produced by methods of manufacture or assembly. Common examples are stresses induced by internal structural changes, quenching, cold-forming, and so forth. Stresses induced by assembly include those from welding, press or shrink fit. Such stress corrosion manifests itself in the form of cracks.

Corrosion fatigue is stress corrosion in which the stresses are fluctuating or cyclic in nature.

In general, stress corrosion for a given material depends upon three factors, namely, the stress, the concentration and nature of the corrosive environment, and the temperature. Once localized attack in the form of a pit, crack or crevice begins, the effect is accelerated because these areas serve as stress raisers.

The most common method of combating stress corrosion due to locked-up stresses consists of stress-relieving heat treatment. The use of protective coatings or redesign of equipment to eliminate such stress-raisers as sharp corners helps to minimize stress corrosion. Of course the use of more corrosion-resistant material and changes in corrosive environment are factors to be considered.

In stress corrosion, cracks always grow along grain boundaries and always occur in regions of high stress concentration. Cracks are produced and extended by the electrochemical dissolution of anodic material in the grain boundaries. Stress-corrosion cracks are mostly intercrystalline, slightly transcrystalline and also slightly branched.

Localized precipitation along grain boundaries and also precipitation along planes of slip induced by cold-working, which forms continuous paths anodic to the surrounding grains in a specific corrosive solution, have been demonstrated to be a cause of susceptibility to stress-corrosion cracking.

Corrosion cracking of brass and the caustic embrittlement of boiler plate are well known examples of this phenomenon. Austenitic stainless steels of the 18–8 type disintegrate by progressive chemical attack along the grain boundaries. Stressing of the metal, in combination with carbide precipitation at grain boundaries results in accelerated attack. (See Figures 103 and 104.)

This preferential precipitation of chromium carbides along the grain boundaries depletes the chromium content of the solid solution, resulting in lowering the resistance to corrosion along these zones. Moist ammonia vapor and aqueous ammonia solutions cause stress cracking (also called season cracking) of certain brasses when under stress.

Stress corrosion or intergranular embrittlement are not confined to one kind of material or to one kind of corrosive medium. For example, carbon steel is affected by certain caustic solutions, stainless steel by acid chlorides, aluminum and magnesium alloys by sea water, and copper alloys by ammonia. But it is necessary that the material be under sufficiently high tensile stresses.

The essential conditions for promoting failure by stress corrosion are: (1) tensile stress at the surface of the component (either residual or ap-

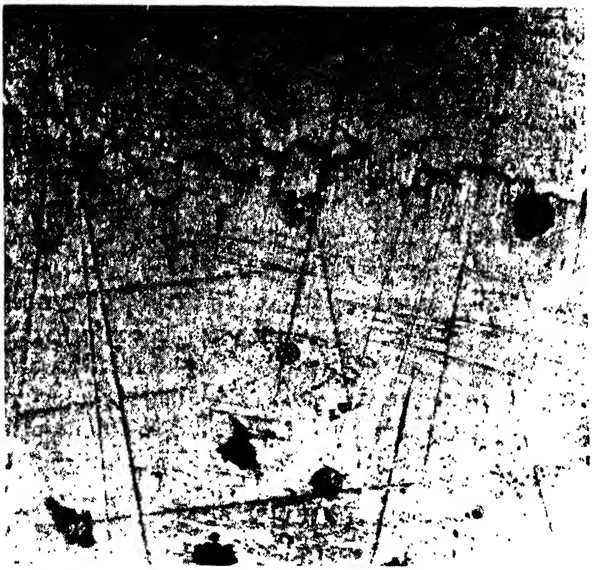


Figure 103. Intergranular corrosion of 18–8 stainless steel. (100X). Attack at grain boundaries.

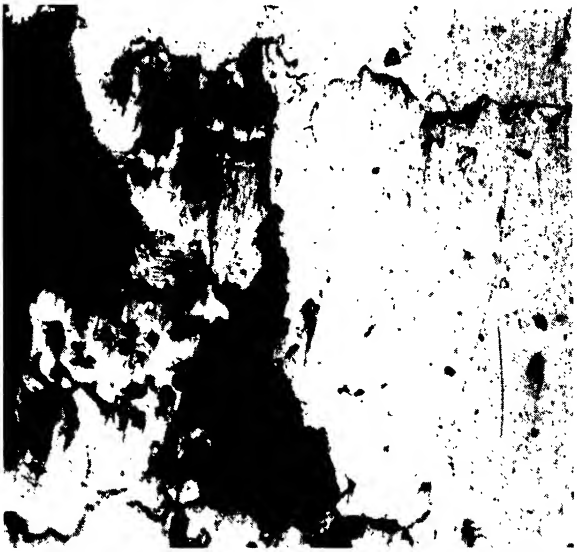


Figure 104. Intergranular corrosion of 18–8 stainless steel (100X). Crack follows an irregular pattern around the grains.

plied), and (2) an attacking medium. When fluctuating stress occurs with simultaneous chemical attack, corrosion fatigue failure may occur. This form of corrosion is probably similar to stress corrosion in that it is the tensile stress part of the cycle which causes breakdown of the structure; the corrosion-fatigue cracking follows an intercrystalline path until corrosion ceases to have effect or until the part fails in tension because of loss of section.

Rusting of Iron

Several points should be emphasized in order to give a clear understanding of the mechanism of rusting. When iron in contact with water first begins to rust, it goes into solution as positively charged iron ions. Simultaneously, hydrogen ions formed by the ionization of water are deposited as hydrogen gas. The hydrogen forms a thin, invisible film on the iron and tends to retard and eventually stop the reaction. However, this film is usually removed either by combination with dissolved oxygen or by escaping as bubbles of hydrogen gas. As long as the gas film is continually removed, the corrosion will continue. The secondary reaction resulting in the formation of rust is the oxidation of the ferrous ions in solution to ferric ions and the subsequent precipitation of insoluble ferric hydroxide.

The mechanism of rusting suggests a means by which it can be controlled. As long as there is no dissolved oxygen present, *i.e.*, as long as air is absent, there would be little or no chance for the hydrogen film to be removed from the iron, thus decreasing or stopping the reaction. In addition, there would be no precipitation of hydrated ferric oxide, which accelerates the reaction by removing ferrous ions from solution and allowing more iron to dissolve. The formation of rust on the surface of the iron ordinarily would tend to retard corrosion; but since the ferric hydroxide (hydrated iron oxide) is porous and not very adherent, it does not completely stop the reaction.

The rusting of iron occurs preferentially under the portions of the metal that are already covered with wet rust. As these parts are less accessible to air, they tend to corrode, as long as oxygen is available to oxidize away the discharged hydrogen ions at the other parts. A similar condition is responsible for the corrosion of iron and steel covered with a partially protective film, such as a loose layer of paint, or in contact over a portion of its surface with a non-metal, such as wet wood or rope, etc. If oxygen has greater access to some parts of a surface than to others, that part to which oxygen does not have access will corrode. The parts of the metal which dissolve are those having the smaller concentration of oxygen. The reason for the observed fact is that hydrogen ions tend to discharge more easily where the resulting hydrogen can be readily oxidized; these are the portions of the metal where there is a good supply of air. In order to complete the galvanic cell, in which the discharge of hydrogen ions occurs, the metal must dissolve at those parts to which oxygen has little or no access.

PREVENTION OF CORROSION

Corrosion prevention is the art of protecting metals by means of applied coatings, chemical treatments, or cathodic protection methods. There are numerous general methods for accomplishing this, namely: (1) coating with certain types of easily removable oils, greases and solvent mixtures, (2) painting, (3) plating, (4) chemical treatments, such as oxide, phosphate, arsenate or sulphide coatings, (5) porcelain enameling, and (6) supplying an electric current, either externally or by galvanic coupling. The first method is referred to as temporary coating, and is applied to operating or functioning metal parts to protect them during manufacture, shipment, or storage. The cathodic protection method is a process of protecting costly parts or equipment at the expense of cheaper and more easily replaced metals. The principle of cathodic protection is the elimination of local anodic areas by the use of an external anode.

Lowering the potential difference of a galvanic cell causes a reduction in the amount of current flowing, which in turn means that the amount of corrosion is reduced. An increase in the resistance of the galvanic circuit will also lead to a reduction in the amount of corrosion.

A reduction in the galvanic potential can be accomplished in practice (1) by selecting materials which are close together in the galvanic series or (2) by applying an opposing potential, usually a low direct current voltage from a generator or rectifier. An increase in resistance can be obtained (1) by insulating the dissimilar metals, (2) by keeping the dissimilar metals apart, (3) by adding a corrosion inhibitor or polarizer to the corrosive solution, (4) by coating the cathode surface with paint, tarry material, etc.

Cathodic Protection

Cathodic protection methods[7] are often used in industry for prolonging the life of equipment by reducing or almost completely eliminating the corrosion that would normally occur. Cathodic protection consists of supplying an electric current, either externally or by galvanic coupling, to a specific metal surface in such a manner that the usual electrochemical corrosion reactions are stifled or counteracted. If both electrodes of a couple can be made cathodic by a current from some other source, in many cases galvanic corrosion of the couple can be prevented. The source of the current may be an inert electrode with externally applied potential, or a metal more anodic than both of those comprising the couple.

Thus the methods of cathodic protection fall into two general classes: those using sacrificial anodes and those involving impressed currents or potentials. In the former, metals or alloys to be protected are electrically connected with the sacrificial anode or the anode is placed in contact with the equipment to be protected. In the second classification, a current is applied by means of an external source of power.

Sacrificial anodes are usually made of zinc, magnesium and aluminum, or alloys of these metals, depending on the nature of the metal or alloy to be protected. The rate of corrosion on these anodes is accelerated, and the attack on the other metal in the couple is reduced, because of galvanic corrosion effects. The sacrificial anodes are so designed that they can be readily replaced if necessary.

Another example of cathodic protection is the coating of a metal with another metal or alloy more anodic than the base metal. Galvanized iron, tin-coated copper, and "Alclad" aluminum alloys are examples of such products.

Electroplated Coatings

A well-known method of providing improved corrosion resistance is by the electrodeposition of metals which offer better resistance to corrosion than the base metal. The chief object of electroplating is to provide a coating which will protect the underlying metal from corroding when exposed to atmospheric or other conditions.

The principle of electroplating requires that the article to be plated be made the cathode of an electrolytic cell. The electrolyte or plating bath consists of a salt of the metal to be electroplated. The anode of the cell is usually the same metal which is to be electrodeposited, for this serves as a means of replenishing the metallic ions which are withdrawn from the electrolyte during plating. When current supplied by a direct current generator or rectifier is passed through the cell, the metal from the anode enters the solution as metallic ions, and metallic ions from the electrolyte are transferred to the cathode (part to be plated), where they are deposited in the metallic state.

Although the process of electroplating is simple, several variables are present which make it necessary to exercise careful control: chemical composition of the bath, temperature of the bath, and cathode current density. These conditions determine the character of the deposited metal. This is all-important if the coating is to serve as a protection for the base metal. The deposit must be continuous and uniformly distributed over the surface. It must be smooth, fine-grained, and free of porosity, and the plated metal must adhere firmly to the base metal.

The part which porosity plays in the protection offered by an electrodeposited coating depends upon the relative positions in the galvanic series of the coating and the base metal. If the coating is anodic toward the base metal in the environment in which the part is being used, porosity in the coating is not serious, for the coating is sacrificed to save the base metal. However, if the base metal is anodic to the coating, *i.e.*, if the plating is cathodic, the presence of porosity results in corrosion of the base metal, indicated by "pinhole" corrosion.

It is apparent that care must be taken in selecting the metal to be electrodeposited on a part for the purpose of corrosion protection. Here again, the galvanic or electrochemical series must be used as a guide. The same condition holds true for plated coatings as in galvanic corrosion. Metals close to each other in the series have little tendency to form electrolytic cells, while those widely separated do so very easily. Another important fact to bear in mind is that the generally accepted procedure in plating for corrosion protection is to deposit a metal which is anodic to the base metal. This practice will insure protection of the base metal even though the coating may become ruptured.

The metals most commonly used for electroplating are cadmium, zinc, tin, nickel and chromium. Cadmium is used extensively for the protection of iron and steel, since it is anodic to iron. Properly applied, cadmium coatings on iron show no corrosion after 250 hours in the salt spray test. Zinc is used quite frequently as an alternate for cadmium, though it does not offer any better resistance to atmospheric oxidation. It does, however, provide good cathodic protection. One of the most satisfactory and inexpensive coatings for atmospheric exposure is zinc applied by hot-dip galvanizing.

Other metallic coatings obtained by alloying such as sherardizing (zinc), calorizing (aluminum), chromizing (chromium), siliconizing (silicon) and also metal spraying are more expensive than hot-dip coats, but offer advantages in certain cases. In other special cases coatings of the very noble metals such as copper, silver, gold and platinum are applied when necessary.

Tin-plating does not provide iron or steel with positive corrosion resistance, because most electroplated tin coatings are porous, and in addition tin is generally cathodic to iron. Until recently, sheet iron for "tin cans" was always hot-dipped, since hot-dipped coatings were somewhat thicker and less porous. However, a method has been developed which makes it possible to electroplate tin cans with minimum porosity by "flowing" the plated tin by immersion in a hot oil bath. Actually both the hot-dipped and the electroplated and "flowed" tin coatings may be very porous and severe rusting occurs in many environments. The usefulness of tin coatings in tin cans is not due to the absence of porosity, but to the peculiar galvanic relationship between tin and iron in a tin can, where the tin is anodic to the iron.

In the absence of air, *i.e.*, inside a sealed can, the high overvoltage of the tin, which is the nobler metal, prevents corrosion of the iron. When air is present, however, the iron is readily attacked; in fact, faulty tin plate will rust more readily than would the iron alone. The reason for this is that numerous short-circuited cells are formed in which the iron is the anode, and consequently dissolves.

Tin is frequently electroplated on copper and copper-base alloys for corrosion protection, for appearance and for subsequent soldering operations. When applied to copper alloys, the tin is anodic to the copper, so any porosity present will have little effect on the rate of corrosion.

Nickel is used on brass and bronze for both decorative and protective purposes. It can be used on iron and steel, but its use in very thin coatings is not recommended because of its porosity and because it is cathodic to iron. However, coatings thicker than 0.005 inch are substantially free from pores, and such electrodeposited nickel coatings have been used very extensively for protecting steel from chemical attack in the process industries and petroleum and gas production equipment.

Chromium plating has become very important in recent years with the development of hard chromium plating. By itself in thin coatings it does not offer good corrosion resistance, so an undercoat, usually nickel, is applied before depositing the chromium. The principle advantage of chromium is its hardness and resistance to abrasion. It is finding widespread use in application to parts where excessive wear is usually experienced.

In the case of an electrodeposit to prevent corrosion, one essential object is to coat a base metal with an adherent and continuous layer of a more noble, and hence less susceptible metal. The effect of less noble metals such as nickel and chromium is the result of their tendency to become passive under oxidizing conditions, that is, become covered with an invisible but strongly protective film of an oxide. As a result, both nickel and chromium may behave as noble metals and consequently are not easily attacked by corroding media. Of course if the plate is faulty so that the underlying metal is exposed, corrosion may be facilitated because of the short-circuited cells set up.

Neither nickel nor chromium deposits resist solutions containing chloride ions particularly well. These ions tend to prevent the onset of passivity by destroying the protective oxide film.

Metal coatings are usually applied to iron and steel by hot-dipping, electroplating, cementation or metal spraying.

Paint Coatings

The prime purpose of many surface treatments is to provide a good base for subsequent paint coatings. Without doubt, paint offers the best method of improving the corrosion resistance of metals. Considerable progress has been made in recent years in the paint industry, and paints are now available which will provide excellent resistance to corrosion even under the severest of conditions. The effectiveness of a paint depends upon the imperviousness of the film. It must be continuous, non-porous, resistant to abrasion, and properly applied, so that a good bond is obtained between the base metal and the paint. The selection of a paint to withstand a particular environment must be made carefully. Many products are especially designed for protecting certain metals and for resisting specific corrosive media.

Painting[6] greatly increases the resistance of the electrical circuit of the possible couple. Obviously, if conditions permit, both the anodic and cathodic alloys should be painted. However, if only one metal can be painted, it would be expected that painting the cathode would be a better procedure than painting the anode. If the anode alone is painted and the coating breaks down at the local areas, then the same amount of attack could be concentrated in these areas, whereas if not painted, it might spread out over the entire area of the anode. Hence, painting of the anode alone might result in highly intensified attack, especially under conditions approaching cathodic control.

Temporary Protection Methods. A method of providing temporary protection for either indoor or outdoor exposure is the use of slushing oils to form a protective "envelope" around the metal. This is quite frequently used to protect parts in the process of manufacture, as well as semi-finished parts which must be stored while awaiting subsequent operations. These slushing compounds contain lanolin, oils, waxes, and resins, and are available as soft, semihard or hard-film compounds. The soft-film compounds containing lanolin are usually preferred because of the ease of removal; hard-film compounds should be used for outdoor exposure.

Slushing compounds, or rust-preventive compounds as they are more commonly called, are used extensively for protecting parts for domestic or overseas shipment to insure arrival in a usable condition. A particular kind of rust-preventive compound, known as the water-displacing or polar type, can be used to definite advantage where water-soluble coolants are being employed for machining or grinding operations. These compounds have a greater affinity for metal than does water; hence they displace water and form a protective film on the surface of the metal. Although this film provides only temporary protection, it eliminates the inevitable rusting of iron and steel which follows any operation which employs water or water-soluble compounds.

Protection of Iron and Steel

The surface treatments applicable to alloys of iron are many and varied. In almost every case, they have a two-fold purpose: to protect the metal by forming a film which is more resistant to corrosion than the base metal or which corrodes in preference to the base metal, and/or to provide a good base on which paint can subsequently be applied.

The most popular method of providing iron and steel parts with a moderate protection and also offering a good paint base is the application of a phosphate coating, such as in the "Parkerizing" * and "Bonderizing" * processes. These treatments are very similar, differing only slightly in the solutions employed and in the nature of the coating formed. They are straight dip operations which bring about insoluble phosphate coatings of iron and manganese on the surface of the iron or steel. The coatings are usually gray in color and crystalline in structure, the "Bonderized" being finer than the "Parkerized." The dimensional changes effected by the processes are slight—in the vicinity of + 0.0003 to + 0.0005 inch. The coatings produced are corrosion-resistant to some extent, though they are not considered to be rustproof unless they are impregnated with wax or oil. Surfaces to be subsequently painted require no impregnating.

There are several other processes which are similar to Bonderizing and Parkerizing in that they produce insoluble phosphate coatings on the surface of iron and steel. The "Granodizing" † and "Granosealing" † processes give coatings which offer moderate corrosion resistance and provide satisfactory paint bases.

"Electro-Granodizing" † produces a zinc phosphate coating which is superior in corrosion resistance to that produced by "Bonderizing" or "Parkerizing." However, this differs from the previously mentioned processes in that it is electrolytic, and operates on alternating current. It requires only a few minutes to produce the coating and the build-up may be as much as 0.005 inch. Although "Electro-Granodizing" produces one of the best rustproof coatings on iron and steel it is not widely used, probably because of the high installation costs and the trouble usually experienced with electrolytic processes.

A treatment known as the "Du-Lite" process has been developed ‡ for producing a black, somewhat corrosion-resistant coating on steel. The coating is essentially molybdenum and iron oxides formed by the oxidation of the steel surface. The process is a simple immersion operation and causes no dimensional changes on the parts treated. It is used primarily as a color-

---

*** Developed by the Parker Rust Proof Co.**

† Developed by the American Chemical Paint Co.

‡ Du-Lite Chemical Corp.

ing process, though the corrosion resistance can be improved by impregnating with oil or wax. The "Du-Lite" process is commonly used to blacken such parts as guns, clock and camera parts, pins, needles, tacks, drills, and dies.

Several chemical treatments result in the formation of a coating of magnetic iron oxide (Fe_3O_4) on the surface of iron or steel. The chief purpose of these processes is to give a black finish and to provide some corrosion resistance. Here again, the coating must be impregnated with oil or wax if a reasonably corrosion-resistant finish is desired. The better known processes which result in a magnetic iron oxide coating are the "Houghto-Black," the "Black Magic," the "Ebonol," the "Penetrate," and the "Jetal."

The oxide coating is formed by immersing the parts in a solution consisting essentially of a strong alkali containing oxidizing agents. The temperature and time vary somewhat with the individual processes.

Other surface treatments for increasing the corrosion resistance of iron and steel are "Calorizing," which produces an aluminum-iron alloy coating on the steel, and "Siliconizing" or "Ihrigizing," which produces a highly corrosion-resistant surface of about 14 per cent silicon-iron alloy. "Calorizing" protects steel from oxidation and scaling at elevated temperatures and is used on oil-refining equipment, rotary kilns, pyrometer protection tubes, and burner nozzles. "Siliconizing" improves the heat, wear, and corrosion resistance, and is used for treating automotive parts such as rocker arms, cylinder liners, and valve guides.

The "Sherardizing" process illustrates the application of the electrochemical theory to the prevention of rusting. The process consists of coating steel with zinc by heating the steel in an atmosphere of zinc dust. The coating produced consists of iron-zinc alloys of definite composition, which varies between the base metal and the outside surface of the coating. The advantage of the treatment lies in the fact that since zinc is anodic to iron, *i.e.*, above iron in the galvanic series, it will corrode in preference to iron if the coating is abraded or scratched so that the base metal is exposed. The process is not extensively used, however, since it is slow and rather costly.

Galvanizing by hot dipping in a molten zinc bath and electroplating with zinc for rust protection have been for many years the most widely practiced methods. Hot tin dip and tin electroplate are also extensively used.

An excellent sample of the use of cathodic protection is its application in the protection of iron pipe lines buried in extremely corrosive soils, where even organic coatings break down in comparatively short times. The method consists in placing metal anodes in the soil at definite intervals along the structure. A small direct current is then applied in such a way that the pipe line to be protected is at a more positive potential than the anodes, and the current flows from the anodes to the pipe. Thus, the pipe line is cathodic to the auxiliary electrodes, which are slowly corroded by electrolysis. The anodes are replaced when they have gone into solution completely, thus assuring continuous protection of the pipe line.

Protection of Aluminum

The chemical treatments applied to aluminum and aluminum alloys are fewer, but they are far more effective in corrosion resistance than those applied to iron or steel. The basis of the two types of treatment generally used is the formation of a film of aluminum oxide on the surface of the metal. This film is impervious and consequently offers excellent resistance to corrosion; it also provides an excellent paint base.

The best method of forming an aluminum oxide film is known as *anodizing*, so called because it is an electrolytic process, employing a suitable electrolyte, in which the aluminum is made the anode. The two electrolytes most commonly used are sulphuric acid and chromic acid, and the methods are identified as the "Alumilite" process (sulphuric acid) and the "Chromic Acid" process.*

In the "Alumilite" process, the parts are made the anode in a 15 to 18 per cent sulphuric acid solution maintained at room temperature, and 10 to 22 volts are applied with a current density of 12 amperes per square foot. The time of electrolysis is 30 minutes, after which the parts are "sealed" in boiling water or boiling 5 per cent sodium dichromate to improve the corrosion resistance. Properly "Alumilited" parts show no corrosion after 700 hours in a standard salt spray corrosion test. The process can be used on all aluminum alloys regardless of copper content, and it effects a change in dimensions of + 0.0002 to − 0.0003 inch on a side. The coating itself is approximately 0.0001 to 0.0004 inch thick, and is hard and abrasion-resistant.

Owing to the absorptive nature of the oxide film, it is frequently dyed black by immersion in a black dye bath containing nigrosine. This treatment is solely for appearance and does not affect the corrosion resistance appreciably.

The "Chromic Acid" anodizing process is similar, except that a 6 to 9 per cent solution of chromic acid is used as the electrolyte, and 30 to 45 volts are applied for a period of one hour. The coating produced by this method also withstands a 700-hour standard salt spray test. This process can be applied only to alloys of aluminum containing less than 5 per cent copper. Also, the nature of the film is somewhat different from that produced by the "Alumilite" process, being softer, thinner, and less abrasion-resistant. The dimensional changes effected by this treatment are approximately 0.0000 to + 0.0002 inch on a side.

The second type of process for developing an oxide film on aluminum

---

* Patented by the Aluminum Company of America.

differs from those just described in that it is not electrolytic. Known as the "Alrok" process,* it consists of a simple immersion in a solution containing sodium carbonate and potassium dichromate, maintained at 190° F. for 20 minutes. The coating formed is somewhat thinner and less abrasion-resistant than anodized films, and it offers considerably less corrosion protection, though it gives a good paint base. The dimensional changes are of the order of + 0.0001 inch. The main advantages of the "Alrok" process over anodizing are that less costly equipment is required and that castings containing inserts of other metals can be "Alroked" but not anodized.

Adequate protection of aluminum may be obtained by the use of duplex or clad aluminum alloys. The electrochemical action is such that the attack of the alloy is confined to the coating and penetration of the base alloy is prevented. The clad coating is anodic to the base alloy.

Protection of Magnesium

The position of magnesium at the very top in the galvanic series indicates that protecting it and its alloys is a difficult problem. This assumption is correct, for magnesium is very prone to oxidize, the oxide film so formed being less corrosion-resistant than that formed on aluminum.

Considerable work has been done to develop a suitable protective coating for magnesium. The generally accepted method has been the application of paint to all exposed surfaces. There are, however, several treatments which can be applied to magnesium alloys to provide improved corrosion resistance and also a good paint base.

One of the most popular surface treatments for magnesium alloys is the "Dichromate Coating" or the "Chrome-Pickle" treatment. The coating produced offers moderate protection to atmospheric corrosion, though it will not withstand salt solutions or salt spray. It does, however, provide a satisfactory paint base. The coating is a thin film consisting essentially of chromates, dichromates, and chromium salts. The desired color is a matte gray to yellow-red iridescent, with a uniform etch which is visible under a microscope.

The process is a simple dip operation of ½- to 2-minute duration in a bath containing 1.5 pounds of sodium dichromate and 1.5 pints of nitric acid per gallon. The etching action removes approximately 0.0006 inch of metal on each surface. The color, luster, and etch produced vary with the age of the solution, the composition of the alloy, and the type of heat treatment. Die-castings and alloys containing high aluminum (8 per cent and over) are difficult to chrome-pickle because of the formation of a powdery gray deposit on the surface of the casting. This deposit (Mg_3Al_2) can be eliminated by heating the solution to 120–140° F. (50–60° C.) and decreasing the time of treatment to 10 to 15 seconds.

---

* **Patented by the Aluminum Company of America.**

The chrome-pickle solution ordinarily employed cannot be used for machined surfaces because it removes too much metal. However, by reducing the strength of the bath to 0.75 pound of sodium dichromate and 0.50 pint of nitric acid per gallon, it is possible to treat machined castings with a resultant loss in dimensions of about 0.0001 inch per surface. Castings containing bronze, steel and cadmium-plated inserts can be treated by this process.

An alternative treatment to chrome-pickling, which can be used when dimensional changes must be kept at a minimum, is known as the "Alkaline-Dichromate" treatment. No dimensional losses result from this treatment, but increases in dimensions up to 0.0003 inch on a surface may occur. The treatment requires a 20- to 60-minute immersion in a boiling solution of ammonium sulphate, sodium dichromate, and ammonia. The coating formed will vary in color from gray to black and offers a suitable base for paint. Castings containing steel, brass, or bronze inserts can be treated satisfactorily.

The process which imparts to magnesium the best salt-water resistance consists of a 5-minute immersion in a 15 to 20 per cent hydrofluoric acid solution maintained at room temperature, followed by 45 minutes in a boiling 10 to 15 per cent sodium dichromate solution saturated with magnesium fluoride. The coating formed by this treatment will vary in color from dark brown to black, depending upon the alloy composition and condition of the bath. It consists essentially of magnesium oxide and complex chromates and dichromates. As the treatment effects no dimensional changes, it can be applied after machining. Castings containing brass, bronze and steel inserts can be satisfactorily treated, but cadmium- or zinc-plated inserts will be attacked by the hydrofluoric acid and must be protected.

A treatment for anodizing magnesium in the same manner as aluminum has been successfully developed. It consists essentially in making the part to be treated the anode in an electrolytic bath. The oxide coating can be applied by either alternating or direct current, and the time required is approximately 30 minutes. The bath contains ammonium sulphate, sodium dichromate and ammonia. It is usually recommended that the parts be thoroughly cleaned before anodizing by immersing for five minutes in a water solution containing 15 to 20 per cent by weight of hydrofluoric acid at room temperature. As yet this process has not been used extensively.

Protection of Copper and Copper Alloys

Generally, copper and its alloys offer good resistance both to atmospheric corrosion and to many corrosive atmospheres, because they are cathodic to most of the common metals and alloys. Under ordinary atmospheric exposure conditions, copper and its alloys slowly assume a black to green tarnish which usually is not objectionable in appearance and offers some added protection. In locations where the concentrations of hydrogen sulphide and sulphur dioxide are high, however, the attack is more serious, and often results in pitting.

Several surface treatments are applicable to copper and its alloys, but their main purposes are to provide a black color for appearance and a good paint base. The coatings do, however, offer some improved corrosion protection, since they are films of cupric oxide.

A treatment which produces a jet black, dull, velvet coating is known as the "Ebonol C" process. It is a very adherent coating of cupric oxide and can be applied to copper and most of its commercial alloys. The treatment consists of immersion in "Ebonol C" solution, maintained at 190 to 215° F. for a sufficient time to produce a uniform black coating. The dimensional changes on parts so treated are negligible, being of the order of a few thousandths of an inch.

Another treatment, known as the "Electro-Jetal" process requires an anodic oxidation to form the cupric oxide coating. The coating so formed is intense black, slightly velvety in character. In improves the corrosion resistance of the base metal, but it can be used only on copper or copper-plated metals. The coating is applied by making the part the anode of an electric circuit suspended in the "Electro-Jetal" bath and anodically treated at 20 to 30 amperes per square foot at 2 to 4 volts until the desired black color is obtained.

The "Bon White" process is used on copper or brass. It is somewhat different from those previously described, in that it results in the formation of a silvery white deposit of metallic tin on the surface of the part. However, it is an immersion treatment, not an electrolytic process. The work to be treated is immersed in an aqueous solution containing sodium cyanide and the "Bon White" paste. A ten-second immersion in this solution, maintained at 70 to 75° F., produces the required coating, which offers some added corrosion resistance.

Protection of Zinc and Zinc Alloys

Since zinc and zinc alloys are very close to aluminum in the galvanic series, they are very much like aluminum in their resistance to corrosion. Zinc withstands ordinary atmospheric corrosion well because of the formation of a protective film probably consisting of zinc oxide or zinc carbonate. The film is smooth and adherent, and forms quickly after the metal is exposed to the atmosphere.

Various surface treatments are commonly applied to zinc and zinc-base alloys to improve their corrosion resistance. The "Cronak" process provides a good corrosion-resistant coating but a poor paint base. Where the latter is desired, the metal should be treated by the "Bonderizing" process already described.

"Cronak" coatings are produced by immersing the part in the "Cronak" solution maintained at 60 to 90° F. for 5 to 30 seconds. The solution contains sodium dichromate and sulphuric acid. The coating produced varies in color from a light, iridescent greenish-yellow to a deep yellow brown. It consists of an insoluble layer and a slightly soluble film, and is composed of chromates and dichromates of zinc plus some soluble alkali-metal dichromates and chromates.

A treatment known as the "Ebonal Z" process offers some improved corrosion resistance to zinc and zinc-base alloys. The côating produced is jet black in color and is probably composed of black molybdenum salts. The process consists of immersion for 3 to 10 minutes in the "Ebonol Z" solution maintained at 180 to 200° F. The coating produced is thin, and the dimensional changes effected are of the order of a few hundred-thousandths of an inch. The process may also be applied to electroplated zinc.

SUMMARY

One who understands the mechanism of corrosion, and knows what conditions, environment, or combinations of metals will cause or accelerate it, is in an excellent position to eliminate, or at least minimize, corrosion by his design and specifications. He can intelligently recommend a treatment or protective coating to be applied to a metal or alloy so that its superior physical or mechanical properties may be utilized, even though its resistance to corrosion may be poor. Listed below are the most important facts for the design and production engineer to keep in mind when recommending materials for construction, so that loss due to corrosion will be kept at a minimum.

(1) Use care in selecting the metals or alloys; wherever possible use those which are as close together as possible in the galvanic series.

(2) Insulate dissimilar metals by chemical surface treatments, electroplated deposits, or paint. Wherever possible, protect both the alloys. If cases exist where it is not practical to do so, it is far better to protect the cathodic than the anodic material.

(3) When necessary to employ combinations of metals which are far apart in the galvanic series, design the part so that the area of the cathodic metal is small and that of the anodic metal large. This will minimize corrosion, since the cathodic area will ordinarily become polarized quickly under corrosive conditions, thus retarding and often stopping the action. For example, if a steel rivet were employed in a "Monel" plate, the small anodic rivet would rapidly disintegrate in the presence of an electrolyte.

This can be realized when we consider that to diminish or stop the process of corrosion, the cathodic area must become polarized or covered with corrosion. Thus, before the comparatively large "Monel" cathode could be covered with a film of gas or corrosion which would retard the corrosion rate, the steel rivet would be seriously attacked. The reverse combination—a "Monel" rivet in a steel plate—would, however, be satisfactory. It is good practice to use the more noble metal for fastenings or other parts in equipment built largely of less corrosion-resistant material.

(4) Iron will not corrode appreciably at normal temperatures in the absence of moisture. Rusting of iron will be slower in slightly alkaline solutions than in neutral or acid solutions.

(5) Discontinuities of any metal surface can result in galvanic corrosion just as much as contact of dissimilar metals. Care should be taken to eliminate or insulate any discontinuities.

(6) Variations in the composition or concentration of a solution in contact with a metal may result in a galvanic cell and cause serious localized pitting. If possible, add inhibitors to the corrosion solution according to the nature of the solution to be inhibited.

(7) Provide all metals which are subject to corrosion (except the most noble metals) with some protective coating, the nature of which will depend upon the environment to be encountered.

(8) Avoid joining materials well apart in the galvanic series by threaded connections, as the threads will probably deteriorate excessively.

(9) Brazed joints should employ a brazing alloy more noble than at least one of the metals to be joined.

Table 112, compiled by E. Thum, shows the corrodibility[13] of some common metals and alloys. The estimated corrosion resistances under different conditions are relative only. In designing equipment, service temperatures are usually the deciding factors.

Figures 105A and 105B are photomicrographs showing intergranular corrosion of nickel shrouding after several years of service in a high-temperature steam turbine in a chemical plant. Figure 105A shows the complete cross-section of the shrouding as removed from the turbine. The holes and pits on the surface and edges are due to actual grains of metal removed during service or during polishing in preparing the specimen for photographing. Figure 105B indicates the complete envelopment of grains by intergranular corrosion products. The material at the grain boundary is probably nickel oxide.

Figure 106 shows the destructive effect of erosion-corrosion on a high-alloy stainless pump impeller after several weeks of service. The form of corrosion designated as erosion-corrosion (by Fontana) often causes unexpected and rapid deterioration of plant process equipment. The rate of

TABLE 112. *Corrodibility of*

Class of Material	Nominal Composition						Atmospheres	
	Carbon	Chromium	Nickel	Silicon	Copper	Other Constituents	Sea Shore	Industrial
Ingot iron or wrought iron	0.03				0.08		P	P
Low C steel	0.10				0.08		P	P
Copper and high tensile steels	0.10				0.25		F	F
Hot galvanized iron & steel							G	G
Calorized iron & steel							G	G
Gray cast iron	2.8 graphite, 0.7 combined carbon						F	FG
High silicon iron	0.60			14.25			E	E
Nickel cast iron	3.30		3.50	1.50			FG	FG
Chromium cast iron	2.50	25.00		2.00			G	G
Ni-Cr-Cu cast iron	3.00	2.00	14.00	1.50	6.00		G	G
Nickel steel: Low Ni	0.18		3.00				FG	FG
High Ni	0.30		28.00				G	G
Chromium steels: 5 % Cr	0.15	5.00				Mo 0.5	F	F
7 % Cr	0.15 max	7.00		0.75		Mo 0.5	F	F
9 % Cr	0.15 max.	9.00		0.50		Mo 1.0	F	F
12 % Cr	0.10 max.	12.00					G	G
17 % Cr	0.10 max.	17.00					G	G
17% Cr, 4 % Mo	0.10 max.	17.00				Mo 4.0	G	G
27% Cr	0.35 max	27.00		0.75		N 0.25	GE	G
Silcrome; (8 % Cr, 3 % Si)	0.45	8.25		3.50			F	FG
Cr-Ni steels: 8-20	0.20	8.00	20.00				G	G
18-12, 2½% Mo	0.15	18.00	12.00			Mo 2.5	E	E
18-8	0.10	18.00	8.00				E	G
18-12	0.10	18.00	12.00				E	G
18-35	0.50 max.	18.00	35.00	1.00			E	G
25-12	0.25 max	25.00	12.00				E	G
25-20	0.25 max.	25.00	20.00	1.50			E	G
Stellite	3.0 max.	30.00				Co 55.0, W 15.0	E	E
Hastelloy A			55.00			Mo 20.0, Fe 20.0	G	G
Hastelloy B			64.00			Mo 28.0, Fe 6.0	G	G
Hastelloy C		14.00	58.00			Mo 17.0, W 5.0, Fe 6.0	E	E
Hastelloy D			85.00	10.0	4.0		G	G
Commercially pure Ni			99.20				E	G
Nickel alloys: Monel metal	0.15		67.50	0.50	28.50	Mn 1.50	E	G
Nichrome, 60-15	0.12	15.00	60.00				E	G
Inconel, 14% Cr		14.00	80.00			Fe 6.0	E	G
80% Ni, 20% Cr		20.00	80.00				E	G
Commercially pure Cu					99.90		G	G
Copper alloys: Red brass					85.00	Zn 15.0	G	G
Tobin bronze					60.00	Zn 39.2, Sn 0.75	G	FG
Phosphor bronze					95.00	Sn 5.0	G	FG
Silicon bronze				3.00	95.00	Mn 1.0 or Zn 1.5, Sn 0.5	G	G
Aluminum bronze			0.50		90.00	Al 9.0, Fe 0.5	G	G
Nickel silver			20.00		75.00	Zn 5.0	G	G
Admiralty metal					70.00	Zn 29.0, Sn 1.0	G	G
Commercially pure Al						Al 99.20	GE	E
Aluminum alloys: 3S						Al 98.8, Mn 1.2	GE	E
Alclad 3S	Duplex product; 10% Al alloy over 3S						E	E
24S-T					4.50	Mn 0.6, Mg 1.5, Al bal	PG	FG
Alclad 24S-T	Duplex product; 5% Al coating over 24S-T						E	E
61S-T		0.25		0.60	0.25	Mg 1.0, Al bal.	GE	E
Commercially pure Mg							G	G
Cast Mg alloys	A S T M AZ63, AZ92, AZ90						F	G
Wrought Mg alloys	A.S T M. M1, AZ31X, AZ61X, AZ80X						G	G
Commercially pure Sn							G	G
Commercially pure Pb					0.06	Pb 99.90	G	G

E - Excellent; almost unlimited service
F - Fair
G - Good: will give good service
P - Poor

Originally compiled (1933) by Jerome Strauss; revised (1946) by E. E. Thum using

Some Common Metals and Alloys[13]

Water						Oxidation Resistance Max Safe Temp. °F.			Fruit, Vegetable Juices	Dairy Products	Other Food Products	Acids Moderate Concentration 5-15%					Alkalies		Salt Solutions Medium Concentration			Hot Sulphite Liquor	Dye Liquor	Refinery Crudes Below 400°F	
Domestic	Mine	Sea	Saline with H_2S	Brackish with HCl	Wet Steam	Oxidizing Gases	Reducing Fuel Gas	Sulphur Rich Gas				HCl	H_2SO_4	HNO_3	Acetic	Phosphoric	1 to 20% Sol	Fused	NH_4Cl	$MgCl_2$	$MgSO_4$			Sweet	Sour
F	P	F	F	F	FG				P	P	P	P	P	P	P	P	G	G	P	FG	FG	P		F	P
F	P	F	F	F	FG	1000	1000		P	P	P	P	P	P	P	P	G	G	P	FG	FG	P		F	P
F	P	F	P	F	FG				P	P	P	P	P	P	P	P	E	G	P	FG	FG	P		F	P
FG	PF	FG	FG	FG	FG				P	P	P	P	P	P	P	P	P	F	P	FG	FG	P		F	P
P	P	P	P	P		1650	1650	1650	P	P	P	P	P	P	P	P	F	F	P	P	P	P	F	G	FG
G	F	F	F	F	F				P	P	P	P	P	P	P	P	G	G	P	FG	FG	P	P	G	F
E	G	E	E	E	E				E	E	E	FG	E	E	G	G	FG	P	G	G	G	P		G	F
F	F	FG	FG	FG	F	1200	1200		F	P	P	P	P	P	P	P	GE	FG	P	FG	FG	P	P	FG	PF
G	G	FG	FG	FG	G	1750	1750	1750	G	G	G	P	P	G	G	F	E	FG						G	G
G	F	G	G	G	G	1400	1400	1200	PF	F	F	F	F	P	FG	FG	FG	E	FG	G	G	PF	F	G	G
F	F	F	FG	F	F				P	P	P	P	P	P	P	P	GE	G	P	FG	FG	P		FG	PF
G	FG	G	G	G	G				F	F	FG	F	FG	P	FG	F	E	G	FG	G	G	P		G	G
F	P	F	P	F	FG	1150	1150	1150	P	P	P	P	P	P	P	P	G	FG	P	P	FG	P	P	G	F
F	P	P	P	P		1250	1250	1200	P	P	P	P	P	P	P	P	G		P	P	F	P	P		G
F	P	P	P	P		1300	1300	1250	P	P	P	P	P	P	P	P	G		P	P	F	P	P		G
G	F	PF	PF	PF	G	1350	1350	1300	G	FG	G	P	P	G	G	F△	G	P	F	F	G	P	F	E	G
G	FG	PG	PG	PG	G	1550	1550	1500	GE	G	GE	P	P	E	E△	P	G	P	FG	G	G	P	F	E	GE
G	FG	PG	PG	PG	G				G	G	G	P	P	G	G	F	G	P	FG	G	G	F		E	GE
E	GE	G	FG	FG	E	1900	1900	1800	E	G	E	P	P	E	F	G	G	P	E	E	E	GE		E	E
F	F	PF	PF	PF	FG	1500			F	F	F	P	P	FG	FG	P	G	P	F	F	FG	P	PG	E	GE
G	FG	PG	F	FG	GE	1500	1500		G	FG	G	P	FG	F	G	FG	E	G	FG	G	G	F		GE	GE
E	E	FE	FE	FE	E				E	E	E	PF	G	E	E	E	E	F	GE	G	G	E		E	E
E	FE	FG	PG	FG	E	1650	1650	1100	GE	E	E	P	PG	E	E	E	E	F	G	G×	G	GE	F	E	E
E	FE	PG	PG	PG	E	1650	1650	1100	E	E	E	P	F	E	G	G	G	F	G	G	G	G		E	E
E	FG	PG	PG	PG	E	2100	2000	1900	E	E	E	F	G	G	G	G	E	G	G	G	G	PG		E	E
E	G	G	PG	G	E	2100	2000		E	E	E	P	P	E	E	E	E	G	G	G×	G	GE	G	E	E
E	G	G	E	G	E	2100	2000			E		P	F	E	G	G	E	FG	G	G	G	G	G	E	E
E	E	E	E	G	E	2100	2100		E	E	E	F	F	FG	E	E	E		G	G	E	E	E	E	E
G	F	G	F	G	E	1400	1800	P	G	G	G	G	G	P	E	E	E	P	G	G	G	P	P	G	G
G	G	G	F	G	E	1400	1800	P	G	G	G	E	E	P	E	E	E	P	E	E	E	P	P	E	E
E	E	E	E	E	E	2100	2100	P	E	E	E	G	E	G	E	E	E	P	E	E	E		E	E	E
G	P	G	F	F	G				G	G	G	G	E	P	E	E	E	P	G	G	E	P	P	E	E
E	FG	FE	FE	FE	E	1900	2300	1000	G		GE	FG	FG	P	FG	FG	E	E	G	G	G	P	G	E	GE
E	PE	GE	GE	GE	E	1000	2000	1000	G		FG	FG	G	P	FG	G	E	E	GE	GE	E	P	E	E	G
E	G	FE	FE	FE	E	2050	1900	P	E	E	E	F	F	F	G	G	G	G	G	E	G	P		E	E
E	G	FE	FE	FE	E	2000	2100	1500	E	E	E	F	F	F	G	G	E	G	G	E	G	P		E	E
E	G	FE	FE	FE	E	2000	2100	1500	E	E	E	FG	FG	G	G	G	E	G	G	E	G	P		E	E
G	FG	G	PF	FG	G				FG	P	FG	PG	FG	P	FG	FG	G	F	FG	G	G	G	FG	FG	PF
FG	FG	G	PF	FG	G				P	P	FG	PF	FG	P	FG	FG	G	F	FG	G	G	G	FG	G	F
FG	F	G	F	FG	G				FG	P	FG	P	F	P	F	F	FG	PF	F	FG	FG	F	F	G	F
G	F	G	FG	G	G				PF	P	F	P	FG	P	FG	FG	G	F	FG	G	G	G	FG	G	F
G	FG	PG	PF	PG	G				F	P	F	F	FG	P	G	G	FG	F	FG	G	G	G	FG	G	F
G	FG	G	G	G	G				F	P	F	F	FG	P	FG	FG	FG	PF	FG	G	G	G	FG	G	FG
G	G	GE	FG	FG	G				FG	PF	G	F	G	P	FG	FG	E	FG	G	G	G	FG	FG	G	FG
G	FG	FG	FG	FG	G				FG	P	FG	P	FG	P	FG	FG	FG	F	FG	G	G	F	FG	G	F
FG	PG	G	G	PG	G	600	800	800	F	G	G	P	F	P	G	P	P	P	F	G	G	F	FG	E	E
FG	PG	G	G	PG	G	800	800	800	G	GE	GE	P	F†	P‡	Gǂ	P	P	P	F	G	G	F	FG	E	E
GE	PG	GE	GE	PG	G	800	800	800	FG	FG	G	P	F†	P‡	Gǂ	P	P	P	F	GE	GE	F	FG	E	E
PF	P	P	P	PF	F	P	P	P	F	F	F	P	P	P	F	P	P	P	P	P	P	F	P	F	F
GE	PG	GE	GE	PG	G	300	300	300	FG	FG	G	P	P†	P‡	Fǂ	P	P	P	F	GE	GE	F	FG	E	E
FG	PG	G	G	PG	G	800	800	800	G	GE	GE	P	F†	P‡	Gǂ	P	P	P	F	G	G	F	FG	E	E
F	P	P	P	P	P		400	400	P	P	PE	P	P	P	P	F	E		P	P	P	P	PE		
F	P	P	P	P	P		400	400	P	P	PE	P	P	P	P	F	E		P	P	P	P	PE		
F	P	F	F	F	P		400	400	P	P	PE	P	P	P	P	F	E		P	P	P	P	PE		
E		G		G	G				G	G	G	P	P	P	P	P	F	P				P			
PG	G	G		G	G				P	P	P	F	E	P	P	G	P	P	FG	FG	G	G	F		

△ Below 50°C

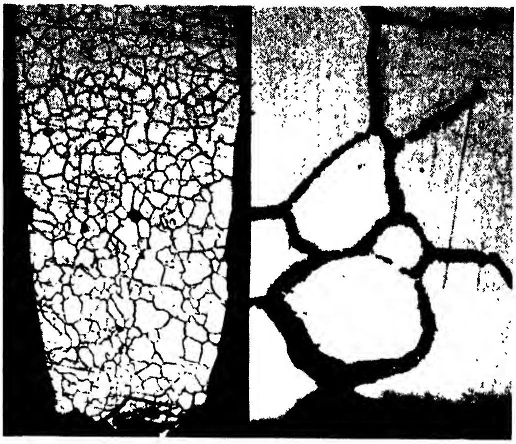
× May crack under certain conditions

† GE for fuming H_2SO_4

‡ E for HNO_3 above 80%

ǂ E for glacial acetic

data furnished by several specialists. "*Metal Progress Data Sheet*," Nov. 1946.



(*Courtesy M. G. Fontana*)

Figure 105A. (50X). Figure 105B. (500X).

Intergranular corrosion of nickel shrouding.

(*Courtesy M. G. Fontana*)

Figure 106. Erosion-corrosion of pump impeller.

corrosion can be greatly accelerated when mechanical or abrasive conditions are present, such as liquids moving at substantial velocities, solids in suspension (that is, slurries), marked turbulence, and impingement.

Figure 107 shows pitting on a copper pipe which handled domestic fresh water.

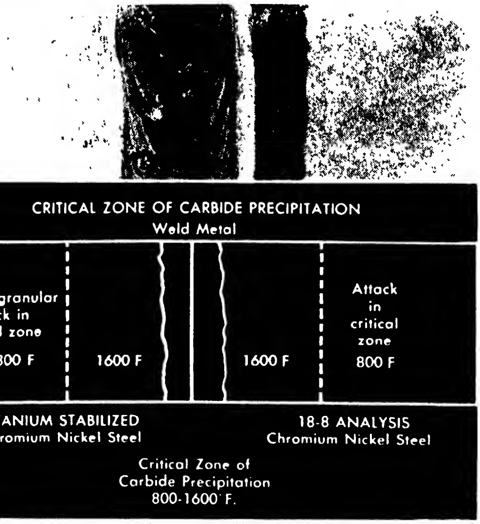
Figure 108 shows a section of a brass pipe after service in handling water. The dark inner portion of the pipe is the dezincified area. The outer portion is the unaffected yellow brass. Dezincification has progressed uniformly through approximately half the wall thickness of the pipe.

(*Courtesy M. G. Fontana*)

Figure 107. Pitting of copper pipe by domestic water.

Figure 108. Uniform dezincification of brass.

(*Courtesy M. G. Fontana*)



(*Courtesy Titanium Alloy Mfg. Company, Division National Lead Co., Niagara Falls., N. Y.*)

Figure 109. Weld decay zone in standard stainless steel.

Figure 109 (top) shows intergranular corrosion in 18–8 stainless steel as a result of welding and subsequent exposure to a corrosive environment. A plate of standard stainless steel and a titanium-stabilized stainless steel were welded together, and the photograph shows the top view of the weld. The localized corrosion of the standard stainless steel just to the right of the weld and the complete absence of corrosion of the titanium-stabilized stainless steel at the left of the weld are readily apparent. Below is a schematic sketch of the photograph, showing the critical zone of carbide precipitation.

References

1. Whitney, "Corrosion of Iron," *J. Am. Chem. Soc.* (1903).
2. Bancroft, "The Electrolytic Theory of Corrosion," *J. Phys. Chem.* (August, 1924).
3. "Symposiums on Protecting Metals Against Corrosion," A.S.T.M., 1938.
4. Mears and Brown, "Causes of Corrosion Currents," *Ind. Eng. Chem.* (August, 1941).
5. Burns, "Mechanism of Corrosion," *A.S.T.M. Bulletin,* No. 126 (January, 1944).
6. Brown, "Galvanic Corrosion," *A.S.T.M. Bulletin,* No. 126 (January, 1944).
7. Fontana, M., "Corrosion," *Ind. Eng. Chem.,* (July, August and September, 1947).
8. "Corrosion," International Nickel Co. bulletin.
9. Burns and Schuh, "Protective Coatings for Metals," New York, Reinhold Publishing Corp., 1939.
10. Leighou, "Chemistry of Engineering Materials," New York, McGraw-Hill Book Co.
11. McKay and Worthington, "Corrosion Resistance of Metals and Alloys," Reinhold Publishing Corp., 1936.
12. Speller, F., "Corrosion, Causes and Prevention," New York, McGraw-Hill Book Co.
13. Thum, E., "Corrodibility of Some Common Metals and Alloys," *Metal Progress Data Sheet* (November, 1946).
14. Uhlig, H., "Corrosion Handbook," John Wiley & Sons, Inc., 1948.
15. "Corrosion of Metals," American Society for Metals, 1946.

Chapter XV

Highly Corrosion-Resistant Materials

In designing, constructing and manufacturing parts and equipment for use in the chemical industries, the materials selected must have the chemical, physical and mechanical properties necessary for satisfactory life and performance in service. They must be economical, and available in the required forms and condition for processing or fabrication. Moreover, the ease with which they can be machined, stamped, spun, drawn, forged, heat-treated or otherwise processed affects the overall cost of the finished product.

In many applications only certain materials can be used because of their special and unusual properties; in other cases more costly alloys may be preferred to cheaper alloys for increased service life and better performance, thus compensating for the original high cost. It would be a simple matter to select the strongest metal, or the hardest, toughest, or most corrosion-resistant alloy. However, when the service conditions are unusually severe, it is a question of searching for the metal or alloy having the most desirable combination of essential qualities.

The economic importance of corrosion in industry is commonly known. Corrosion is generally acknowledged to play an important, if not a dominant part, in the commercial success of many processes. Therefore, where corrosive materials are produced or are used in the production of other materials, it has been the part of economy to seek those which will serve usefully without excessive costs due to replacement and without danger of contaminating the products.

Nickel-Base Alloys *

Nickel is one of the most important metals in modern engineering design and construction. Its great demand in many fields of application is indicated by the fact that it ranks ninth in the world's consumption of metals. Nickel is a white, malleable, non-corrodible metal, having high strength, relatively high heat conductivity and good heat-resisting properties. These characteristics make it desirable for many uses where other metals are not suitable.

---

* This section on nickel-base alloys was previously published by the author in *Materials and Methods*, December, 1946.

As an alloying element in iron, steel, copper and aluminum, the improvements imparted by nickel are well recognized and established. In small percentages it toughens and strengthens iron, steel and copper. It makes aluminum maintain strength at elevated temperatures. In larger quantities, especially when combined with chromium, it makes iron and steel corrosion- and heat-resistant. Nickel also imparts special magnetic properties to iron and has a marked effect on its coefficient of expansion.

The high-nickel alloys, *i.e.*, the nickel-base alloys containing more than 50 per cent nickel, are in a class by themselves, as they have physical and mechanical properties not readily duplicated by other base alloys. They are tougher, stronger and harder than copper and aluminum alloys, and are as strong as alloy steel. They are highly resistant to corrosion by most of the normal and special corroding agents found in industries, and they resist oxidation and scaling at elevated temperatures. All the high-nickel alloys are characterized by exceptionally good strength, toughness and high ratios of strength to ductility in all conditions of mechanical and thermal treatments. Some of these alloys respond to a precipitation-hardening heat treatment for maximum properties. All, with few exceptions, can be cold-worked, with subsequent increase in strength and hardness.

Fabrication methods in general are more similar to those used for steel than for the softer non-ferrous metals. High-nickel alloys can be readily hot-worked; but this must be done in sulphur-free atmospheres because of the embrittling effect of sulphur on nickel. During cold-working operations, such as deep-drawing and spinning, more frequent anneals are required between operations to remove the rapid hardening and stiffening effect of the cold work. For either hot or cold working, heavier equipment is required than for steel. These alloys are not difficult to cut, but their high strength and ductility require machining procedures somewhat different in detail from those employed for less tough metals and alloys. Several of the alloys have been modified in composition to make them more free-cutting and also suitable for automatic screw machines. These can be readily joined to similar metals or dissimilar metals by normal procedures of soldering, brazing and welding.

Because of their combination of excellent strength and high corrosion resistance, high-nickel alloys are extensively used in equipment for handling, transporting and storing acids, alkalies and other corrosive materials used in the production of steel, oil and coal products, paper and pulp, paints and varnishes, drugs, explosives, rubber, soap, textiles and commercial chemicals. They are used for equipment for food processing, milk and dairy products, laundry and dry cleaning, leather tanning and pickling. They find wide use in architectural trim, marine applications, aircraft and railroad service. Agitator units, autoclaves, tanks, kettles, evaporators, mixers, pickling vats, heat exchangers, coils and pipe are just a few items listed to illustrate the type of equipment for which high-nickel alloys are especially well suited.

Their high heat resistance and ability to maintain strength at elevated temperatures are utilized in parts and equipment requiring resistance to oxidation, creep and scaling, *e.g.*, heat-treating boxes, carburizing and nitriding containers, furnace parts and aircraft engine exhaust manifolds. Some of these alloys have exceptional magnetic and other properties, which makes them suitable for electrical instruments and equipment. Several of the wrought alloys are used for springs, especially in applications at elevated temperatures where failures are ordinarily caused by corrosion or heat.

Classification of Available Materials. The mill products of the high-nickel alloys have been classified by Mudge[3] into six main groups according to their composition. The kind and quantity of alloying element or elements added to the nickel determine in which group the alloys belong. This classification is shown in Table 113.

Table 113. *Classification According to Composition*

Group I.	Nickel 93.5 to 99.5% nickel (and a maximum of 4.5% manganese)
Group II.	Nickel-Copper 63 to 70% nickel, 29 to 30% copper
Group III.	Nickel-Silicon 85% nickel, 10% silicon
Group IV.	Nickel-Chromium-Iron 54 to 78.5% nickel, 12 to 18% chromium, 6 to 28% iron
Group V.	Nickel-Molybdenum-Iron 55 to 62% nickel, 17 to 32% molybdenum, 3 to 22% iron
Group VI.	Nickel-Chromium-Molybdenum-Iron 51 to 62% nickel, 15 to 22% chromium, 5 to 19% molybdenum, and 3 to 8% iron

The trade mark alloys which fall into the above six groups and their nominal compositions are shown in Table 114. The five grades of nickel, the six "Monels," and the one grade of "Inconel" are products of the International Nickel Co., Inc. The four "Hastelloy" alloys are manufactured by the Haynes-Stellite Co., and the two "Chlorimet" alloys by the Duriron Co. The "Illium" alloy is manufactured by the Burgess-Parr Co. However, the 60 nickel, 15 chromium type of alloy comprises a large number of alloys under specific trade names of their manufacturers; some of these are "Midvaloy BTG," "B & W 700" and "B & W 701," "Firearmor A" and "Fire-

TABLE 114. *Nominal Chemical Composition*

Material	Ni* (%)	Cu (%)	Fe (%)	Mn (%)	Si (%)	Cr (%)	Mo (%)	C (%)	Other elements (%)
"A-Nickel"	99.4	0.1	0.15	0.2	0.05	—	—	0.10	———
"L-Nickel"	99.5	0.02	0.05	0.2	0.15	—	—	0.01	———
"Duranickel"	93.5	—	0.35	0.30	0.5	—	—	0.15	4.5 aluminum
"D-Nickel"	95.2	0.05	0.15	4.5	0.05	—	—	0.10	———
"E-Nickel"	97.7	0.05	0.10	2.0	0.05	—	—	0.10	———
"Monel"	67.0	30.0	1.4	1.0	0.1	—	—	0.15	———
"R-Monel"	67.0	30.0	1.7	1.1	0.05	—	—	0.10	0.035 sulphur
"K-Monel"	66.0	29.0	0.9	0.85	1.0	—	—	0.15	2.75 aluminum
"KR-Monel"	66.0	29.0	0.9	0.85	1.0	—	—	0.30	2.75 aluminum
"H-Monel"	65.0	29.5	1.5	0.9	3.0	—	—	0.30	———
"S-Monel"	63.0	30.0	2.0	0.9	4.0	—	—	0.10	———
"Inconel"	78.5	0.2	6.5	0.25	0.25	14.0	—	0.08	———
60Ni–15Cr	62^{-}	—	bal.	0.1^{-}	1.0^{-}	12^{-}	—	0.06^{-}	———
Type Alloy	54	—	—	1.0	1.5	20	—	1.0	———
"Illium G"	58.0	6.0	6.0	1.25	0.65	22.0	6.0	0.20	Tungsten
"Hastelloy A"	57.0	—	20.0	2.0	1.0	—	20.0	0.15	———
"Hastelloy B"	62.0	—	6.0	1.0	1.0	—	30.0	0.15	———
"Hastelloy C"	55.0	—	6.0	1.0	1.0	15.0	17.0	0.15	5.0 tungsten
"Hastelloy D"	85.0	3.0	—	1.0	10.0	—	—	—	1.0 aluminum
"Chlorimet 2"	63.0	—	3.0	1.0	1.0	—	32.0	0.15	———
"Chlorimet 3"	60.0	—	3.0	1.0	1.0	18.0	18.0	0.07	———

* The nickel values shown in the above table include a small amount of cobalt, approximately 0.75% of the nickel content. ("Duranickel" was formerly "Z-Nickel").

armor B," "Amsco F5" and "Amsco F6," "Thermalloy A," "Tophet C," "Chromel C," "Nichrome," and many others.

Another group of alloys of the 80 nickel, 20 chromium type has been developed particularly for electrical resistance wire and heating elements at service temperatures up to 2100° F. They combine high electrical resistance and low temperature coefficient with an oxidation resistance of a high order. They also retain their strength well at high temperatures. They are sold under a variety of trade marks of their respective manufacturers, such as "Chromel A," "Nichrome V," "Tophet A" and "Alray A."

Still another group comprises the nickel-iron alloys of 70 to 85 per cent nickel content used as electromagnetic materials in electrical and magnetic equipment. These alloys have high magnetic permeability after proper heat treatment. They are discussed in detail in the chapter on Magnetic Materials.

There are five specific grades of commercial nickel, namely, "A Nickel," "D Nickel," "E Nickel," "L Nickel," and "Duranickel," each having a definite chemical composition for specific propertes and applications. The commercially wrought form of nickel is known as "A Nickel" and is generally referred to as "nickel" to distinguish it from electrolytic nickel (99.95 per cent pure) and from nickel-base materials containing minor quantities of alloying elements which are added to impart special properties. "D Nickel" and "Duranickel" are two such special alloys, but "L Nickel" is a low-carbon grade of "A Nickel," commonly known as "carbon-free nickel" of 0.02 per cent maximum carbon content, used particularly for difficult deep-drawing and spinnng operations.

"A Nickel" is the basic material and is the commercially pure, malleable material having an average nickel content of 99.4 per cent, which includes less than 1 per cent cobalt; the latter is counted as nickel because its effect upon the significant properties of nickel is slight. The cast form of commercial nickel contains about 1.5 per cent silicon to improve its fluidity and castability. Wrought nickel combines excellent mechanical properties with good corrosion resistance. It responds readily to all commercial fabricating processes and practices, and can be joined by all regular methods of soldering, brazing and welding. Its mechanical properties are similar to those of mild steel. It resists hydrogen chloride, chlorine, caustic soda, oxidation and scaling, retains its strength to an excellent degree at elevated temperatures, and its ductility, toughness and strength at sub-zero temperatures. In fact the yield point and elongation are 40 to 50 per cent higher at − 300° F. than at room temperature. It has excellent corrosion-resisting properties and is free from season cracking and other forms of stress corrosion in atmospheric conditions.

Commercial nickel is used where strength combined with resistance to corrosion and oxidation is required. The chemical, soap and allied industries use rolled nickel for the construction of evaporators, jacketed kettles, tanks, heating coils and other processing equipment. Support wires and other parts of incandescent lamps and hot cathodes in radio tubes are made of nickel.

"L Nickel" has essentially the same nominal composition as "A Nickel," with the exception that the carbon content is kept to a minimum (0.01 to 0.02 per cent). It is softer than the regular grade and does not work-harden as rapidly. Its yield strength and elastic limit are lower than those of "A Nickel," and the ductility is greater. For these reasons the "carbon-free" grade of nickel is often preferred for the fabrication of spun or stamped articles. It is particularly used for applications which require resistance to oxidizing atmospheres up to 2000° F., such as nickel crucibles and combustion dishes.

"D Nickel" and "E Nickel" generally conform to the composition of "A Nickel," the most important difference being the inclusion of about 4.5 per cent and 2.0 per cent, respectively, of manganese replacing a like amount of nickel. The manganese addition increases resistance to atmospheric attack and to sulphur compounds at elevated temperatures to a point higher than that of "A Nickel." "D Nickel" is used extensively for spark plug electrodes, ignition tubes, radio tube grid wires, and for marine boiler refractory bolts. "E Nickel" wire is found useful for furnace lead-in wires and support wires in incandescent lamps.

"Duranickel" is a wrought, age-hardenable alloy containing approximately 93.5 per cent nickel; it has good strength, hardness and high resistance to corrosion. It work-hardens much more rapidly than "A Nickel" even prior to heat treatment, which does not destroy the effect of cold-working during fabrication, but supplements it to produce unusually good mechanical properties. The heat treatment is of the precipitation-hardening type and is carried out below the annealing temperature. Tensile strengths as high as 240,000 psi. and hardnesses up to Rockwell 45 C can be obtained for heat-treated spring temper wire of small diameter. "Duranickel" possesses the ability, characteristic of all nickel-base alloys, to retain its impact strength and ductility at temperatures down to that of liquid air. "Duranickel" is suitable for such applications as coil and flat springs, diaphragms, radio antennae, safety tools, extrusion dies for plastics, pump parts and other applications requiring a material combining high corrosion resistance with unusually high mechanical properties. It is also used for parts to resist very high temperatures.

Nickel-Copper Alloys. The second class of commercial nickel-base alloys is the so-called "Monel" type, containing approximately two-thirds nickel and one-third copper. There are six grades of such alloys: "Monel," "R Monel," "K Monel," "KR Monel," "H Monel" and "S Monel." The nominal compositions of these alloys are shown in Table 114 and their typical physical and mechanical properties in Tables 115, 116, 117 and 118. These alloys are all strong, tough, rustproof and highly resistant to corrosion.

"Monel" is the most important alloy in this group. Its combination of high strength, ductility and excellent resistance to corrosion makes it a general-purpose rather than a specialized material. "Monel" is more resistant than nickel under reducing conditions and than copper under oxidizing conditions. It cannot be hardened by heat treatment, but its strength and hardness can be increased by cold-working. The properties of "Monel" are not much affected by temperatures up to 750° F. Short-time tests show a practically straight-line drop in tensile strength from 70,000 psi at 800° F. to 15,000 psi at 1500° F. Creep stress required to produce 0.1 per cent elongation in 1000 hours is 31,000 psi at 750° F., 24,000 psi at 800° F. and 12,500 psi at 900° F. Its toughness is not diminished by lowering the temperature. Izod impact tests made at −300° F. yield about the same values as at room temperature. At the low temperatures the tensile strength and yield strength are approximately 40 per cent higher.

"Monel" has high resistance to corrosion by salt water, dilute sulphuric acid and strong caustic soda. It also resists cold hydrochloric acid, phosphoric acid, hydrofluoric acid, various organic acids and chlorinated hydrocarbons. However, it is not resistant to nitric acid, sulphurous acid and ferric chloride. It is used for all applications requiring strength and high resistance to corrosion, as in building construction, vats, tanks, kettles, valves, pumps, shafts and propellers in marine industries, oil refining and chemical plant equipment, paper and pulp equipment and untold other products.

"R Monel" is a free-cutting grade of "Monel" obtained by adding about 0.035 per cent sulphur to the alloy. It was developed primarily to improve the machinability of "Monel" for automatic screw-machining. The additional sulphur does not impair or affect the strength or corrosion resistance of the alloy. It can be fabricated readily by cold-forming operations, but is not generally recommended for hot-forming. It is used for bolts, screws, precision parts and many other items requiring considerable machining.

"K Monel" and "KR Monel" are non-magnetic, age-hardening alloys of high strength and hardness comparable to those of heat-treated alloy steel. They are highly corrosion-resistant. These alloys are of the "Monel" composition with about 2.75 per cent aluminum. "KR Monel" is similar in composition to "K Monel," but has a higher carbon content to facilitate machining. The two alloys are available in wrought form only, especially as hot-rolled or forged rods, tubes, cold-drawn rods and wires and strip of various tempers. They are suited for applications requiring the high re-

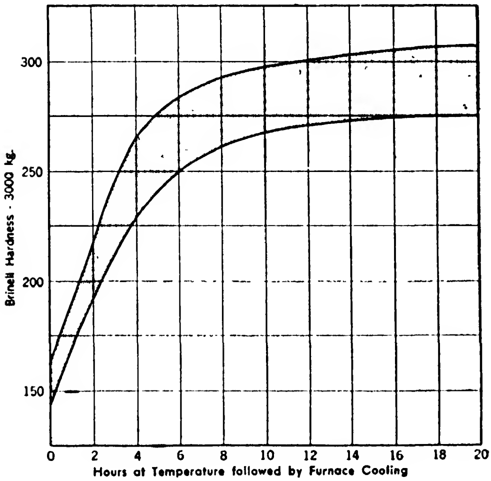


Figure 110. Hardening of "K" Monel. Effect of time at temperature (1080° to 1100° F.). Shaded area indicates range for commercial hot-rolled rods or forgings.

(Courtesy International Nickel Co., New York, N. Y.)

sistance to corrosion of "Monel" but higher mechanical properties, such as turbo-pump shafts, marine pump shafts, steam valve disks and seats, hydraulic valves, springs, wearing sleeves, liners, surgical blades, etc. Their non-magnetic properties are the basis of applications for high-strength parts of oil-well survey equipment.

"H Monel" and "S Monel" are two cast alloys containing silicon for castability. The former, with 3 per cent silicon, provides increased, but not maximum, hardness, with adequate ductility. It is used for parts requiring corrosion and erosion resistance where stresses are high, as in cast turbine nozzles. "S Monel," with 4 per cent silicon, can be age-hardened to 350 Brinell and has good resistance to galling and erosion. The material is particularly suitable for valve seats and plugs, sliding and other moving elements, bushings and disks for high-temperature steam, pump liners and sleeves that must withstand severe abrasion and corrosion.

Nickel-Silicon Alloys. "Hastelloy D" is the best-known commercial alloy falling in the third group of nickel-base alloys. It contains about 10 per cent silicon and small percentages of copper, aluminum and manganese. It is strong, tough and extremely hard. It has properties similar to a high grade of alloy cast iron and is not workable. Because of its high hardness (about 360 Brinell) it can be machined only with great difficulty and must be finished by grinding. Its chief characteristic is its exceptional resistance to corrosion in hot or cold sulphuric acid, acetic acid, formic acid and phosphoric acid. However, it is not resistant to strong oxidizing acids. "Hastelloy D" is a cast alloy and is well suited for use in equipment where resistance to sulphuric acid and sulphuric anhydride is essential. It can be used for kettles, evaporators, reaction vessels, mixers, pipe lines and fittings. This alloy is supplied as castings and as cast welding rod.

Nickel alloys with smaller percentages of silicon (less than 3 per cent) are sometimes used in wire or filament form for electronic tube cathodes and as spark plug materials. The other grades of nickel-base alloys having small percentages of silicon are not included in this group, since the silicon is not present as the major alloying element.

Nickel-Chromium-Iron Alloys. The fourth class of nickel-base alloys comprises those containing large percentages of chromium and iron as alloying elements. There are two types of alloys in this group, the 78 nickel, 14 chromium type, represented by "Inconel," and the 60 nickel, 15 chromium type, represented by a large number of cast and wrought alloys of various manufacturers. "Inconel" has the highest nickel content of all the alloys in this group, approximately 78.5 per cent nickel, while the other alloys of this type have a lower nickel range of 54 to 62 per cent, but with larger percentages of chromium and iron.

The 60 nickel, 15 chromium type has good resistance to oxidation, heat fatigue and to carburizing gases. It is used widely in cast and wrought form for heat-treating equipment, carburizing and nitriding containers, furnace parts, heating elements and other equipment that must withstand temperatures up to 1700° F. and must be free from scaling and intercrystalline attack.

"Inconel" combines the inherent corrosion resistance, strength and toughness of nickel with the extra resistance to atmospheric and high-temperature oxidation that is imparted by chromium. It resists the attack of such corrosives as caustic soda, hot fatty acids, dilute hydrochloric acid, nitric acid and other oxidizing liquids. The 60 nickel, 15 chromium type of alloys have almost similar corrosion resistance but are not as effective. The unmatched ability of "Inconel" to withstand repeated heating and cooling in the range of 0 to 1600° F. without becoming embrittled makes it the outstanding alloy for exhaust manifolds of airplane engines, for sheathing electric heating elements and for hot upset-head bolts that are used to reinforce the linings of fireboxes on ships. Its high corrosion resistance makes it suitable for the construction of brine-jacketed tanks and cooling equipment used for processing milk and milk products by the dairy industry, food-processing equipment, heaters and condensers in the chemical industries, and equipment in allied industries.

In addition to high corrosion resistance, "Inconel" possesses a desirable combination of high strength and workability, both hot and cold. Tensile strengths reach as high as 185,000 psi in heavily cold-worked wire. This alloy is excellent spring material, especially at elevated temperatures, since it can be used up to 900° F. without losing its spring properties. "Inconel" exhibits excellent resistance to so-called relaxation of load loss when subjected to such high temperatures while under high stress. The springs are usually heated after forming for one hour at 900° F. for best resistance to fatigue and to high-temperature exposure.

Gas welding wire and flux weldings electrodes of these materials are supplied for welding of the alloys.

"Inconel X" is an age-hardenable "Inconel" and is one of the so-called "super-alloys." It was developed during the war for gas-turbine, supercharger, and jet-propulsion parts and is available now in forgings, bar stock, and wire. The alloy has good resistance to oxidation and high strength at elevated temperatures. Its stress-to-rupture strength, 1,000 hours at 1500° F., is in the range of 18,000 to 20,000 psi.

Nickel-Molybdenum-Iron Alloys

The alloys of the fifth class contain large percentages of molybdenum and iron as alloying elements, and are comparable in strength and ductility to alloy steel. Three well known alloys, "Hastelloy A," "Hastelloy B" and

"Chlorimet 2," fall into this group and are characterized by their high resistance to corrosion in hydrochloric acid and wet hydrogen chloride gas; "Hastelloy B" is preferred for boiling acid. Maximum corrosion resistance, however, is developed when the materials are in the soft condition obtained by quenching from 2100 and 2150° F. Since the "Hastelloys" are austenitic they will not respond to age-hardening heat treatment, but can be cold-worked for increased hardness. "Hastelloy B" is richer in molybdenum and nickel than "Hastelloy A" and consequently has better mechanical properties and superior corrosion resistance. "Hastelloy A" resists hydrochloric acid at moderate temperature and dilute sulphuric acid. "Hastelloy B" has better corrosion resistance to boiling hydrochloric acid and sulphuric acid.

The "Hastelloys" are supplied in both the cast and wrought iron forms. They find wide use in the chemical and allied industries for equipment to handle, transport and store acids and other corrosive materials. They are used for agitators, mixers, kettles, condensers, heat exchangers, dryers, evaporators and similar equipment.

"Chlorimet 2" is a nickel-molybdenum cast alloy containing approximately 63 per cent nickel, 32 per cent molybdenum and 3 per cent maximum iron. It has good resistance to hydrochloric acid of all concentrations and temperatures. It is recommended for use with all concentrations of sulphuric acid up to about 176° F. and for concentrations up to about 60 per cent at boiling temperatures.[6]

"Chlorimet 2" can be age-hardened to 500 Brinell by water-quenching from 2050° F., followed by an aging treatment at 1290° F. It is supplied only in the cast form and is used chiefly for pumps and valves.

Nickel-Chromium-Molybdenum-Iron Alloys

"Hastelloy C" and "Illium G" are in the sixth group of alloys which contain large percentages of chromium, molybdenum and iron with nickel. They are especially characterized by their high corrosion resistance to oxidizing acids and mixtures, such as nitric, chromic and sulphuric acids, copper sulphate, etc. They are somewhat hard, and while difficult to hot- and cold-work, are available in several wrought forms as well as the more common castings. Their machinability can be improved by air-cooling from the annealing temperature of 2150 to 2200° F. Welding can be done by either the oxy-acetylene or electric-arc method. "Hastelloy C" responds to age-hardening heat treatment for increased strength and hardness. Both alloys have high resistance to thermal shock.

These alloys are used in industries requiring a strong alloy to resist corrosion in highly oxidizing acids and such oxidizing agents as free chlorine, bleaching compounds, and the like. They are used extensively for pump and valve parts, spray nozzles, piping and similar parts.

"Hastelloy C" can be obtained, in addition to castings, in plate, sheet, welded tubing and cast welding rod. "Illium G" is available only in cast forms as castings, hardware, bar stock, centrifugally cast pipe and welding rod.

"Chlorimet 3" is a nickel-molybdenum-chromium alloy containing approximately 60 per cent nickel, 18 per cent molybdenum, 18 per cent chromium, and 3 per cent maximum iron. It is particularly useful for handling wet chlorine and hypochlorites and for other oxidizing conditions. It is resistant to sulphuric acid solutions up to 35 per cent in concentration at temperatures up to about 176° F., and to a variety of acid chloride salts. It is furnished only in the cast form and is used chiefly for pumps and valves.[6]

Clad Plate

Nickel-clad, "Monel"-clad and "Inconel"-clad steel plates are also available. Clad plate is steel plate, usually "flange" quality, protected on one or both sides by a dense, homogeneous layer of nickel, "Monel" or "Inconel." The material is bonded firmly to the steel plate by hot-rolling and does not separate during fabrication or forming operations, nor during pressure and temperature changes.

The thickness of clad is a substantial portion of the total plate thickness. The composite plate, having a total thickness of $\frac{3}{16}$ inch or more, is produced with thickness of cladding of 5, 10, 15 and 20 per cent. The 5 per cent cladding is used only on $\frac{1}{2}$ inch or heavier plate. The choice among the three compositions and thicknesses of cladding to meet particular corrosive conditions is governed by service requirements. The availability of wide and thick clad plates makes possible the construction of equipment such as storage tanks, evaporators and tank cars with a corrosion-resistant inner surface free from the many disadvantages of thin, loose linings.

The material responds readily to hot- and cold-forming, spinning, pressing, and bending. Therefore, any desired shape or form can be made in clad material, especially since electric-arc welding can be done efficiently. In welding, the steel side of the clad plate should be welded with a steel electrode and the clad side with the appropriate nickel or nickel alloy welding rod.

PHYSICAL CHARACTERISTICS

The most important physical constants of the wrought and cast materials are shown in Tables 115 and 116. The specific gravity of each of these high-nickel alloys exceeds that of steel and is about the same as that of copper alloys. The melting points are lower than for steel but higher than for copper alloys, while the electrical resistivity is much higher than that of

TABLE 115. *Physical Constants of Wrought Materials*

Material	Specific gravity	Melting point (° F.)	Thermal conductivity Btu/sq. ft./hr./° F./in.	Specific heat Btu/lb./° F.	Electrical resistivity ohms/cir. mil foot	Modulus elasticity 10^6 psi.
"A Nickel"	8.89	2,615–2,635	420	0.130	57	30
"L Nickel"	8.89	2,615–2,635	420	0.130	—	30
"Duranickel"	8.75	2,615–2,635	420	0.130	260	30
"D Nickel"	8.78	2,600	335	0.130	110	30
"E Nickel"	8.68	2,600	335	0.130	85	30
"Monel"	8.84	2,370–2,460	180	0.130	290	26
"R Monel"	8.84	2,370–2,460	180	0.130	—	26
"K Monel"	8.47	2,400–2,460	130	0.130	350	26
"KR Monel"	8.47	2,400–2,460	130	—	—	26
"Inconel"	8.51	2,540–2,600	104	0.010	590	31
60Ni–15Cr	8.2–8.6	2,450–2,550	95–100	—	675	31
"Hastelloy A"	8.80	2,370–2,425	116	0.094	760	27
"Hastelloy B"	9.24	2,410–2,460	78.5	0.091	813	30.8
"Hastelloy C"	8.94	2,320–2,380	87	0.092	800	28.5

TABLE 116. *Physical Constants of Cast Materials*

Material	Specific gravity	Melting point (° F.)	Thermal conductivity Btu/sq. ft./hr./° F./in.	Specific heat Btu/lb./° F.	Electrical resistivity ohms/cir. mil ft.	Modulus elasticity 10^6 psi.
"A Nickel"	8.34	2,540–2,600	410	0.130	125	21.5
"Monel"	8.63	2,400–2,450	180	0.130	320	18.5
"H Monel"	8.48	2,350–2,400	180	0.130	370	20.0
"S Monel"	8.36	2,300–2,350	180	0.130	380	21.0
"Inconel"	8.3	2,500–2,550	—	0.110	—	22.7
60Ni–15Cr	8.3–8.5	2,450–2,550	25–100	—	675	30–31
"Hastelloy A"	8.8	2,370–2,425	116	0.094	760	27.0
"Hastelloy B"	9.24	2,410–2,460	78	0.091	813	30.8
"Hastelloy C"	8.94	2,320–2,380	87	0.092	800	28.5
"Hastelloy D"	7.8	2,030–2,050	145	0.109	680	28.9
"Illium G"	8.31	2,375	—	0.105	735	—

copper, iron and steel. As reported by the International Nickel Co., the modulus of elasticity of their alloys is in general lower for the cast than for the wrought material.

Mechanical Properties. Tables 117 and 118 show the mechanical properties of the high-nickel alloys in the cast and wrought condition. The values are the maximum and minimum properties that can be obtained in the different conditions of temper and treatment. For more detailed and

TABLE 117. *Mechanical Properties of Wrought Materials*

Material	Yield strength 0.2% offset psi. 10^3	Tensile strength psi 10^3	Elongation in 2 in. %	Reduction area %	Brinell Hardness	Charpy impact ft.-lb.
"A Nickel"	15–155	60–165	50–2	75–50	90–230	222–195
"L Nickel"	15–25	55–75	55–35	75–50	25–55(a)	——
"Duranickel"	30–150	90–250	50–2	65–15	140–380	240–36(b)
"D Nickel"	35–125	75–140	50–2	75–60	140–230	——
"E Nickel"	35–80	75–100	40–25	75–60	140–190	——
"Monel"	25–160	70–170	50–2	75–50	110–250	220–150
"R Monel"	25–130	70–140	50–4	70–50	110–230	196–140
"K Monel"	40–175	90–200	45–2	70–25	140–320	170–42(b)
"KR Monel"	40–175	90–200	45–2	70–25	140–320	——
"Inconel"	25–175	80–185	50–2	70–40	120–290	77–62 (c)
60Ni–15Cr	40–160	80–175	35–0.5	70–40	180–235	78–68 (c) 40–34 (c)
"Hastelloy A"	47–52	110–120	48–40	54–40	200–215	——
"Hastelloy B"	60–65	130–140	45–40	45–40	210–235	——
"Hastelloy C"	55–65	115–128	50–25	—	160–210	——

(a) Rockwell B
(b) Specimens fractured completely
(c) Izod Impact

TABLE 118. *Mechanical Properties of Cast Materials*

Material	Yield strength 0.2% offset psi. 10^3	Tensile strength psi. 10^3	Elongation in 2 in. %	Brinell Hardness	Izod impact ft.-lb.
"A Nickel"	20–30	45–60	30–15	80–125	90–75
"Monel"	32.5–40	65–90	45–25	125–150	80–65
"H Monel"	45–75	90–115	20–10	175–250	45–35
"S Monel"	80–115	110–145	4–1	275–375	9–1
"Inconel"	30–45	70–95	30–10	160–190	85–70
60Ni–15Cr	40–60	60–70	5–2	170–210	——
"Hastelloy A"	43–45	69–78	12–8	155–200	35–25
"Hastelloy B"	55–57	75–82	9–6	190–230	16–11
"Hastelloy C"	45–48	72–80	10–15	175–215	14–9
"Hastelloy D"	36–41	36–41	0	50–55(a)	——
"Illium G"	50–64	60–73	9–4	160–210	40(b)
"Chlorimet 2"	55	80	5	250	——
"Chlorimet 3"	50	75	10	225	——

(a) Rockwell C
(b) Charpy

specific properties the reader is referred to the manufacturer of the alloys and to their publications.

Hardness. Hardness is the most important factor, in addition to ductility and toughness, in effecting ease of fabrication and resistance to service wear and erosion. The high-nickel alloys are all relatively hard and tough. Some can be softened by regular thermal treatments or by a high-temperature quench. Others are hardened by cold-working or by age-hardening heat treatment. These alloys, depending on their compositions and also on their thermal and mechanical treatment, vary in hardness from 90 Brinell for annealed nickel to 550 Brinell (55 Rockwell C) for as-cast "Hastelloy D."

Shear Strength. The high-nickel alloys have shear strengths approximately 12 to 25 per cent above those of steel for the equivalent hardness. The ratio of shear strength to tensile strength is 0.5 to 0.77, depending on composition and temper.

Compressive Strength. The yield strengths in compression are about equal to those in tension. Tests of the alloys showing that the material does not fracture indicate that service overloads may cause only permanent set rather than sudden failures with subsequent damage to equipment. This is an important point in design.

Fatigue Strength. The endurance ratio, *i.e.*, ratio of endurance limit to tensile strength, varies from 0.31 to 0.52 for the alloys depending on composition, temper, and thermal and mechanical treatments.

Impact Strength. The impact strength of the wrought materials is very high, making them highly resistant to service shock and impact. Izod impact values reach a high of 120 foot-pounds for hot-rolled or annealed nickel, "Monel," "K Monel" and "Duranickel" to a low of 25 foot-pounds for the same alloys in the heat-treated condition. Annealed "Hastelloy" A and B have impact values of 62 to 78 foot-pounds for the wrought material and 11 to 35 for the cast. It is to be expected that the impact values will be much lower in the as-cast than in the as-wrought condition.

Corrosion Fatigue. High-nickel alloys have excellent resistance to corrosion fatigue—the combination of corrosive conditions and fatigue stresses acting together simultaneously. McAdam[2] showed (Table 119) how nickel and "Monel" compare with carbon steels in their resistance to corrosion-fatigue when exposed to fatigue stresses in air, in carbonate tap-water and in brackish estuary water:

Modulus of Elasticity. In construction of equipment, depending on its service and application, saving in weight can be made by selecting material of high strength and high modulus of elasticity. The latter property determines rigidity and stiffness: the higher the modulus the stiffer the material and the greater its resistance to sagging and deflection under load. Table 120

TABLE 119. *Endurance Limit and Apparent Corrosion-Fatigue Limit*

Material	Condition	Endurance limit 10^8 cycles psi.	Apparent corrosion-fatigue limit 10^8 cycles psi.	
			Fresh water	Brackish water
Nickel	Annealed	33,000	21–24,000	20–22,000
	Cold-worked	50,000	21–24,000	20–22,000
"Monel"	Annealed	36,000	21–24,000	27–29,000
	Cold-worked	50,000	21–24,000	27–29,000
Carbon Steels	–	25–42,000	16–24,000	6–8,000

shows comparative modulus values of the high-nickel alloys and other structural materials. This table can be used as a working guide in design and construction.

TABLE 120. *Modulus of Elasticity*

Material	Tension or compression Young's modulus psi.	Shear or torsion rigidity modulus psi.
"Monel"	26,000,000	9,500,000
"K Monel"	26,000,000	9,500,000
"A Nickel"	30,000,000	11,000,000
"Duranickel"	30,000,000	11,000,000
"E Nickel"	30,000,000	11,000,000
"Inconel"	31,000,000	11,000,000
Brass	14,500,000	5,000,000
Silicon Bronze	15,000,000	5,000,000
Carbon Steel	30,000,000	11,500,000
14Cr-Steel	28,000,000	10,000,000
18:8 Steel	28,000,000	10,500,000
"Hastelloy A"	27,000,000	
"Hastelloy B"	30,750,000	
"Hastelloy C"	28,500,000	
"Hastelloy D"	28,880,000	

Magnetic Properties. Nickel is magnetic at temperatures below its transformation point, approximately 680° F. The magnetic induction is approximately 6100 gauss at a field strength of 60 gauss. Permeability or magnetic conductivity at low field strengths increases with temperature up to about 600° F. The high nickel-iron alloys, mentioned earlier, possess valuable magnetic properties. Certain of these, by special heat treatment, can be made to emphasize one or more of the magnetic characteristics of this group. The high nickel-iron alloys (70 to 85 per cent nickel) are characterized by high permeability at low field strengths and a low degree of magnetic retentivity or residual magnetism. The best magnetic properties are obtained after a high-temperature annealing (about 2000 to 2100° F.) in a hydrogen atmosphere followed by a very slow cool to room temperature at a rate not exceeding 200° F. per hour. These alloys have been designated "Permalloys" by the Bell Telephone Laboratories and "Mumetal" by the Allegheny-Ludlum Steel Co.

The very low permeabilities of "K Monel" and of "KR Monel" are not affected by cold-working or by age-hardening, and the non-magnetic alloys can be used safely as low as −150° F. The permeability of "Inconel" varies with cold work and thermal treatment. Cast "Monel" is weakly magnetic, while the two silicon "Monels," "H" and "S," are non-magnetic down to −70° F.

Electrical Properties. The electrical resistivity in ohms per circular mil foot for the high-nickel alloys is shown in Tables 115 and 116. Some of these are comparable to the special 80 nickel-20 chromium alloys, developed for their high electrical resistance (about 650 ohms per circular mil foot). However, the 80 nickel-20 chromium and the 60 nickel-15 chromium alloys are materials which give optimum life in an electrical heating unit at high temperature. The maximum operating temperature for the 60 nickel-15 chromium alloys is about 1700° F., compared to 2100° F. for the 80 nickel-20 chromium. "Hastelloy" and "Illium" oxidize too rapidly at the service temperature to be useful for this purpose.

High-temperature Properties. Two characteristics essential for heat resistance are strong resistance to oxidation (scaling) and good mechanical properties at elevated temperatures. All the nickel-base alloys have high strength, high impact value and high resistance to oxidation, scaling, creep and intercrystalline attack at elevated temperatures. Their tensile and impact strengths are maintained at the high temperatures encountered in service. The higher the nickel content of the alloy, the greater its resistance to oxidation and scaling. The nickel-chromium-iron alloys are well established as heat-resisting materials.

Because of its high melting point pure nickel is desired for industrial use at temperatures up to 2300° F. under reducing and sulphur-free conditions, where stress is negligible and resistance to scaling is of prime importance. "Inconel" under the same conditions is recommended for use up to 2100° F., but it can operate under high stresses. For parts or equipment involving oxidizing atmospheres, thermal shock and resistance to sudden or constant stress, "Inconel" is preferred to nickel. However, if sulphur-containing gases are present, it can be used safely only up to 1500° F. and nickel up to 1000° F. in oxidizing atmospheres, and to 1000 and 500° F., respectively, in reducing atmospheres. The advantage of these heat-resisting alloys which maintain their strength at elevated temperatures is that they do not deform under load.

Low-temperature Properties. At subzero temperatures the nickel-base alloys have increased strength and hardness, and at the same time retain their toughness. This is in marked contrast to other engineering materials, which become brittle and have low ductility at low temperatures.

A summary of the low-temperature properties of nickel, "Monel," "K Monel" and "Inconel," which shows that the strength factors increase as the temperature is lowered, is given in Table 121. Freedom from low-temperature brittleness is indicated by the high impact strength at subzero temperatures. The virtue of the nickel-base alloys for industrial use at very low temperatures is that there is no appreciable loss in impact strength, even though the tensile strength increases considerably. The fatigue strength and modulus of elasticity likewise increase at lower temperatures. In general the ductility, as measured by the per cent elongation and contraction, also increases to some extent as the temperature drops.

TABLE 121. *Mechanical Properties at Low Temperatures*

Material	Conditions	Temp. deg. F.	Yield strength 0.2% offset psi.	Tensile strength psi.	Elongation in 2 in. %	Reduction of area %	Charpy impact strength ft.-lb.
"Monel"	Forged	70	67,000	92,000	31.0	72.7	216
		−297	91,500	128,250	44.5	71.8	216
		−423	96,400	142,000	38.5	61.0	—
	Annealed	70	31,300	78,650	51.5	75.0	216
		−297	49,500	115,250	49.5	73.9	212
Nickel	Hot-rolled	70	24,600	65,600	—	—	195
		−112	27,500	76,400	—	—	236
		−292	28,000	98,000	—	—	—
		−310	——	103,000	51.0	—	227
"Inconel"	Hot-rolled	70	——	87,000	42.5	71.9	213
		−315	——	116,750	51.0	72.7	169
	Cold-drawn,	70	——	145,000	10.0	35.1	69
	50% reduction	−315	——	182,000	10.0	49.5	61
"K Monel"	Cold-drawn,	70	125,900	157,300	15.5	37.4	—
	age-harden	−110	134,600	171,550	17.3	41.1	—

HOT-FORMING

Hot-Working. Hot-working and hot-forming of high-nickel alloys necessitates more careful control of atmosphere and temperatures than for steel and other non-ferrous alloys. The susceptibility of nickel and nickel alloys to intergranular attack by sulphur at high temperatures requires working of the material in a sulphur-free atmosphere, or at least in an atmosphere produced from fuel containing not more than 0.5 per cent sulphur. Coal and coke as furnace fuels are not recommended, as they produce atmospheres too high in sulphur. Satisfactory fuels are natural gas, butane, propane, and low-sulphur city gas or fuel oil. Excessively long periods at high heat are undesirable, and soaking at high heat must be avoided. The material should be heated just long enough to insure uniformity of temperature throughout the mass or throughout each piece. However, long periods of heating are not particularly detrimental to "Hastelloys."

Nickel-base alloys do not scale readily nor do they carburize. Thus a slight excess of reducing atmosphere, about 2 per cent carbon monoxide, will prevent oxidation. Furnace atmospheres must never be allowed to alternate from reducing to oxidizing, as severe intergranular attack with resulting embrittlement will occur.

After hot-forming the materials are cooled in air except the age-hardenable alloys, which must be quenched in water to prevent hardening during slow cooling.

Hot-Forging. Since nickel-base alloys are stronger and tougher than steel at forging temperatures, heavier forging hammers and larger presses are usually required, especially for single-blow operations, as in pressing and in heading bolts. However, forging of these alloys can be readily done by the hammer forge, drop forge or press forge, if correct heating methods are followed. The "Hastelloys" are somewhat stiffer at high temperatures than the "Inco" high-nickel alloys, and therefore do not forge as readily. Best results are obtained with hydraulic forging presses. The heat-atmosphere in contact with the metal should be reducing to about 2 to 5 per cent excess carbon monoxide.

The high-nickel alloys show important differences among themselves in respect to proper forging temperatures, particularly in the upper safe heating limits, and in tendencies toward red-shortness. Too high temperatures are damaging; nickel must not be heated above 2300° F. It is not practical to forge "Hastelloy C." Of course it is understood that cast alloys cannot be forged.

Hot-forging temperatures are the same as those used for hot-forming, as shown in Table 122. "Hastelloys" must be forged at temperatures above 1900° F., preferably around 2100° F., because of the great danger of cracking in the brittle range below 1900° F. These alloys have a brittle range between 1200 and 1900° F., and cracking may occur in this range unless the flow of the metal is extremely slow. If heat treatment is to follow the hot-forging operation of the age-hardenable alloys, it is necessary to reheat and quench to avoid self-hardening and setting up of stresses that may result in cracks or surface tears. "Duranickel" should be quenched from 1900 to 2000° F., and "K Monel" from above 1450° F.

The metal in the forging furnace should be supported on steel rails and should not be allowed to touch the furnace floor because of possible contamination with sulphur from the hearth slag. Billets should not be exposed to combustion gases in a heating furnace longer than the minimum time required to heat them uniformly through.

The use of regular hot-rolled rods for forging is satisfactory provided that they are overhauled at the mill. The overhauling of stock 1″ and over consists of de-skinning on a special continuous turning machine. Rods under 1″ are centerless-ground. Overhauling of sections other than rounds can be done only by hand grinding.

TABLE 122. *Hot Working Temperatures*

Material	Temperature, ° F.
"A Nickel"	2,300–1,600
"L Nickel"	2,300–1,600
"Duranickel"	2,150–1,850
"D Nickel"	2,150–1,600
"E Nickel"	2,150–1,600
"Monel"	2,150–1,600
"K Monel"	2,150–1,900
"KR Monel	2,150–1,900
"Inconel"	2,300–1,850
60Ni–15Cr Type	2,250–1,850
"Hastelloy A"	2,200–1,950
"Hastelloy B"	2,200–1,950
"Hastelloy C"	2,250–2,000

Hot-Working Temperatures

The recommended hot-working, hot-forming and hot-forging temperatures are as indicated in Table 122.

Precautions: Nickel stiffens rapidly at about 1600° F. Do not heat above 2300° F. Forge lightly between 1000 and 1200° F. for high physical properties. Hot bend between 2250 to 1900° F.

"Duranickel" stiffens rapidly below 1800° F.

"D Nickel" and "Monel" must not be heated above 2150° F. Heavy forging should be done above 1850° F., and the hot bending between 2150 and 1850° F.

"K Monel" and "KR Monel" should never be charged in a cold furnace, but always in a hot furnace. The parts should be quenched from forging or hot-working heat and should not be allowed to air-cool.

"Hastelloy A, B and C" harden and become brittle between 1200 and 1900° F., and this temperature range should definitely be avoided.

Die Steels: Nickel-chromium-molybdenum steel of about 0.50 to 0.55 per cent carbon, heat-treated to 42 to 44 Rockwell C, makes the best forging dies. The tendency for the hot metal to stick to the die can be prevented by swabbing the die faces with a mixture of heavy grease and graphite, or by throwing sawdust into the die.

HEAT-TREATING

Annealing. Nickel and the nickel-base alloys are subjected to annealing heat treatments to soften them after cold-working, welding or machining; to improve machinability; and to restore corrosion resistance. The same precautions must be taken during heating and cooling on annealing as on hot-working.

Soft Anneal. The purpose of a soft anneal is to decrease hardness and increase ductility of partially cold-worked material in order to complete fabrication by cold work without rupture. As with other alloys, the greater the amount of cold work to which the materials have been subjected, the lower the annealing temperature required to produce the same degree of softness without increased grain size, or the shorter the time required at temperature. Soft annealing requires a sulphur-free atmosphere and accurate control of time and temperature to avoid intergranular embrittlement by the sulphur and abnormal grain growth by too high a temperature. The temperatures required are high enough to cause surface oxidation. Heating in atmospheres that fluctuate from oxidizing (excess air) to reducing (excess carbon monoxide and hydrogen) causes severe intercrystalline attack, with resulting embrittlement, even though the atmosphere is sulphur-free. This trouble can be avoided by maintaining a slight excess of reducing gas in the atmosphere during heating and cooling. Since the rate of cooling after anneal has no specific effect on the resulting softness of the material, it is advisable to quench from the annealing temperatures to minimize oxidation. However, furnace-cooling is essential for "Hastelloy D." The age-hardening alloys must be cooled rapidly to prevent self-hardening.

Material can be either box-annealed or open-annealed. Open-annealed material should be quenched in a solution of 2 to 3 per cent denatured alcohol in water to reduce the oxide flash when the work is brought into the air, thus a silvery white surface on the part is obtained.

The recommended soft-annealing temperatures for open annealing are as follows:

1,500 to 1,700° F. for "A Nickel," "L Nickel," "K Monel," and "KR Monel".
1,600 to 1,800° F. for "D Nickel," "E Nickel," and "Monel."
1,600 to 2,000° F. for "Duranickel" and 60 Ni–15Cr Type
1,800 to 1,950° F. for "Inconel"
2,100 to 2,150° F. for "Hastelloy A and B"
2,200 to 2,250° F. for "Hastelloy C."

Box annealing can be done about 250° F. lower than open annealing, but it requires more time. It is not generally used except for small parts requiring special handling. Special work with small parts can be soft-annealed in salt baths of molten chlorides and carbonates of sodium and potassium. The addition of powdered borax or charcoal to the fused salt bath removes all traces of sulphur which might embrittle the work. The annealed material is quenched in water to remove the adhering salts, and then flash-pickled.

Temper Anneal. Temper or partial anneal is limited to light sections and is applied to strip and wire where full-annealed material is not required, or where partial softening is desired. The temper is lower than that for stress-equalizing or stress-relief anneal. Lower temperatures and shorter times are recommended for temper anneal.

Stabilizing Anneal. "Hastelloy" alloys are usually used in the fully annealed condition. They are given a stabilizing anneal at 1925 to 1960 ° F. from 2 to 4 hours to reduce loss of corrosion resistance and toughness due to exposure in the temperature range of 1200 to 1900° F. Hard, brittle "Hastelloy D" is toughened by heating at 1925 to 1950° F. for 2 to 4 hours and furnace-cooling. For "Hastelloy C" it is recommended to air-cool from 2050 to 2075° F.

Stress-Equalizing Anneal. Stress-equalizing or partial stress-relief anneal requires a low-temperature thermal treatment of cold-worked or hot-worked material to develop the optimum combination of strength and ductility, and to prevent distortion and warping during subsequent machining. This treatment does not relieve or remove the stresses and does not alter the grain structure, but it does increase the proportional and elastic limits. Hot-worked material requires a higher temperature than cold-worked for this type of anneal. The recommended stress-equalizing temperatures for cold-worked materials are: 525 to 750° F. for "Monel," "R Monel" and nickel; 800 to 900° F. for "Inconel"; 950 to 1000° F. for the 60 nickel-15 chromium alloys; and 1100° F. for "Hastelloys." High-tensile forgings of nickel, "Monel" and "Inconel" are treated at 1000° F. Cold-worked and unage-hardened "K Monel," "KR Monel" and "Duranickel" are treated at 525 to 750° F.

Bright Anneal. Most alloys can be bright-annealed in reducing atmospheres containing small amounts of steam and carbon dioxide. However, "K Monel," "Duranickel" and the chromium-containing alloys require a pure hydrogen or hydrogen-nitrogen atmosphere. Bright-annealing is easier by open-annealing methods than by closed-box or pot methods. Suitable atmospheres for bright-annealing include hydrogen, cracked ammonia, nitrogen, cracked and sulphur-free natural or city gas, cracked hydrocarbons, or a generated atmosphere containing principally a mixture of carbon monoxide and hydrogen. Hydrogen is preferred for the "Hastelloy" alloys.

Age-Hardening. Only six of the high-nickel alloys can be age-hardened by suitable heat treatment: "Duranickel," "K Monel," "KR Monel," "S

Monel," "Chlorimet 2," and "Hastelloy C." The other alloys do not respond to age-hardening thermal treatment and can be hardened only by cold work. In this age-hardening heat treatment the alloys are quenched from temperatures ranging from 1450 to 2225° F., and aged at temperatures ranging from 900 to 1600° F., the exact temperature depending upon the composition. The alloys are soft when quenched, and harden during the aging cycle, which is the direct opposite of the hardening heat treatment of steel, which hardens as quenched and softens on aging or tempering. The age-hardening temperature used for "Hastelloy C" is detrimental to its corrosion resistance. The same precautions for proper atmosphere control during age-hardening should be taken as for soft annealing.

The recommended aging treatments are: "K Monel," "KR Monel" and "Duranickel," 6 to 16 hours at 1000 to 1100° F.; "S Monel," 4 to 6 hours at 1080 to 1100° F.; "Hastelloy C," 8 to 16 hours at 1575 to 1600° F. and air-cool.

The variation in time and temperature for each alloy depends entirely upon the degree of cold work performed prior to age-hardening. Cold-worked material responds more rapidly to heat treatment. For best results, it is always recommended to age-harden in sealed boxes inside the furnace.

Cold-Forming

Most of the high-nickel alloys can be cold-worked. The cast alloys ("H Monel," "S Monel," "Hastelloy D" and "Illium G") are too brittle and hard for any cold-forming operation. "Hastelloys A, B and C" can be cold-worked; but this is not very practical and they are, therefore, not supplied in the cold-rolled or cold-drawn condition. Alloys that can be cold-worked satisfactorily are available as cold-rolled sheet and strip, cold-drawn bars and rods, and cold-drawn seamless tubing and wire.

Nickel, "Monel" and "Inconel" behave similarly in many respects to mild steel in mechanical cold-working operations, such as cupping, drawing, swaging, die-forming and bending. However, because of their higher elastic limit, more power is required. "Inconel" is tougher to cold-work than either nickel or "Monel." "L Nickel" is softer than regular nickel and does not work-harden as rapidly. The ductility of "Duranickel" permits excessive cold-working without danger of fracture, despite the fact that it work-hardens more rapidly than regular nickel. However, more frequent annealing is required for "Duranickel" during heavy cold-working. "K Monel" is harder than "Monel" and also has a greater rate of hardening with cold work. The high ductility of "K Monel" in the annealed condition permits deformations without danger.

Cold-working increases the elastic limit and hardness of the material, and excessive cold stress-cracking of the material may occur. Therefore, for heavy cold-working or severe cold-forming operations intermediate anneals are required, the number depending on the severity of the cold-working effect. The different alloys will work-harden at various rates. If heavy drafts are taken, it is important to keep the surface free from tool and die marks. For the more severe forming operations on these materials, best practice calls for hot-forming. In other words, hot-forming at a few hundred degrees above room temperature may be necessary for very severe forming operations, to avoid stress-cracking or possible rupture.

Deep Drawing. Special, cold-rolled, deep-drawing quality nickel, "Monel" and "Inconel" sheet and strip are recommended for deep-drawing operations. A standard, cold-rolled, soft-temper sheet is produced that can be used for moderate drawing and all bending operations. The former grade has higher ductility than the latter and is available in a range of tempers from dead soft to full hard. Soft-temper stock with fine to medium grain is the most suitable for deep-drawing. Dead soft material has the highest ductility but has a coarse-grained structure, which causes a pebbled surface on the finish-drawn part.

"Hastelloys A, B, and C" work-harden in deep-drawing, but not sufficiently to necessitate subsequent heat treatment for maximum corrosion resistance. Severe deep-drawing must be performed hot within the temperature range of 1900 to 2200° F. The brittle range of 1200 to 1900° F. for these alloys must be avoided. After all forming operations, either hot or cold, the parts should be given a full anneal or stabilizing anneal for maximum corrosion resistance.

For die materials, heat-treated nickel-chromium cast iron, hard alloy bronze, chromium-plated hardened alloy die steel or carbides can be used. Sulphur-free lubricants having high film strength are preferred for drawing nickel and the high-nickel alloys; beef tallow, castor oil, or a mixture of the two, is recommended.

Lubricants should be thoroughly removed from drawn articles, especially those to be subjected to high temperatures or intermediate annealing; otherwise embrittlement of the material by the lubricant is likely to result. Water-soluble or oil-soluble lubricants containing fillers are also good lubricants. In general, the same die equipment as that used for drawing steel and brass is suitable for high-nickel alloys.

Spinning. In the annealed condition, nickel, "Monel" and "Inconel" sheet and strip are less ductile than the softer materials, such as copper, brass and aluminum, but have adequate ductility for the operation. More power is required when spinning the nickel-base alloys and more frequent annealing is necessary because of the greater rate of work-hardening. Work-hardening affects the power required for spinning. Since hardness and elastic limit increase with work-hardening, the more the material is deformed in spinning, the more difficult it becomes to continue the spinning without annealing. The work should be laid down on the chucks firmly with long, powerful strokes; the metal should not be crowded, and reworking over the same surface should be avoided as much as possible. Spinning should be stopped as soon as the metal ceases to flow. If the spinning is carried too far, numerous small surface cracks will be developed, indicating overstrained material which cannot be restored by either annealing or burnishing.

Hard alloy bronze, highly polished, is recommended for bar tools, and hardened chromium-plated tool steels are preferred for roller and beading tools. Spinning tools should be made broad and flat to distribute plastic flow over a greater area and to reduce overstraining.

The lubricant used is an important factor in the successful spinning of these materials. It should be heavy-bodied to withstand the high pressures and temperatures developed. Yellow laundry soap is used most frequently, but beeswax, tallow, or a mixture of the two is also satisfactory. Removal of lubricants from spun articles is just as essential as from drawn articles. Dead soft-annealed material is undesirable for spinning, because of the coarse grain.

Special spinning stock is available from the mill and should be specified. "L Nickel," the carbon-free grade, spins almost as easily as copper.

Shearing. Shearing of nickel, "Monel" and "Inconel" sheet and strip require from about 115 per cent in the soft tempers to about 130 per cent in the full hard tempers of the power needed for mild steel of equal gauge. The "Hastelloys" require still higher power, closer to 150 per cent, and can be sheared hot or cold. Shear blades must be set up tight and kept sharp.

Punching. Punching and perforating require about 15 to 20 per cent more shear load for high-nickel alloys than for mild steel of equal gauge. The material should be soft to skin-hard temper. Usually a total punch and die clearance of 3 to 6 per cent of the thickness of the stock punched is satisfactory for punching and perforating nickel, "Monel" and "Inconel." It is advisable to have close clearance between the punch and the stripper plate. A heavy sulphur-base oil is recommended as lubricant. The same precaution regarding the removal of lubricants should be observed as that described previously for deep drawing and spinning.

Soft, skin-hard and quarter-hard temper material is recommended for perforating. A cleaner cut is obtained with quarter-hard temper material, and the choice of temper depends upon the job at hand.

JOINING

The regular joining practices and processes of soldering, brazing and welding employed for steel can be used for the high-nickel alloys, with slight modifications. The method of joining and the filler used depend on the design, service stresses and service exposure to elevated temperatures and corroding media. Each method produces satisfactory joints and has its own field of application.

Soldering is satisfactorily performed with the 50–50 and 60–40 tin-lead soft solders using "cut acid" fluxes. Soldered joints can be used only in those applications where the joint does not come into contact with corroding agents, high temperatures and high stresses. Due to the chromium oxide film on "Inconel" and the 60 nickel-15 chromium alloys, stronger fluxes are required when soldering these than for nickel or the "Monels." In all cases the oxide film should be removed by grinding, polishing or pickling before soldering. Pretinning the surfaces before soldering and after cleaning is highly recommended; this can be done with the same solder as that to be used for the joint. Soft soldering is performed with a soldering iron, with an oxy-acetylene or an air-acetylene flame.

Brazing requires silver brazing alloys which flow at less than 1400° F., preferably those that melt or flow in the range of 1160 to 1325° F. Two well recommended alloys are Handy and Harman's "Easy-Flo" (50 Ag; 15.5 Cu; 16.5 Zn; 18 Cd) which melts at 1160° F. and flows at 1175° F., and their Grade RT (60 Ag; 25 Cu; 15 Zn) which melts at 1260° F. and flows at 1325° F. "Handy Flux" is used with both of these brazing alloys with the proper melting and flow temperatures. Borax and boric acid fluxes cannot be used because they are not fluid at the brazing temperatures. Phosphorus-containing alloys, although excellent brazing materials for copper and brass, are not recommended for high-nickel alloys because of the high embrittling effect of phosphorus. Brazing operations are generally avoided with the "Hastelloys" because of the severity of the corrosion problems involved.

The strength of a properly designed joint should be approximately 50,000 psi in tension and 30,000 psi in shear. Recommended clearances of 0.002- to 0.003-inch should be used to allow proper drawing of the molten brazing alloy through the joint by capillary attraction. Excessive clearances result in low strength.

Brazing can be done by heating with a neutral or slightly reducing oxy-acetylene flame, by heating the assembly in an electric furnace, by induction heating, or by dipping in a bath of molten salt. Since brazing is performed well below the annealing temperatures of the high-nickel alloys, there is little softening effect. The age-hardenable alloys can be heat-treated before or after brazing.

Furnace brazing, and copper and brass brazing of high-nickel alloys are used for special purposes only.

High-nickel alloys can be welded by the oxy-acetylene, the electric arc (metallic-arc) or the electric resistance method. Because of the low temperature of the oxy-hydrogen flame this method of welding is not practical. Hammer welding is not possible because union does not occur unless the metal is actually melted. Carbon-arc welding, although practical, has been displaced by the more efficient metallic-arc welding because of the highly improved electrodes for this process. The atomic hydrogen and the "Unionmelt" submerged metal welding methods are used for special purposes only. Most welding is now being done by the metal-arc or oxy-acetylene methods, and the same procedures and practices used for steel are applicable to the high-nickel alloys, with only slight modifications to insure adequate fusion and penetration resulting from their different physical and mechanical properties.

Castings of all these alloys, except "H Monel" and "S Monel" can be welded satisfactorily by any of the above methods. Joining these castings by welding is not recommended because of their tendency to crack.

For properly welded "Inco" alloys no thermal or chemical (passivation) after-treatment is needed to retain or restore corrosion resistance, since the joints are equivalent in corrosion resistance and strength to the parent metal. Specific thermal treatments for stress-stabilizing anneal or for age-hardening of the hardenable alloys are used and recommended. The "Hastelloys" should be given a full anneal after welding to restore maximum corrosion resistance and to overcome any hardening or embrittling that may have occurred beside the welds where the sheet was held in the hardening range of 1200 to 1900° F.

Welding rods and wire are in general of the same composition as the alloy being welded to insure uniform corrosion resistance without galvanic effects.

Machining

The combination of high strength, high ductility and toughness of the nickel-base alloys decreases their machinability rating below that of machinery steels and requires machining procedures somewhat different from those employed for materials of lower strength, toughness, hardness and ductility. The alloys are not difficult to machine when the proper tooling, feed and speed and cutting compound are used. Furthermore, two of the alloys, "R Monel" and "KR Monel," have been developed for free-cutting and automatic screw machining.

The best grades of wrought nickel and "Monel" for easy machining are those in the "as-cold-drawn and normalized" temper, while the desired condition for "Inconel" and "K Monel" are annealed, hot-rolled or cold-drawn bars and rods. Nickel and the high-nickel castings are nearly always machined in the as-cast condition. "S Monel," which responds to hardening by thermal treatment, has the highest order of machinability in the annealed condition. Unless difficult and extreme machining is involved, the as-cast material is satisfactory. The "Hastelloys," "Chlorimet" alloys and "Illium G" must be machined in the soft-annealed condition.

Slower cutting speeds and lighter cuts than for machinery steels are generally recommended. In turning and boring it is desirable and decidedly more economical, from a tool life point of view, whether cutting dry or with a lubricant, to take a deep cut and light feed rather than a light cut and heavy feed. Cutting edges must be kept sharp and tools must be cutting when against the work. If allowed to ride on the work without cutting, it will be difficult for the tool to pick up and cut again. Tools must be properly supported, for otherwise chattering will develop. Sufficient true rake on the tool face must be ground to keep chip pressure, chip abrasion, and resultant frictional heat at a minimum and to provide for convenient chip disposal.

Proper chip disposal is an important factor in heavy roughing operations, and chip breakers aid materially. A heavy, continuous spiral chip cannot be properly disposed of on heavy rough cuts with tools not utilizing a chip breaker. Chip control is assisted by reducing the normal side rake to a degree where the heavy chip will pack against the tool face, become embrittled, and break when it curls back against the work.

In practice, recommendations are to use cutting tools ground with sharp cutting edges having minimum relief, to avoid excessive speeds and feeds, and to keep the work well flooded with lubricant. Carbon tool steels cannot be used with the high-nickel materials, because of the high frictional heat developed, which draws the temper of the cutting edge; high-speed and super high-speed steels are recommended. The higher hot hardness of the latter type affords longer tool life between grinds. The cast non-ferrous and cemented carbide tools follow in order in respect to higher hot hardness and increased cutting speeds. For machining the hard-cast alloys, it is advisable to use tungsten- or tantalum carbide-tipped tools or non-ferrous cutting tools, such as "Rexalloy," "Stellite 2400," "Star J" Metal or "Tantung G." The selection of the cutting tool depends on the alloy, the condition of the alloy being machined, and also on the machine tool set-up.

For intermittent cutting and heavy roughing, high-speed steel should be heat-treated to 58 to 61 Rockwell C. For light, smooth lathe turning and for automatic machining, tools above 61 Rockwell C hardness are preferred. The ground rakes and angles on the cutting tool vary with the material being cut and with the particular machining operation. However, they should be ground with sharp edges, greater rakes to reduce chip pressure, and blunt noses to provide maximum support for the cutting edge.

Sulphurized oil is recommended for machining nickel and the high-nickel alloys with high-speed steel tools, and a rich emulsion for cemented carbide tools. A rich emulsion of water-soluble oil is sometimes preferred for planing and shaping because of its lesser tendency to smoke. Turpentine or gasoline is recommended for drilling under $\frac{3}{32}''$; lard oil, water-soluble oil or sulphurized oil, depending on the alloy, is used for drilling for $\frac{1}{4}''$.

Grinding is done with a lubricant of soda and water or a lean mixture of soluble oil and water. The manufacturers of the "Hastelloys" do not recommend the use of sulphurized oils for their alloys, but prefer water-soluble oil, lard oil or mineral-lard oil. Discoloration produced by sulphurized oil can be removed readily by soaking the work from 20 to 30 minutes in a cold 10 per cent sodium cyanide solution.

Cleaning and Pickling

As with other base alloys the types of oxide produced in nickel-base alloys vary with the composition and heating conditions. Thus, the proper pickling solution for each case must be chosen accordingly. The nickel oxide film on metal that has been properly heated is formed during contact with the air after the work is drawn from the furnace. Hot-forgings, hot-headed bolts, hot-rolled and hot-formed products, and annealed metal cooled in air are all subject to oxide skin formation. Chromium-bearing nickel-base alloys form a superficial chromium oxide film. The oxide films are all thin and tightly adherent. With improper heating heavy oxide films and scale may result.

Drawn or spun parts, cold-headed rivets, cold-drawn wire and other cold-worked products finished by annealing in a strongly reducing sulphur-free atmosphere and either cooling out of contact with air or quenching in a 2 per cent alcohol-water solution may develop a slight discoloration or tarnish that will require pickling or brightening. Some materials acquire a brown discoloration when machined at high speeds with sulphur-base cutting oil because of the formation of sulphur compounds. The surface of the metal may be attacked during heating if sulphur is in the atmosphere, or if the hot parts come into contact with sulphur compounds in the furnace hearth, sulphur-containing paint and marking pencils, or even oil or grease from the preceding mechanical operation. In any case the metal has to be cleaned and pickled before service. Thorough cleaning of the parts of all oil, grease and dirt is essential before pickling.

Cleaning and Degreasing. Grease, oil, fats and lubricants can be removed before pickling by standard cleaning methods. Soluble oils can be removed with soap and hot water. Tallow, fats and fatty acids are removed with a hot 10 to 20 per cent soda ash or caustic soda solution; while mineral oils and greases are removed by immersion in any organic solvent (carbon tetrachloride or kerosene) followed by a final dip in caustic soda or trisodium phosphate.

Tarnish Removal by Flash Pickling. .Cold-worked products, after proper annealing in a sulphur-free atmosphere, develop slight discoloration or tarnish. A bright, lustrous white finish can be obtained by flash pickling or bright dipping. The recommended pickling bath for "Monel" and "K Monel" contains 1 gallon water, 1 gallon 38° Bé. nitric acid, and ½ pound sodium chloride, maintained at 70 to 100° F. for 5 seconds maximum immersion; the bath for nickel and "Duranickel" contains 1 gallon water, 1½ gallons 66° Bé. sulphuric acid and 2¼ gallons 38° Bé. nitric acid plus ¼ pound common salt maintained at 70 to 100° F. for 5 to 20 seconds. "Inconel" cannot be flash-pickled without first descaling.

Reduced Oxide Removal. Hot-worked products develop oxide films, which after annealing in a sulphur-free atmosphere, are converted into rather spongy and lightly adherent layers. This spongy layer on nickel is reduced metallic nickel, and on "Monel" it is a mixture of reduced metallic nickel and copper. Since the oxide film on "Inconel" does not respond to complete reduction, but is reduced selectively to a mixture of metallic nickel and chromium oxide, it becomes difficult to pickle. Nickel, "Monel," "K Monel" and "Duranickel" are pickled in a solution containing 1 gallon water, ¾ pint 66° Bé. sulphuric acid and ½ pound sodium nitrate held at 180 to 190° F. for 30 to 90 minutes.

Oxide Film or Scale Removal. When hot forgings, hot-rolled or hot-formed parts are annealed and allowed to cool in air, moderately thick and tightly adherent oxide films form on all the alloys during contact with the air. "Monel" and "K Monel" are pickled in a bath containing 1 gallon water, 1.2 gallons 20° Bé. hydrochloric acid, and ¼ pound cupric chloride maintained at 180° F. for 20 to 40 minutes, then rinsed in hot water and immersed in a second bath containing 1 gallon water, $\frac{1}{10}$ gallon 66° Bé. sulphuric acid, 1$\frac{1}{10}$ gallons sodium dichromate maintained at 70 to 100° F. for 5 to 10 minutes. Nickel and "Duranickel" are pickled in a solution containing 1 gallon water, ½ gallon 20° Bé. hydrochloric acid, ¼ pound cupric chloride held at 180° F. for 1 to 2 hours, followed, if desired to brighten, by a dip for a few seconds in a solution containing 1 gallon water, 1½ gallons 66° Bé. sulphuric acid, 2¼ gallons 38° Bé. nitric acid. "Inconel" is pickled in a solution of 1 gallon water, 1 gallon 38° Bé. nitric acid, 1¼ pints 40 per cent hydrofluoric acid held at 70 to 100° F. for 15 to 90 minutes.

Heavy Scale Removal. Sand-blasting or grinding may be necessary to remove heavy scale, especially if the surface below the scale is rough and cracked. Following this with a flash pickle will brighten the surface.

"Hastelloy" and "Illium" Pickling. Because of the greater tenacity of the oxide and scale on the surface of "Hastelloy" alloys, pickling is more difficult, but it can be done efficiently by immersion in a bath containing

18 parts water, 6 parts concentrated hydrochloric acid and one part concentrated nitric acid held at 200° F. for about 20 to 30 seconds, or in a solution of 10 per cent sulphuric acid, 5 per cent sodium nitrate and 5 per cent sodium chloride held at 200° F. for 30 to 60 minutes. "Hastelloy C," being more corrosion-resistant than "Hastelloy" A or B, requires longer pickling. "Illium G" is pickled in a solution of 10 per cent nitric acid and 2 per cent hydrofluoric acid at 100° F. for a short time.

Discoloration Removal from Automatic Screw Machine Parts. During high-speed machining in the automatic screw machines using a sulphur-base cutting oil, brown discoloration may occur, especially on "Monel." It can be removed by immersion in a bath containing ½ to 1 pound sodium cyanide to 1 gallon water held at 70 to 100° F. for 5 to 30 minutes.

Coppering. Unless proper precautions are taken during pickling operations coppering will occur occasionally on the high-nickel alloys containing an appreciable percentage of copper. Small proportions of nitric acid or ferric chloride added to the pickling bath will prevent it. The copper flash, if it does occur, can be removed readily by immersing in an aerated ammonia solution containing approximately 1 part of commercial aqua ammonia to 1 gallon water at room temperature for a minute or so.

Corrosion

Nickel and the high-nickel alloys are especially characterized by their high resistance to all kinds of corrosive media. They are highly resistant to most of the normal and special corroding agents found in industries. An attempt is made below to outline the resistance of these alloys to various atmospheres and other corrosive conditions. For detailed test data and penetration test results the reader is referred to the manufacturer.

In general these alloys are not attacked by inside and outside atmospheres unless there is a sulphurous condition. Marine atmosphere may have slight effect, but rural and suburban atmospheres have none. "Inconel" remains bright and is not subject to fogging; "Illium" and the "Hastelloys" remain bright; the nickel-copper alloys may take on a brownish to green tarnish in sulphur-bearing atmospheres, but there is no destructive corrosion.

All the alloys are completely resistant to any corrosion by fresh water.

Quiet or stagnant sea water will attack all the alloys through pitting, except "Hastelloy C" and "Illium G," but the nickel-copper alloys have their greatest use in sea water under conditions of high velocity where resistance to effects of impingement and cavitation are important.

Alkalies. All the nickel-base alloys are extremely resistant to alkalies. Nickel has outstanding resistance to caustic soda, but ammonium hydroxide in concentrations over 1 per cent will corrode nickel appreciably. The nickel-copper alloys can be used in ammonium hydroxide in concentrations up to

3 per cent, but the nickel-chromium-iron alloys resist all concentrations. In concentrated caustic soda at 800° F. the chromium content of "Inconel" and the other chromium-bearing alloys makes them subject to corrosion.

Wet and Dry Gases. Dry gases at room temperature do not affect these alloys. "Inconel" is completely resistant to mixtures of steam, air and carbon dioxide. However, wet chlorine, bromine, and sulphur dioxide attack nickel, "Monel" and "Inconel." Wet nitric oxide and ammonia corrode nickel and "Monel." Both nickel and "Inconel" resist mixtures of nitrogen, hydrogen and ammonia in the nitriding process; "Inconel" is somewhat superior. Chlorine and hydrogen chloride do not attack nickel and "Inconel" up to 1000° F. or "Monel" up to 850° F. Gases of sulphur compounds will attack all the nickel-base alloys at elevated temperatures. "Chlorimet 2" resists wet hydrogen chloride gas.

Neutral or Alkaline Salts. In general all the nickel-base alloys are highly resistant to neutral or alkaline salts.

Oxidizing Salts. Nickel and the nickel-copper alloys are attacked by oxidizing acid salts. The chromium-containing alloys demonstrate useful resistance to these media. Nickel, "Monel" and "Chlorimet 3" are not resistant to solutions containing appreciable percentages of ferric, cupric and mercuric chlorides. "Hastelloy C" has unusual resistance to ferric chloride up to 160° F. and to cupric chloride up to 100° F. It also resists at moderate temperatures such mixtures of oxidizing salts as chromates and nitrates in sulphuric and hydrochloric acid solutions. "Illium G" resists acid phosphates and acid sulfates, also mixtures of oxidizing salts in acid solutions.

Oxidizing Alkaline Salts. "Inconel" is unaffected by hydrogen peroxide solutions. Hypochlorites are less corrosive to "Inconel" than to "Monel" or nickel. The recommendation is to avoid exposure to solutions containing more than 3 grams of available chlorine per liter and to use these alloys only when the exposure is part of a cyclic operation in which there is intermittent exposure to weak acid solutions. "Hastelloy C" possesses unusual resistance to oxiding solutions, especially those containing chlorides, and to hypochlorite solutions and moist chlorine. "Chlorimet 3" is used for handling hypochlorite bleaches at temperatures below 105° F.

Mineral Acids. Nickel and nickel-copper alloys resist air-free sulphuric acid under 80 per cent concentration. "Monel" is good in boiling solutions in concentrations under 20 per cent. "Inconel" has fair corrosion resistance to sulphuric and hydrochloric acids at atmospheric temperature but is not used for hot or concentrated hydrochloric acid; in such cases, "Hastelloy" A or B is preferred. However, "Inconel" has the higher resistance to hydrogen sulphide solutions. Strong oxidizing acids like nitric acid attack nickel readily. "Hastelloy" A and B were developed primarily to resist hydrochloric acid. "Hastelloy D" resists concentrated sulphuric acid; "Hastelloy D" does so at elevated temperatures; while "Illium G" resists sulphuric acid under all conditions of concentration and temperature. "Illium G" is not recommended for strong or hot and dilute hydrochloric acid but is used for phosphoric acid and hydrogen sulphide. "Hastelloy C" is highly resistant to all the mineral acids. Additions of small amounts of oxidizing salts, such as ferric sulphate or cupric sulphate to sulphuric acid solutions increases the passivity range of the nickel-chromium-iron alloys. "Chlorimet 2" also gives excellent service in sulphuric acid of 35 to 60 per cent concentration at temperatures up to boiling. "Chlorimet 3" is good for hot sulphuric acid solutions of less than 35 per cent concentration.

Oxidizing Acids. Nickel is attacked by such oxidizing acids as nitric acid, and so are the nickel-copper alloys, except in concentrations below 1 per cent at room temperature. "Inconel" and the nickel-chromium-iron alloys are highly resistant to these acids at moderate temperatures, and the higher the chromium content the wider the range of concentration and temperature in which passivity exists. Sulphurous acid solutions, especially when hot, attack nickel and "Monel" but are resisted by the chromium-containing alloys. "Hastelloy C" is resistant to dilute nitric acid up to 150° F., and to concentrations over 40 per cent only at room temperature. "Hastelloy A, B and D" are not recommended for nitric acid or other strongly oxidizing acids. Both "Hastelloy C" and "Illium G" resist mixtures of nitric and sulphuric acids, chromic and sulphuric acids, sulphuric and dichromates, permanganates and persulphates, and similar combinations of sulphuric acid and nitric acid over a wide range of temperatures.

Organic Acids and Compounds. Neutral and alkaline organic compounds have no effect on nickel, but organic acids do corrode it moderately. The nickel-copper alloys have good resistance to organic acids, neutral and alkaline organic compounds, as well as fruit and other food acids. The nickel-chromium-iron alloys have complete resistance to the organic acids occurring in food products, are only fairly resistant to hot, concentrated organic acids such as acetic and formic, but are particularly resistant to fatty acids at elevated temperatures. The "Hastelloy" alloys and "Illium" resist all organic acids and neutral and alkaline organic compounds.

Stainless Steels

The most familiar of the stainless steels is the austenitic 18–8 type, containing 18 per cent chromium and 8 per cent nickel. As indicated in Chapters 5 and 16 there are numerous modifications of this class of materials, ranging from the straight-chromium steels (such as the 12 per cent chromium) to alloys of chromium, nickel and molybdenum that are virtually iron-free. They are all highly corrosion-resistant, the degree of resistance varying with the alloy content, carbon content, thermal treatment and condition of the surface.*

Chromium is the only alloying element which has been found to produce in iron alloys a condition approaching complete resistance to atmospheric corrosion. More than 11 per cent chromium is necessary to provide this characteristic, even in pure iron. The presence of carbon in the alloy necessitates additional chromium because, under certain conditions, each unit of carbon may combine with as much as 18 units of chromium and render that portion of the alloying element ineffective in its protective function.

In the 5 per cent chromium steels (Types 501 and 502) corrosion is retarded to about one-fifth the rate of ordinary steel.[12] They are often alloyed with small percentages of molybdenum and are largely used in oil-refinery work, in preheater tubes, bubble caps, furnace parts and still bottoms, even in the processing of very sour crudes.

The 7 to 9 per cent chromium steels containing some molybdenum are used for somewhat more severe service conditions in the same applications as the 5 per cent chromium steels.

The 13 per cent chromium steels (Types 403, 405, 410, 416 and 420) resist corrosion from the atmosphere, mine waters, steam, carbonic acid, crude oil, mercury, soap and sugar solutions. These steels, with less than 0.08 per cent carbon, are not hardenable by heat treatment, but do respond to hardening heat treatment with increasing carbon content. Maximum corrosion resistance of the hardenable grades is obtained in the fully hardened condition.

The addition of nickel to the 13 per cent chromium grade (Type 414) improves its corrosion resistance to certain chemicals and also makes the alloy respond more readily to a hardening heat treatment.

The 17 per cent chromium steels (Types 430, 431 and 440) have better corrosion resistance than the 13 per cent chromium steels, especially against nitric acid and milk. This grade is used in the nitric acid industry, in the rubber, oil, baking and meat-packing industries, and also for septic and similar tanks.

These steels with carbon content below 0.12 per cent are not hardenable by heat treatment, although with higher carbon contents they can be hardened. However, the increase in carbon content impairs corrosion resistance. Alloyed with about 2 per cent nickel, this steel (Type 431) develops good heat-treating, tensile and corrosion-resisting properties, especially against electrolytic corrosion in contact with some non-ferrous metals in the presence of salt water (sea water or brine) and similar electrolytes.

---

* See Chapter 5 for chemical composition of the different AISI types of stainless steels according to the type number.

The 20 per cent chromium steels (Types 442 and 443) are not hardenable by heat treatment. They are similar to the 17 per cent chromium grade but have slightly better corrosion resistance. The addition of 1 per cent copper improves the resistance to corrosion in some media. In some respects the anti-corrosion features, especially toward sulphuric acid, are also better, but halogen acids attack the steel severely. The material is free from intergranular corrosion effects.

The 28 per cent chromium steels (Types 443 and 446) are not hardenable by heat treatment but are among the most heat- and corrosion-resisting of the stainless steels. They are used in applications where acid mine waters, sulphur gases or mixed acids are encountered at high temperatures. Some special analyses have been developed with about 5 per cent nickel and 2 per cent molybdenum for more severe corrosion conditions.

Chemical passivity is imparted to chromium steels when they are first cleaned with a 20 to 40 per cent solution of warm (130–150° F.) nitric acid and then immersed in a mixture of ½ per cent nitric acid and ½ per cent potassium dichromate and boiled for 30 minutes. This treatment effectively removes surface impurities picked up in fabrication, and puts the metal in a condition for best corrosion resistance. Passivation should be followed by a thorough rinse in hot water.

The element nickel is next in importance to chromium as an alloy in the field of corrosion-resisting steels, and the addition of nickel to straight-chromium steels provides a series of alloys having superior resistance to corrosion.

The composition 18 per cent chromium and 8 per cent nickel (Types 302, 303 and 304) has the best combination of resistance to corrosion and desirable mechanical properties. These alloys are not hardenable, as they are austenitic in structure. They are immune to most organic chemicals, sterilizing solutions, foodstuffs, dyestuffs and a wide variety of inorganic chemicals. They resist nitric acid well, halogen acids poorly, and the sulphur acids moderately.

Aqueous solutions containing a chloride ion, as for example, solutions of ferric chloride or sodium hypochlorite, have a tendency to pit 18–8 steels rapidly. The addition of approximately 3 per cent molybdenum to 18–8 (Types 316 and 317) combats this tendency successfully.

Molybdenum in proportions above 2 per cent substantially improves the resistance to a great number of severely corrosive media. It is particularly advantageous where the corrosive media tend to be of a reducing nature. The molybdenum grade of 18–8 steel has been notably successful in the handling of sulphite pulp liquor, acid dyestuff, acetylating and nitrating mixtures, sulphuric, sulphurous, phosphoric, formic, citric and strong lactic acids, bleaching solutions, etc. Molybdenum also acts as a partial stabilizing agent in reducing localized corrosive attack resulting from carbide precipitation.

Carbide precipitation can be serious if the metal is exposed to active corrosive agents. The lower the carbon content, the less the carbide precipitation when exposed to the temperature range 800 to 1600° F., as explained in detail in Chapter V. A carbon content of less than 0.08 per cent minimizes intergranular corrosion. Therefore, low carbon and adequate heat treatment is the answer to the intergranular corrosion problem in normal austenitic alloy steels. When the carbon is high, carbides precipitate at the grain boundaries if the metal is heated for a short time within the critical temperature range or cooled slowly through this temperature range. Active electrolytes corrode the metal in the zone of the precipitated carbides and gradual disintegration or sudden failure will occur eventually as a result of the intergranular attack.

Stabilized stainless steels are of the 18–8 type to which a minimum percentage of titanium equal to four times the carbon content (Type 321) or of columbium equal to ten times the carbon content (Type 347) has been added to render the material immune to intergranular corrosion. These two alloys, when properly heat-treated, exhibit complete freedom from this attack even under the most severely corrosive conditions.

To insure maximum corrosion resistance to prolonged outdoor exposure, parts made from the austenitic 18–8 type of stainless steel are passivated by immersing them in a solution of nitric acid for 20 to 30 minutes, washing in water, and drying.

The industrial reagents which are incapable of attacking clean surfaces of 18–8 would make a very long list, and no attempt will be made to tabulate all of them. However, an impression of the kind of environment in which 18–8 is highly corrosion-resistant may be formed from the following examples:

Acetic acid, cold, at any concentration
Acetic acid, hot, up to about 10%
Alkaline solutions in general, including ammonium hydroxide
Bichloride of mercury, dilute (usual antiseptic strength)
Carbolic acid
Carbonated water
Citric acid, cold, moderate strength
Copper sulphate
Fruit and vegetable juices
Hydrogen peroxide
Hydrogen sulphide
Laundry solutions, with few exceptions
Milk and dairy products
Nitric acid
Photographic solutions
Salt solution
Sea water
Sulphuric acid, cold, very slight action
Sulphurous acid
Wood pulp
Yeast
Zinc chloride, cold
Zinc sulphate

As is well known, stainless steels resist corrosion by the formation of an oxide film which prevents further attack; hence, oxidizing conditions are necessary for these alloys to resist corrosion. With a chromium content of approximately 12 per cent, normal atmospheric conditions are sufficiently oxidizing to promote the formation of a protective film. With this chromium content, stainless steels resist corrosion in normal atmospheric and similar conditions. As the conditions of service become less and less oxidizing, successively higher chromium contents are necessary to promote the formation of a protective film.

It is well to mention that the most important factor affecting the service obtained from stainless steels is the condition of the surface. To obtain the best results and to facilitate film formation, it is necessary to have a clean, smooth surface free from foreign material and imperfections.

Table 123 gives a partial list of the resistance of several stainless steels to various corrosive media. As numerous factors affect the corrosion resistance of materials, such as aeration, agitation and temperature, this listing should be used as a guide rather than as a final recommendation.

The foregoing A.I.S.I. type numbers of the different grades of corrosion resistant and stainless steels refer to the wrought material only. The standard designations of these alloy compositions for corrosion resistant castings are shown in Appendix as published by the Alloy Casting Institute. Clad stainless steels are used extensively for low cost equipment and in many cases are just as serviceable as the non-clad materials.

Several high nickel-chromium alloys containing molybdenum and copper are very resistant to sulphuric acid. "Durimet T," a low-carbon alloy containing 21 to 23 per cent nickel, 18 to 21 per cent chromium, 1.75 to 2.25 per cent molybdenum and 0.90 minimum per cent copper has found its greatest use in handling sulphuric acid. It is unattacked in any concentration of sulphuric acid at room temperature, and likewise will handle all concentrations up to 78 per cent at 125° F. The presence of small amounts of oxidizing agents, as nitric acid, ferric sulphate, or copper sulphate, greatly improves the resistance under the most severe conditions. This alloy can be cast, rolled and forged.

On stronger sulphuric acid solutions, "Durimet 20" or "Carpenter 20" is recommended. The former is available only in cast form, while the latter is available in wrought form. A nickel content of 28 to 30 per cent with 19 to 21 per cent chromium and 1.75 to 3.0 per cent molybdenum provides a suitable matrix to place 4.0 to 4.5 per cent copper in solid solution, which is of fundamental importance in securing good physical properties, together with unusually high resistance to hot concentrated sulphuric acid.

In the cast form "Durimet T" has a tensile strength of 60,000 to 70,000 psi, a yield point of 25,000 to 30,000 psi, an elongation in 2 inches of 35 to 50 per cent, and a Brinell hardness of 130 to 150.

The mechanical properties of "Durimet 20" and "Carpenter 20" are shown in Table 124.

TABLE 124.

	"Durimet 20" casting quenched-annealed	"Carpenter 20" rolled
Tensile strength (psi)	65,000–75,000	85,000
Yield point (psi)	26,000–32,000	35,000
% Elongation (2")	50–35	35–50
% Reduction of area	60–40	50–70
Izod impact, foot-lbs.	88–80	——
Brinell hardness	120–150	150–180

The superior corrosion resistance of these two alloys compared with that of 18–8 alloys is well established. For example, the rate of corrosion of 18–8 steel by a 10 per cent sulphuric acid solution is over 100 times greater than the rate of corrosion on "Durimet 20." A similar difference in corrosion resistance is that shown on 80 per cent acetic acid at 175° F.

For further information on the properties and fabrication characteristics of these stainless alloys refer to Chapters 5 and 16.

OTHER CORROSION-RESISTANT ALLOYS

Wherever corrosive liquids and gases are encountered, the usefulness of a 14 per cent silicon-iron alloy containing about 1 per cent manganese is generally recognized. Such equipment as centrifugal and reciprocating pumps, valves, pipe, fittings, kettles and exhaust fans are made of this alloy under the trade mark "Duriron," which is practically unaffected by sulphuric acid, nitric, acetic and most other commercial acids of any strength or at any temperature. Hot hydrochloric acid of high concentration has an appreciable action on "Duriron"; however, it is the most economical material that is commercially available because of its relatively long service. It is not recommended for handling bromine, fused alkalies, hydrofluoric acid, hot concentrated ferric chloride, or the chlorides of sulphur.

"Duriron" is a cast alloy, too hard to machine with cutting tools. All parts therefore must be cast to shape and all machining operations are accomplished by grinding equipment. However, "Duriron" may be readily welded with an oxy-acetylene flame. Careful preheating and cooling of the parts to be welded are essential. "Duriron" has high resistance to wear by abrasion. Table 125 shows some of its physical properties.

Although hydrochloric acid and most of the chlorides have little effect on "Duriron" at room temperature and low concentrations, for elevated temperatures and higher concentrations an alloy known as "Durichlor" has been developed. It has greatly improved resistance to the chlorides and has found wide commercial use. "Durichlor" has approximately the same physical characteristics as "Duriron," but has greatly improved corrosion resistance to hydrochloric acid in all concentrations up to the boiling point. This

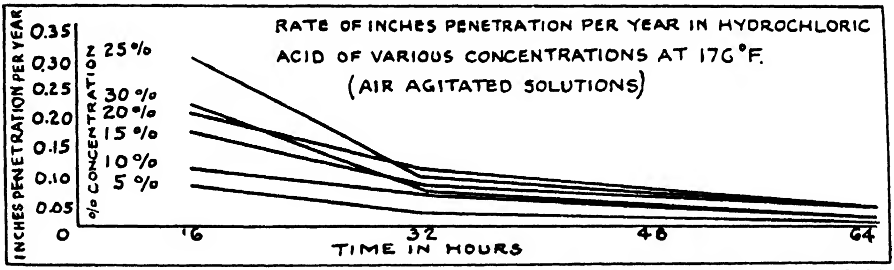
TABLE 125. *Physical Properties of "Duriron."*

Specific gravity	7.00
Tensile strength (psi)	10,000
Transverse strength (lbs.)	1,000
Transverse deflection (inches)	$\frac{1}{16}$ to $\frac{1}{8}$
Compressive strength (psi)	70,000
Melting point	about 2,300° F.
Coefficient of expansion per ° F.	0.0000156
Shore scleroscope hardness	49–51
Contraction allowance in casting (in./ft.)	$\frac{3}{16}$
Thermal conductivity (Ag = 1)	0.32° F.

all-purpose alloy results from the addition of molybdenum; the nominal composition is 14.5 per cent silicon, 3 per cent molybdenum, 0.9 per cent carbon, 1 per cent manganese, remainder iron.

The specific resistance to hydrochloric acid at 175° F. is shown in Figure 111. It will be observed that the time for film formation and passivation to develop optimum corrosion resistance requires from 32 to 48 hours. This alloy is not recommended for use with mixtures of chlorine gas and steam, or where strong sulphuric or weak nitric acid is alternated with hydrochloric acid; the latter conditions break down the acid-resistant film, resulting usually in a high rate of deterioration.

An aluminum bronze of the composition 87.5 per cent copper, 7.5 per cent aluminum, 3.5 per cent iron and 1.5 per cent manganese or nickel combines excellent acid-resisting properties and mechanical strength. It is resistant to many inorganic chemicals, and in addition, it can be used with a wide range of organic acids, animal and vegetable oils or oil refinery sludge acids. However, it is not suitable for hot concentrated hydrochloric acid, nitric acid and mine water. It has good resistance to fatigue, retains strength at elevated temperatures, resists wear and has in general good mechanical properties. It can be cast, forged, rolled, drawn and machined. Some of the physical properties of this alloy ("Alcumite") are shown in Table 126. It



(*Courtesy Duriron Co., Dayton, Ohio*)

Figure 111. Specific resistance of "Duriron" to HCl.

may be annealed by heating to 1400–1600° F., and either quenching in water or cooling rapidly in a blast of compressed air.

TABLE 126. *Physical Properties of "Alcumite"*

Specific gravity, cast	7.75
Melting point ° F.	1,900
Coefficient of expansion, per ° F.	0.00000935
Thermal conductivity, Btu per ° F., difference in temp. per one foot thickness	60
Electrical conductivity	9% of copper
Casting shrinkage (inch per foot)	3/16
Modulus of elasticity	16,500,000

Form	Brinell hardness	Tensile strength (psi)	Yield point (psi)	% Elong. in 2 inches	% Reduction of area
Green sand castings	110–120	75,000	25,000	30	35
Hot-rolled rod (Not annealed)	160–210	85,000–100,000	40,000–60,000	15–25	20–25
Hot-rolled rod (Annealed 1,400° F.)	150	76,000	35,000	40	45
Hot-rolled rod (Annealed 1,500° F.)	130	76,000	28,000	40	45
Hot-rolled rod (Annealed 1,600° F.)	110	76,000	25,000	40	45
Hot-rolled sheet (Annealed)	110	76,000	25,000	40	45

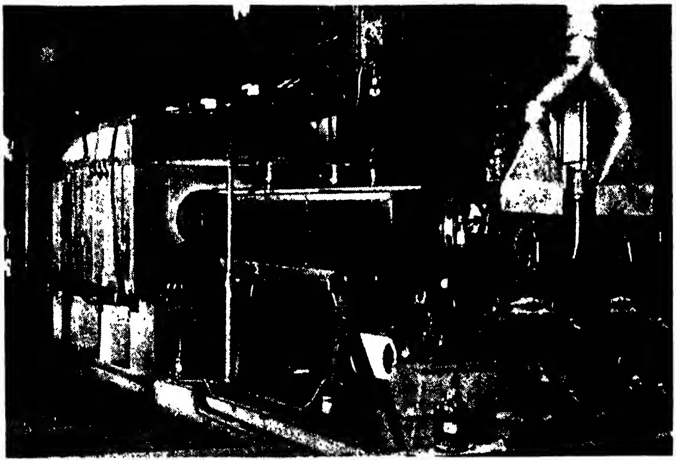
A great many other base alloys of iron, copper, nickel, and aluminum are used in the chemical and allied industries for corrosion resistance. These are too numerous to discuss here and the reader is referred to the manufacturers' publications and bulletins for further information.

Figure 112 shows a reduction furnace viewed from discharge end. Tubes in fire-box are centrifugally cast "Misco Metal" analyzing 35 per cent nickel, 15 per cent chromium, balance iron.

Figure 113 shows an exhaust manifold made entirely of "Inconel" by the Kellet Autogiro Corporation.

Figure 114 shows a 17-foot hydrofluoric acid regenerator column, the inside of which is lined with 1/16 inch "Monel" metal sheet. The two grids are also made of "Monel."

Figure 115 shows a complete centrifugal pump of cast "Hastelloy" B, used in the production of aromatic hydrocarbons, where the alloy successfully resists hydrochloric acid and chloride catalysts. The pump bodies, impellers, shafts, discharge pipes, and suction lines are all made of this alloy. Figure 116 shows the Simpson-Mantius sulphuric acid concentrator equipped with "Hastelloy" D heater tubes, operated at 500 lbs. steam pressure, for concentrating spent sulphuric acid up to 96 per cent.

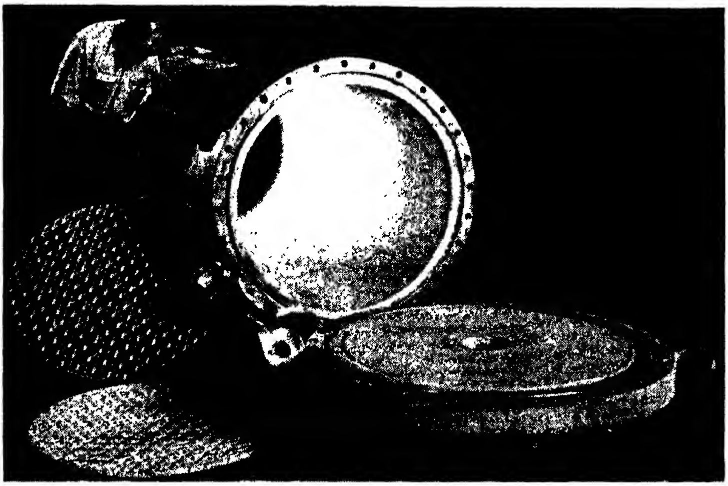


(Courtesy International Nickel Co., New York, N. Y.)

Figure 112. Reduction furnace.

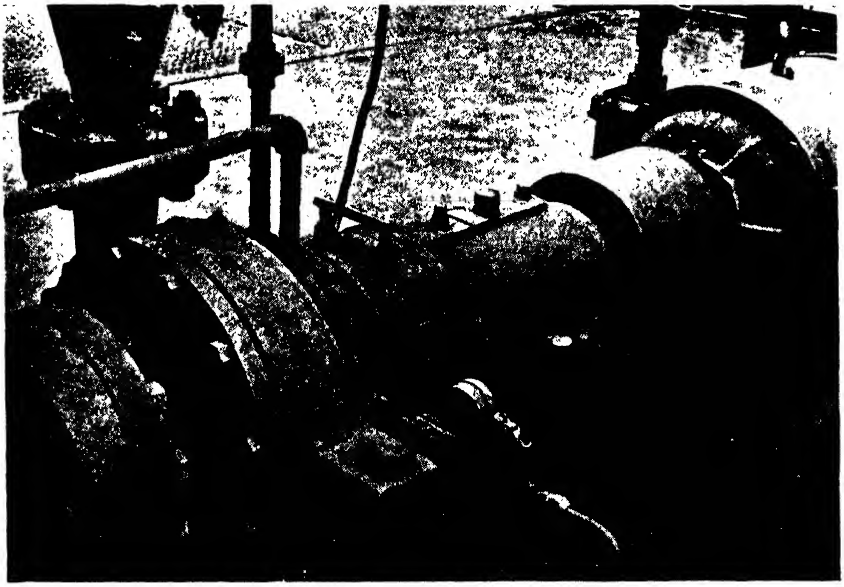
(Courtesy International Nickel Co., New York, N. Y.)

Figure 113. "Inconel" exhaust manifold.



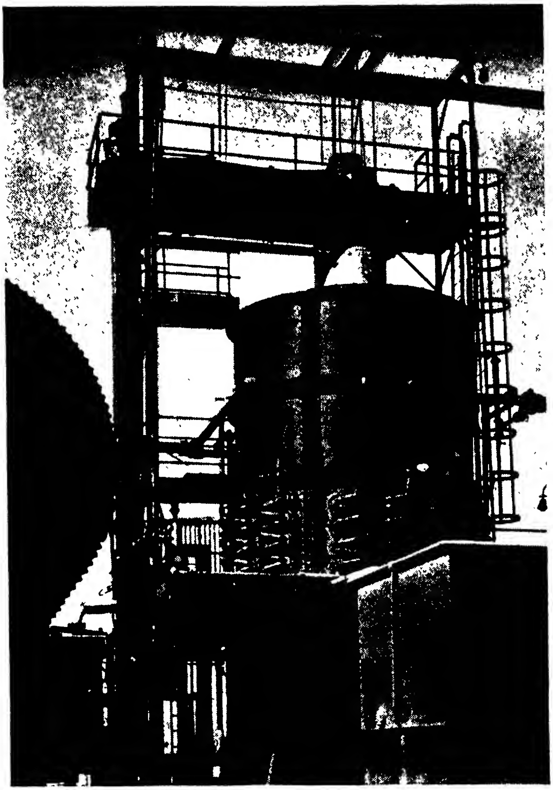
(*Courtesy A. O. Smith Corporation, Milwaukee, Wis.*)

Figure 114. Hydrofluoric acid regenerator.



(*Courtesy Haynes Stellite Co., Kokomo, Indiana*)

Figure 115. Centrifugal pump.



(*Courtesy Haynes Stellite Co., Kokomo, Ind.*)

Figure 116. Sulphuric acid concentrator.

Figure 117 shows strip welding "Hastelloy" B 12-gauge liner in an isomerization tower. In this application, the alloy effectively resists the hydrochloric acid formed when the aluminum chloride catalyst hydrolyzes. Figure 118 shows a "Chlorimet" Durcopump installed in a pharmaceutical plant. It was made of "Chlorimet 2" alloy. A similar pump made of "Chlorimet 3" was used successfully for nitric acid.

The various proprietary alloys mentioned in this chapter are registered trade names of the following manufacturers:

American Manganese Division American Brake Shoe Company.
"Amsco F 5" "Amsco F 6"

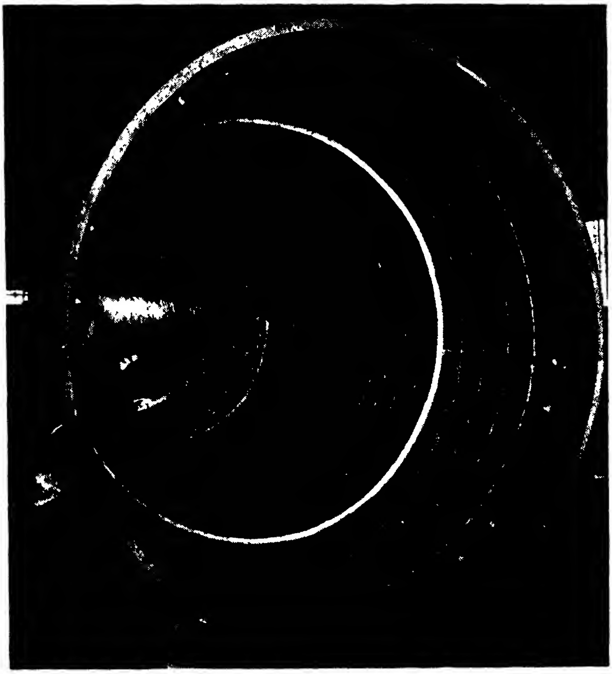
Babcock-Wilcox Co.
"B and W 700" "B and W 701"

Burgess-Parr Corp.
"Illium"

Carpenter Steel Co.
"Carpenter 20"

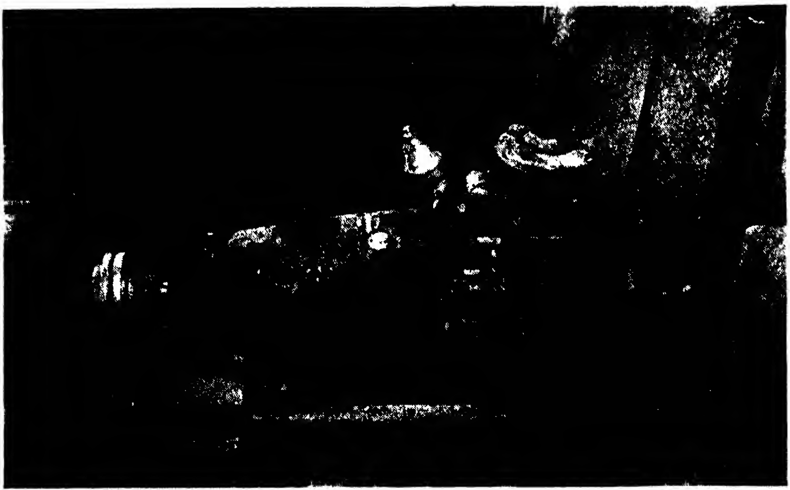
Driver-Harris Co.
"Nichrome"

- Duriron Co.
  - "Chlorimet 2"
  - "Chlorimet 3"
  - "Durimet T"
  - "Durimet 20"
  - "Alcumite"
  - "Duriron"
  - "Durichlor"
- Electro Alloys Division American Brake Shoe Co.
  - "Thermalloy A"
- Haynes-Stellite Co.
  - "Hastelloy A"
  - "Hastelloy B"
  - "Hastelloy C"
  - "Hastelloy D"
- Hoskins Manufacturing Co.
  - "Chromel C"
- International Nickel Co.
  - "A Nickel"
  - "D Nickel"
  - "E Nickel"
  - "L Nickel"
  - "Duranickel"
  - "Inconel"
  - "Monel"
  - "H Monel"
  - "K Monel"
  - "KR Monel"
  - "R Monel"
  - "S Monel"
- Midvale Steel Co.
  - "Midvaloy BTC"
- Michiana Products Corp.
  - "Firearmor A"
  - "Firearmor B"
- Wilbur B. Driver Co.
  - "Tophet C"



(Courtesy Haynes Stellite Co., Kokomo, Ind.)

Figure 117. Isomerization tower.



(Courtesy The Duriron Company, Inc., Dayton, Ohio).

Figure 118. Chlorimet Durcopump.

References

1. LaQue, F., "Working of Nickel-Base Alloys," *Mech. Eng.* (March, 1937).
2. Anon., "Working of High Nickel Alloys," *American Machinist* (August 20, 1942).
3. Mudge, W., "Fabrication and Treatment of Nickel and High-Nickel Alloys," *Can. Inst. Min. Metall.* (1943)
4. Betty, B., and Mudge, W., "Some Engineering Properties of Nickel and High-Nickel Alloys," *Mech. Eng.* (December, 1944).
5. Woldman, N. E., "High Nickel Alloys" *Materials and Methods* (December, 1946).
6. Friend, W., "Nickel and High Nickel Alloys," *Ind. Eng. Chem.* (October, 1947).
7. "Properties of Nickel and Nickel-Containing Materials," Mond Nickel Co., Ltd., bulletin.
8. "Nickel and Nickel Alloys," International Nickel bulletins.
9. "Hastelloy," Haynes-Stellite Co., bulletins.
10. "Illium," Burgess-Parr Co., bulletins.
11. "Chlorimet Duriron and Durichlor," Duriron Co., bulletins.
12. Anon., "Stainless Steels," *Product Engineering* (February, 1945).
13. Thum, E., "Stainless Steel," American Society for Metals (1945).

Chapter XVI

High-Temperature Materials

The principal fields of application for metals in high-temperature service are in the oil-refining industry, furnace industry, chemical industry, metallurgical furnaces, heat-treating equipment, automotive valves, power plant equipment, gas and steam turbines, and jet propelled airplanes. Some other fields are the manufacture of molds for cast metals and glass, radio tubes, pyrometry and electrical resistance heating elements.[11]

The requirements vary considerably with the field of application and often within the same field. The properties of different alloys at elevated temperatures show an equal or greater variation, and even today knowledge about them is far from complete. It is certain, however, that no one alloy or family of alloys can be selected having all the properties in the desired degree for universal application.

Before he can even begin to select or develop suitable alloys for a given application, the design engineer must be able to answer certain basic questions. The necessity for this information will become apparent when the characteristic properties of metals at high temperatures are considered. The most important questions are: What will the normal operating temperature and the peak temperature be? Will service at these temperatures be continuous or intermittent? What is the load per square inch? Will it be continuous or intermittent, fluctuating or steady? What is the stress-weight ratio? Is the part stationary, rotating, or reciprocating? What are the hazards of sudden failure? How close must tolerances be held? What clearances must there be between moving parts? What is the required life of the part? Is the part subject to impact loads of appreciable magnitude at room temperature and at elevated temperature? In what medium will the alloy be required to operate?

Required Properties

At operating temperatures in excess of 800° F., room temperature properties begin to lose significance as a means of evaluating service performance. This is because load-bearing and a number of other properties are no longer relatively independent of rate and duration of loading, and because such factors as thermal expansion and oxidation begin to play a more important part. The properties of most importance at elevated temperatures are stress-rupture, creep, thermal expansion, structural stability and corrosion resistance. Fatigue resistance is often important, as are impact strength, damping capacity and hot ductility.

Stress-rupture and creep properties are closely related, but are not identical. For example, stress-rupture tests that do not measure rate are made at higher stress values than are used for creep and tell little about the low rates of plastic deformation or initial deflection on loading which are of interest in creep. On the other hand, creep tests give little information about the load to fracture or the hot ductility. The latter are accelerated life tests, requiring at least a thousand hours each. They are mutually complementary, and a complete evaluation of a metal or alloy for high-temperature service requires that both be determined. However, in stress-rupture tests that measure rates there is no dividing line between the two properties. Proper study requires a family of tests, the lower stress members of which may not break in the test period allotted. The short-time, high-temperature tensile test is of value only as the initial point of the stress-rupture test, and nothing of the life of the part can be predicted on the basis of this test alone. It is more useful for estimating the hot-working properties of the material. In general, creep values are of the order of fifty per cent of stress-rupture values, but this ratio increases, fortunately, with the duration of the test. Scatter bands for 1,000-hour rupture and creep of 0.001 per cent per hour frequently overlap. Where repeated cycles of temperature changes of any appreciable magnitude are to be encountered, a special type of creep test (the relaxation creep test) may be used.

Thermal expansion of an alloy is a quite important property from the standpoint of design, where close dimensional tolerances must be held, because of clearance and of other considerations at junctions between different alloys or similar alloys at widely different temperatures. If these junctions are rigid, destructively high stress concentrations may be set up. Warping is another factor closely related to thermal expansion and generally must be considered. For example, it has been found that the perfectly balanced rotor of a turbine at room temperature may be badly out of balance at operating temperature because of this factor; hence rebalancing at operating temperatures becomes necessary.

Where long life of the unit is a consideration, structural stability of the material is a requirement. Certain types of alloys, even though they possess high initial strength, fail rapidly at much lower stresses at high temperatures because of destructive changes in their internal structure, *e.g.*, precipitation of brittle constituents at grain boundaries, or overaging of solution-treated and aged alloys.

Almost any medium in which a metal is used at high temperatures tends to be corrosive. Corrosion tends to shorten the life and lower the permissible stresses by reduction of section thickness and area over appreciable periods of time. Mild general corrosion is not too serious a factor and can be allowed for by a change in section in the original design. But differential corrosion is more serious. Pitting and grain boundary attack rapidly lead to failure—hence the interest in surface stability. Erosion by gases and dirt may also be a factor.

Fatigue resistance tends to be proportional to stress-rupture properties, but is, of course, affected by such stress raisers as differential corrosion and structural instability. An alarming feature of fatigue life at elevated temperatures is the fact that it does not tend to level off with time, as is the case at room temperature. There is no specific load at which a guarantee can be given that failure by fatigue will not occur, regardless of the number of stress reversals. However, a redeeming feature is that fatigue resistance does not decrease as rapidly as do other properties.

Where there is a possibility that the frequency of stress impulses may approach the resonant point of a metal or alloy, its damping capacity becomes important. Unfortunately, alloys possessing very good high-temperature properties usually have the lowest damping capacity. The method of processing the alloy, however, affects this: cast alloys generally have higher damping capacity than wrought alloys of the same composition.

When failure without warning involves a hazard, hot ductility is important. In general, values for this property are rather low for most of the high-strength, high-temperature alloys and tend to decrease with time. Hot ductility is also of importance in limiting the processing of the material by forging or rolling and also fabrication by welding.

When the stress-weight ratio does not impose too great limitations, as it does in aircraft design, much use can be made of the older alloys, though the required high-temperature data of the type now found necessary may be incomplete.

For high-temperature work an alloy must possess a definite strength at a certain high temperature with a minimum allowable deformation for a definite expected life. The main problems which face engineers are: (1) determination of the ultimate strength of materials which are to be in service at high temperatures for about 100,000 hours, and (2) the choice of a material in which the influence of notches and multi-dimensional stresses does not lead to excessive weakening.

In regard to the first problem, extrapolation over long periods is best done on the basis of stress-rupture tests. Important conclusions as to structural stability may be drawn from several factors. The reduction of area and elongation are of great significance, as the true stress-contraction curves are essential for information on the notch sensitivity. Much useful data from tests with notched bars can be obtained from these curves, which may be S-shaped for many metals.

Room-temperature tensile and impact properties of specimens broken in the stress-rupture test are also important, as well as changes in the metallographic structure. So far insufficient progress has been made to prescribe maximum or minimum values which can be regarded as admissible limits.

To investigate the influence of notches and multi-dimensional stresses, tests must be made on notched bars as well as on whole machine parts. Without the S-shaped, true stress-contraction curve, it is impossible to draw any practical conclusion regarding notch sensitivity.

The view has been expressed that elongation measurements over short periods may be capable of providing information as to the limits of usefulness of a highly heat-resistant steel; but other qualities, such as the tendency to brittleness and structural stability, which cannot be determined by such measurements, are also essential for designing purposes.

It is a thermodynamic fact that the hotter a turbine system is run, the more efficient it will be. Thus if an alloy can be developed that can withstand higher temperatures than present existing alloys, a more efficient system from an energy standpoint will result. The two most important physical properties of such an alloy would be good yield strength and creep strength at high temperatures. An alloy that had the yield characteristics exhibited in Figure 119 as Alloy No. 1 would be far more advantageous than Alloy No. 2, because the yield strength remains fairly constant or falls off very slowly as the temperature increases. Although the above refers to hot yield strength, cold yield strength is important under thermal fatigue conditions.

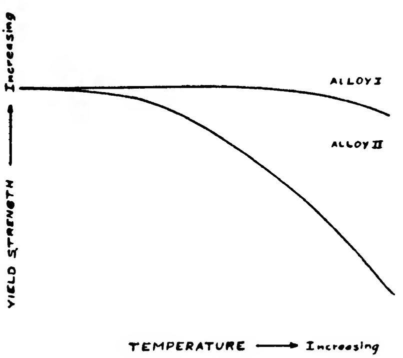


Figure 119. Yield strength versus temperature.

The behavior of metals at elevated temperatures is entirely different from that at room temperatures; consequently, room-temperature properties do not necessarily predict properties at the elevated temperatures. The room-temperature properties[16] used for design purposes are based on the elastic properties of the steel. Regardless of whether the design is based on a certain fraction of the yield point or tensile strength, the resulting stress is always below the proportional limit; consequently the part exhibits no measurable elongation during service other than the elastic deformation which occurs upon application of the load.

On the other hand, metals at elevated temperatures possess both elastic and plastic properties, though the plastic properties predominate under certain conditions. At these temperatures an elastic deformation occurs upon the application of a load below the apparent elastic or proportional limit; but if the temperature is sufficiently high—and this varies with different steels—this deformation is not independent of time, as was the case at room temperature, but increases as the time of application of load is extended. This increase in elongation with time under a constant stress is now called *creep.*

In addition to strength and surface stability, high-temperature steels must also have a suitable degree of structural stability and be capable of retaining good ductility and shock resistance both at operating temperatures and at room temperature after service at elevated temperatures. Hot ductility is usually required for load redistribution and for avoiding thermal stress cracking, rather than shock. Low-alloyed pearlite type steels undergo spheroidization, which tends to decrease the load-carrying ability; whereas austenitic steels undergo carbide precipitation in the grain boundaries, which decreases the corrosion resistance and may impair the ductility.

Elastic properties[1] have little application to high-temperature design. Instead, the plastic or creep properties are employed. Resistance to deformation under constant load has been utilized as a basis for comparing the high-temperature strength of different alloys.

Elevated-temperature tensile tests differ from most service conditions in that they indicate behavior under stresses rapidly and continuously increasing to fracture, while industrial applications ordinarily involve lower, more constant stresses. With drastic overloading in service, accelerated elongation will result and, if failure does not take place, plastic deformation will rapidly decrease the stress. Creep at high rates will then continue until (1) the stresses are relieved by transfer of load to adjacent structural units, or (2) stresses have fallen to safe working levels, or (3) fracture occurs at some stress below the nominal yield strength.

Creep. It has long been known that metals undergo slow deformation, known generally as "creep," when subjected for long periods of time to conditions of high temperature and stress. Creep[18] is a continuing change in the deformation or deflection of a stressed member. It is generally associated with a time rate of deformation continuing under stress intensities well below the yield point, the proportional limit, or the apparent elastic limit for the temperature in question.

The initial creep upon a material not previously strained is invariably rapid, but as the straining progresses, the rate of creep decelerates until, after an appreciable period, a constant rate is approximated. This initial straining at a decreasing rate is frequently designated as the first stage of creep. The second stage is the strain which occurs either at a constant rate or in an asymptotic approach to a constant rate. The design of stressed members is generally based upon the rate of second-stage creep strain. The useful life of a structure is for some purposes adjudged to be the time lapse before the termination of the second stage. The third stage is marked by an accelerating creep rate, leading to fracture. Although stress intensification and "necking" of the section contribute to the promotion of third-stage creep, this stage is generally reached at much smaller deformations than those sufficient to produce rapid creep to fracture through stress intensification alone. Such evidence is held to be indicative of the marked structural changes which strain, time and temperature produce in metals and alloys.

The creep strength of a metal may be affected by a variety of factors, including composition, melting and deoxidation practice, grain size (inherent or actual) and heat treatment. Aside from these influences, creep or plastic flow takes place in a more or less uniform manner, and creep tests show that time-elongation curves take one of three forms, depending on test temperature and on whether normal or excessive stresses are applied. This condition is shown by Figure 120, wherein three types of curves are produced by different constant loads.

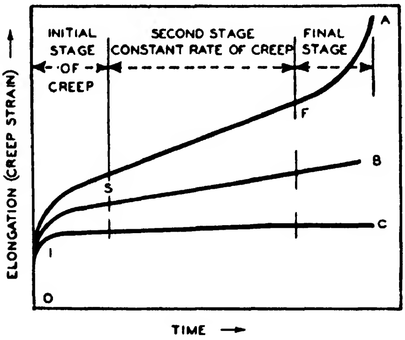


Figure 120. Time-elongation creep curves.

In this figure, Part O to S is common to the three curves and represents initial creep. Part S to F on the upper curve, A, is a constant high rate of creep, and that portion from F upward is the final rapidly increasing rate leading to failure. On the intermediate curve, B, under the intermediate loading, annealing or recrystallization counterbalance exactly, providing a uniform rate of creep over a long period. On the lower curve, C, under low loading, the rate of creep diminishes because of a strain-hardening effect. To ascertain which of these conditions is likely to prevail, it is necessary to extend the tests for an appreciable period—the longer the better—to determine the true behavior under service conditions of stress and temperature.

In general, the creep rate is taken in the so-called second stage of creep, where the deformation rate is approximately constant, and is expressed as per cent per 1,000 hours. Many prefer to express this as per cent per hour. In the customary creep test, the applied stresses are usually low, so that tests can be discontinued before fracture occurs.

Evaluation of the creep of highly heat-resistant alloys under sustained loads is quite intricate and complex. It is currently receiving much attention because of the problems it presents in the design of gas turbines, particularly stationary turbines which must have a much longer life than aircraft turbines.

In Figure 121 is shown stress for secondary rate of creep of 0.10 per cent in 1,000 hours as it varies with temperature and alloy.[4] In the lower temperature range it is probably safe to say that this also holds for 1.0 per cent creep in 10,000 hours. This graph applies only to wrought alloys, as castings are generally stronger.

Stress-Rupture

Stress-rupture tests offer a means of evaluating the characteristics of alloys operating under stress at high temperature over long periods of time. The test is, in essence, a loaded creep test where the test is continued to failure of the specimen. The tests are made by subjecting a series of bars to static stresses of various magnitudes at the selected temperature level and determining the time for fracture. Elongation may be taken during the test, but the total extension of each specimen is taken at conclusion of the test and these values, together with the stresses causing rupture, may be plotted on log-log cross-section paper against time for rupture. The initial point on such a curve is the short-time tensile value.

If the stresses and corresponding fracture times are plotted to Cartesian coordinates, curves of the type[16] shown in Figure 122 will result. These curves appear to become asymptotic to definite limiting stresses, and it is thus possible to obtain an indication of the stress below which fracture will not result for very extended time periods.

A more definite relationship exists when the results are plotted to logarithmic coordinates. This method of plotting usually results in a single

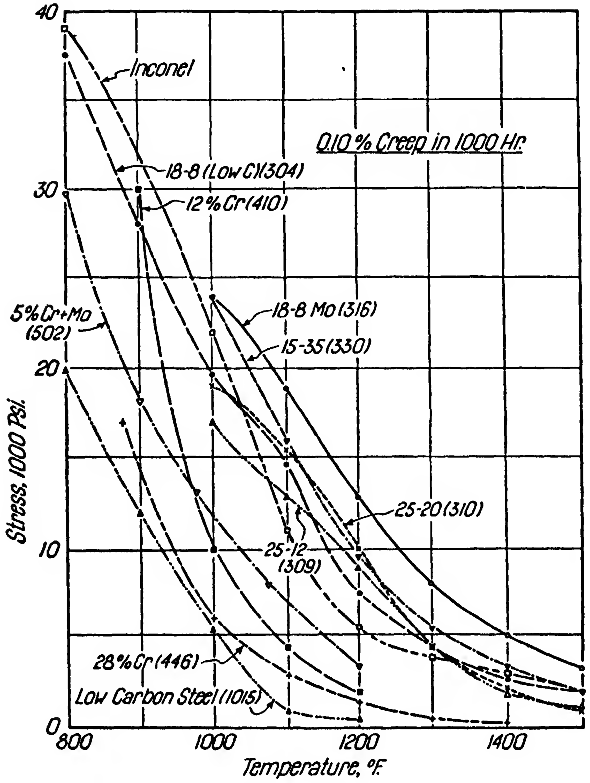
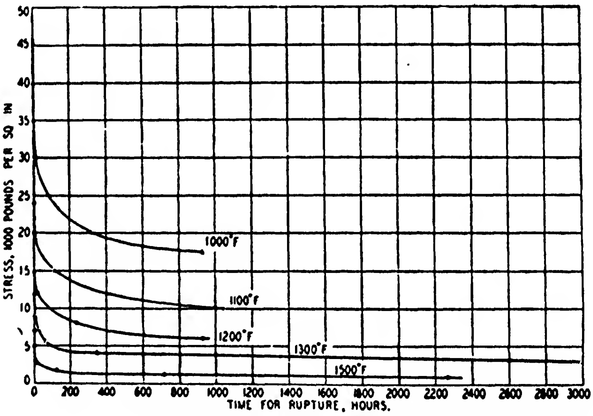


Figure 121. Stress for secondary rate of creep of 0.10% in 1000 hrs. as it varies with temperature and alloy. In the lower temperature range it is probably safe that this also holds for 1.0% creep in 10,000 hrs.

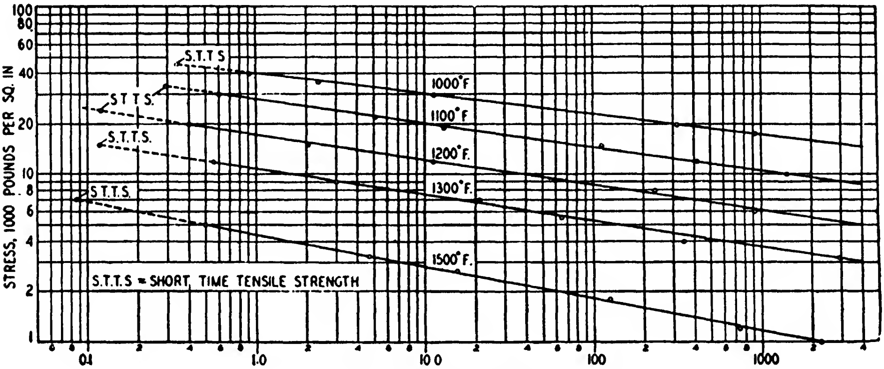


(Courtesy Timken Roller Bearing Co., Canton, Ohio)

Figure 122. Stress-rupture curves for 4–6 Cr-Mo-Si steel at indicated temperatures. (Sicromo 55).

straight-line relationship over the entire period, as shown in Figure 123 for 4–6 chromium, molybdenum, silicon steel.

The rupture test, in addition to determining the stress required to produce failure in a given time, supplies information on the hot plasticity, or the ability to extend and suffer deformation. The abruptness of the fracture, together with microscopic examination of the ends of the specimens, will indicate whether failure occurred by intercrystalline or transcrystalline fracture. In the former case, grain separation occurs and poor ability to elongate under stress may be manifest, while in the latter case, plastic deformation of the grains themselves occurs, and greater stretch and reduction of the cross-section is obtained before parting.



(Courtesy Timken Roller Bearing Co., Canton, Ohio)

Figure 123. Stress-rupture curves at indicated temperatures for 4–6 Cr-Mo-Si steel. (Sicromo 5s).

The rupture test gives information as to the relative strength of metals and indicates how the rate of straining affects elongation and mode of fracture. In general, rapid strain (or creep rate) favors transcrystalline fracture and low strain (or creep rate) favors intercrystalline fracture. The rupture strength of a given alloy is dependent on composition and is affected to some extent by such factors as heat treatment, grain size and microstructure.

The results obtained from stress-rupture tests are valuable not only for showing load-carrying ability but also for indicating hot ductility up to fracture and degree of surface and structural stability under the given test conditions. One of their chief merits is their ability to show the influence of time, temperature and stress on the ductility up to fracture. Information of this type is used to insure against brittle-type failures in service.

Figure 124 is a stress-rupture curve showing the relation between 1,000-hour life to rupture and temperature for several wrought alloys.[4] Changes in the slope of the stress-to-rupture curve indicate either surface instability (oxidation) or structural instability (carbide precipitation, grain growth, phase change).

Creep Relaxation. A plot of strain against time is constructed in which a single specimen of the alloy at a given temperature receives a series of loads which are decreased every time a predetermined constant strain is reached. Such information is especially useful for bolting material.

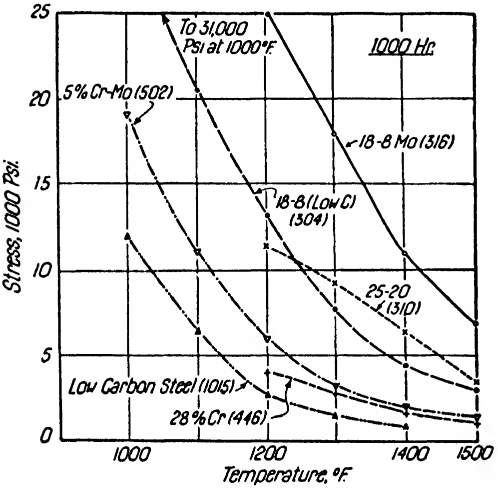


Figure 124. Stress-to-rupture curves.

Damping Capacity. This appears to be an inherent characteristic of each material[4] and is the ability of an alloy to cease vibrating through internal molecular friction. Since alternate pulsations, particularly associated with partial admission turbines, can build up to very high vibrating stresses, the ability of a material to "damp out" quickly would seem to be of considerable importance. This problem is closely associated with high-temperature fatigue. Damping capacity appears to be an inherent characteristic of each alloy and is relatively unaffected by heat treatment or other processing variables. It is much higher in ferritic materials than in austenitic alloys.

Mechanism of Deformation

Jeffries found that the path of fracture[16] in metals varies with the temperature, time and rate of deformation. At the lower temperatures (Figure 125) the path of fracture tends to be transcrystalline, while at the higher temperature it is intercrystalline. The temperature of transition is referred to as the equi-cohesive temperature, that is, the temperature at which the grain boundary material and the crystals proper have equal strength.

For any given analysis this temperature is lowered as the rate of deformation is increased. Relatively slight changes in composition may have a pronounced influence on the position of the equi-cohesive temperature and the lowest temperature of recrystallization. The equi-cohesive temperature is the lowest temperature at which the grain boundary material is sufficiently mobile to allow deformation and hence fracture to occur in the boundaries.

In considering the mechanism of creep, it is important to remember that at elevated temperatures at or below the equi-cohesive temperature, or lowest temperature of recrystallization, the deformation or creep resulting from the application of the stress over a given time is a running balance between the yielding of the material and the strain-hardening caused by such yielding. At or below this range, the strain-hardening tendencies should predominate, and continuous creep will not occur unless the stresses are sufficiently great to overcome the resistance caused by strain-hardening.

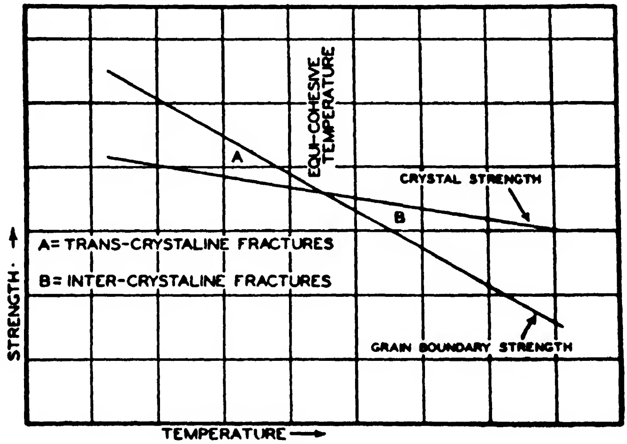


Figure 125. Effect of temperature on the fracture of metals.

The mechanism of deformation also varies at temperatures below the equi-cohesive temperature. Deformation apparently occurs largely within the crystals themselves and since these crystals are perfectly elastic bodies, the metal exhibits elastic properties. Above the equi-cohesive temperature, and if sufficient time is allowed, deformation occurs by the movement of the crystals themselves, that is, within the material surrounding the grains, which is not elastic. Accordingly, metals at temperatures above this critical point exhibit plastic rather than elastic properties.

Effect of Structure

Basically, the structure of an alloy is the connecting link between fabrication factors and its properties, since most of the properties are directly determined by the structure and are influenced by these factors only through their control of structure. It is well to remember, at this point, too, that the structure of an alloy at the outset of its service life is of significance only if it is reasonably stable. It is also necessary to remember that the term "structure" involves several orders of complexity, from macrostructure down through microstructure to the basic lattice pattern.

Possibly because of its naturally greater stability strength and higher ductility at elevated temperatures, the austenite lattice usually gives better service than the ferrite lattice for alloys based on iron. From the standpoint of corrosion resistance (especially of the pitting or intergranular type) and ductility the solid solution type of structure is preferable, though more complex structures of certain types produce higher rupture and creep strengths, usually at the expense of ductility.

The amount and distribution of the secondary phase, with reference to the matrix phase of these more complex microstructures, is of great importance. For optimum strength properties it should be in the form of microscopic or submicroscopic particles uniformly distributed throughout the grains of the matrix phase, and it should retain this distribution under operating conditions. If the particles become rounded (*e.g.*, spheroidized carbides) and/or agglomerated, the secondary phase ceases to be effective in improving strength. If the secondary phase is segregated in the grain boundaries of the matrix phase and is present in amounts sufficient to form a more or less complete envelope around these grains it will be highly detrimental, especially if it is excessively brittle or excessively soft. Experience indicates that alloys having the greatest load-carrying capacity at elevated temperatures are those which are austenitic at normal temperature.

No structures are absolutely stable at the more elevated temperatures. The low-alloyed pearlitic steels undergo spheroidization, which tends to decrease the load-carrying ability, while the austenitic steels undergo carbide precipitation in the grain boundaries, which decreases corrosion resistance and may impair ductility.

Not much is known of the eutectic type of structure, since it is of rare occurrence in most wrought high-temperature alloys; but it is probably inferior in ductility to the solid solution type and will be definitely detrimental if its melting point (hence its softening point) is low with reference to the operating temperature. The eutectic structure, however, is common in many cast heat-resisting alloys.

Regarding microstructure, it has been found that the cast structure is stronger than the wrought for temperatures above 1300° F., while the wrought structure is generally stronger and more ductile than the cast for lower temperatures.

Grain size is also an important factor in structure. In general, it is claimed that coarse grains (preferably elongated in the direction of stress) give better stress-rupture, creep and fatigue properties for operating temperatures above 1300° F., while fine grain structures are preferable below this temperature.

A fine grain size in either the actual or inherent grain structure gives maximum load-carrying ability below the equi-cohesive temperature, whereas a coarse grain structure is superior above this temperature. Since rate of deformation has an important influence on the equi-cohesive temperature, the effect of grain size on the creep and rupture strengths may differ over certain portions of the temperature range.

The heat treatment[16] producing the most suitable grain size imparts the maximum load-carrying ability. For temperatures below the lowest temperature of recrystallization, a quenched and drawn structure is superior, while at higher temperatures an annealed or normalized and tempered structure is superior. However, for austenitic alloys the strongest is the solution heat-treated (quench-annealed) and aged to precipitate fine carbides.

Effect of Alloying Elements

Shown below are two convenient methods by Clarke[16] of classifying the more common alloying elements in ferrous materials. The first method depends on whether the elements go into solid solution or prefer to combine with the carbon to forming carbides. Certain of the elements fall into both classes for, after all the carbon is consumed, the remainder will go into solution. The second method of classification depends on whether the alloying element promotes the formation of ferrite or austenite. It should be

Method I. Solid Solution versus Carbide-forming Elements

A. Solid solution
- Nickel
- Chromium
- Silicon
- Manganese
- Aluminum
- Copper
- Cobalt

B. Carbide formers
- Chromium
- Manganese
- Molybdenum
- Tungsten
- Columbium
- Titanium
- Vanadium

Method II. Ferrite versus Austenite Formers

A. Ferrite
- Chromium
- Silicon
- Aluminum
- Molybdenum
- Tungsten,
- Vanadium
- Columbium
- Titanium

B. Austenite
- Carbon
- Nitrogen
- Nickel
- Manganese
- Cobalt
- Copper

noted that the elements align themselves differently under the two methods of classification. Not all the solid solution elements are austenite formers, nor are all the carbide-forming elements ferrite formers.

The basic type and limits of variation of structure are fixed by the composition of the alloy. In general carbide formers are most effective in promoting high-temperature strength, provided the carbides formed are stable (*i.e.*, neither go into solution, spheroidize nor agglomerate) at operating temperatures. The elements entering solid solution which have greater affinity for corrosive agents than the solvent and which cause the formation of more dense and impermeable oxide layers with better adherence are most suitable in promoting surface stability. Their effectiveness depends in part on their ability to diffuse in sufficient amounts and with sufficient speed to replenish the surface adequately. The softening temperature of the matrix is raised by those solutes which tend to precipitate, and which have high melting points and high softening temperatures with reference to their melting points. Softening temperature is closely related to creep and stress-rupture properties. Usually, but not always, the addition of elements with high melting points improves creep strength, and this effect is greater for austenitic than for ferritic alloys. In general, the influence on properties exerted by elements entering into solid solution is proportionally greater for small additions, and tends to level off as a certain critical percentage is reached. This influence is additive when a number of elements are simultaneously involved, and this principle of course suggests that more advantage can be gained by the addition of small proportions of several elements than by an equivalent proportion of one or two elements.

The influence of individual elements is difficult to describe, especially since it is usually modified considerably by the presence of other elements. The following information is to be interpreted with this in mind, and is supplemented by later discussion of various complex alloy systems.

Aluminum has been used in heat-resisting alloys for many years. It enters into solid solution in both ferrite and austenite and also forms a series of intermetallic compounds with iron and with chromium (though it is soluble in chromium up to 30 per cent). It combines with nickel to form a precipitation-hardening compound. It is also active toward nitrogen, forming a complex AlFeN compound which is stable at rather high temperatures. It is a strong graphitizing agent and probably for this reason tends to stabilize ferrite at high temperature. In amounts greater than required for deoxidation it is difficult to add, and forms brittle and very weak alloys with iron at high temperatures. It is added to high-temperature alloys primarily to increase oxidation resistance at red heat. In this respect it is superior to almost all other possible additions. Oxidation resistance increases with increase in percentage of aluminum. A binary alloy of iron and chromium containing 7 per cent aluminum is equivalent in oxidation resistance to an 80 per cent Ni–20 per cent Cr alloy. Its effect is independent of carbon content. Up to 3 per cent aluminum has been added to 18–8 stainless steel to improve scale resistance and machinability. In general, aluminum adversely affects high-temperature mechanical properties, particularly creep, when used as an alloying element, and should be used only where oxidation resistance is of paramount importance and load-carrying capacity does not matter. It has been used as a coating for high-temperature materials (calorizing) with excellent results.

Beryllium and boron have been used in small proportions in some of the newer heat-resisting alloys. Both have limited solubility of the precipitation-hardening type, but in the amounts used it is difficult to decide whether the improvement they effect is due to their deoxidizing and scavenging action, to precipitation-hardening effects, or both. So far as is known boron does not produce an improvement in high-temperature properties at all proportional to its effect on hardenability.

Calcium has been used in a few alloys, but not enough information is available to evaluate its effect. From theoretical considerations it should rank near aluminum in promoting surface stability, since it is also an excellent deoxidizer, but not enough is known about the type of scale it produces.

Carbon, up to 1.25 per cent, improves high-temperature strength but is sometimes prone to grain boundary segregation, which is harmful from both corrosion and creep-stress rupture standpoints. Combined with elements which form carbides which are small and highly stable (columbium, titanium, tantalum and thorium) at elevated temperatures, it does not segregate badly; hence in this form it is definitely beneficial except for its effect on ductility.

Chromium is perhaps the most important element added to "high-temperature" steels. Its effect with or without the addition of nickel, in increasing the resistance of iron alloys to corrosion is well known, as is indicated by the wide variety of stainless steels now available, containing from 12 to 30 per cent chromium. Chromium is particularly effective in increasing resistance to hydrogen.

Twelve per cent or more of chromium affects impact strength adversely, especially after long heating at approximately 900° F. The ductility and impact properties of chromium-iron alloys having a chromium content of 20 per cent or more may be seriously impaired by slow cooling between 1100 and 700° F.

Cobalt aids in maintaining the properties of the alloy at high temperatures and increases the creep resistance.

Columbium is at least a ferrite promoter because it combines with carbon, thus decreasing the amount of carbon available for combination with the chromium. It is indicated that when columbium is used in an alloy of fixed chromium and nickel content the carbon will need to be increased somewhat to produce a wholly austenitic structure. Columbium improves creep resistance.

Copper has also been used in high-temperature alloys. It is somewhat more soluble in iron at elevated than at room temperature (about 1.8 per cent max. at room temperature) and is effective as a precipitation-hardening constituent. However, it tends to segregate at grain boundaries and to form brittle, weak, low-melting compounds with oxygen when so located as to promote surface instability in air. These harmful effects are largely eliminated, however, when sufficient nickel is simultaneously present.

Molybdenum is added to steels to improve their strength at elevated temperatures, as well as to austenitic 18–8 stainless steels. It eliminates temper brittleness in straight-chromium steels. In the 18 chromium–8 nickel and the 25 chromium–12 nickel heat-resistant steels, molybdenum is a stabilizer of the sigma phase.

Nickel is a toughening agent and a grain refiner. It is a strengthener for alloys having 16 per cent or more of chromium which are more or less brittle in the absence of nickel.

Nitrogen is a strengthening element and is equivalent to two or more times as much carbon in alloys at room temperature and at elevated temperatures. It is a potent austenite stabilizer. It improves the ductility and strength of the 0.35 per cent carbon–28 per cent chromium steels when in excess of 0.15 per cent, and when the nickel is in excess of 2 per cent.

Silicon may affect the load-carrying ability of steels by reduction of creep strength, especially in the range 950–1200° F. It does, however, effect increased surface stability that retards oxidation. Silicon affects the scaling temperature of steels by changing the nature of the scale.

Titanium forms stable carbides and nitrides and also tends to be a ferrite promoter. It also improves creep resistance. In the austenitic 18–8 stainless steels it retards and minimizes intergranular embrittlement.

Tungsten, together with molybdenum and vanadium, are carbide formers (also ferrite formers) and their chief action is to make the steels more resistant to creep or "flow" at elevated temperatures. They tend to promote resistance to softening on tempering and act as restrainers of grain growth. Vanadium, however, impairs oxidation resistance.

Zirconium in alloys containing large percentages of nitrogen forms stable nitrides. In addition, zirconium is a ferrite promoter.

Aluminum, chromium, silicon, titanium, and columbium are able to form tightly adhering refractory oxide scales when added to steel alloys. They thus markedly improve resistance to scaling, although columbium sometimes can seriously impair scaling resistance.

Alloys*

Alloys capable of sustained operation when exposed either continuously or intermittently to operating temperatures which create metal temperatures in excess of 900° F. are classed as heat-resistant. Alloys used in parts for such service fall into the following groups: iron-chromium, iron-chromium-nickel, nickel-chromium base, chromium base, nickel base and cobalt base.[13]

Many low alloy carbon steels can be used successfully for certain low stress applications up to 900° F., and a number of new highly alloyed nonferrous materials have been developed as super-high temperature alloys for high-stress applications up to 1500° F.

Carbon Steel (killed). Killed carbon steel, analyzing 0.10–0.20 C, 0.30–0.60 Mn, 0.25 max. Si, 0.04 max. P, 0.045 max. S, is recommended for general use in applications for service temperatures not exceeding 900° F., where corrosion and oxidation resistance is not important.[15] Its high-temperature properties are shown in Table 127.

TABLE 127. *High-temperature Properties of Carbon Steel*

Temp. (° F.)	Tensile strength (psi)	Yield stress (psi)	Elongation % in 2 in.	Reduction of area (%)	Charpy Impact (ft.-lbs.)
85	62,400	42,000	36.0	67.5	40
750	58,000	24,600	34.0	67.0	36–40
1,000	36,500	20,100	42.5	77.0	30
1,400	9,025	3,750	69.5	77.0	——

Carbon steel possesses a sufficient resistance to general attack at 1000° F. but is subject to pronounced intergranular attack at this temperature. At 1200° F. and over, it undergoes pronounced general attack and has neither surface nor structural stability.

It is generally recognized that load-carrying ability in itself is not a sufficient criterion of a steel's suitability for high-temperature service. In addition to satisfactory strength, there must be sufficient surface stability to prevent the steel from becoming brittle or losing its original strength, and sufficient hot ductility to prevent brittle fractures in service.

SAE 1015 steel was the first "high-temperature" alloy and is still employed in piping, boilers (firebox and flange steel), steam fittings, blower casings, and wherever temperatures can be kept to 1000° F. maximum and stresses are of a low order (not over 2000 psi at 1000° F. and 8000 psi at 800° F.).

Carbon-Molybdenum Steel. Carbon-molybdenum steel,[15] analyzing 0.10–0.20 C, 0.30–0.60 Mn, 0.25 max. Si, 0.45–0.65 Mo, 0.04 max. P, 0.045

*** With permission of the Timken Roller Bearing Co. much information and data on steels for high-temperature service were taken from their published bulletins and used in this chapter.**

max. S, has more than twice the creep strength of killed carbon steel. In stability, corrosion and oxidation resistance it is about the same as carbon steel. Its applications are therefore confined to service in which greater safety is desired than can be obtained with carbon steel. It is used in cracking-furnace tubes at temperatures up to 1000–1050° F. when corrosion and oxidation are not serious, and also for high-pressure boiler tubing, superheating tubing, and high-temperature steam piping.

The tensile properties of annealed carbon-molybdenum steel are practically unchanged by long heating under stress at temperatures up to 1100° F. There is a slight decrease in strength at 1200° F. Under prolonged testing, this steel possesses, under given test conditions, a very low hot ductility at 1000° F. and a relatively low ductility at 1200° F. Its toughness and impact resistance are not changed greatly by heating under stress at the temperatures up to 1200° F. (see Table 128).

TABLE 128. *High Temperature Properties of C-Mo Steel*

Temp. (° F.)	Tensile strength (psi)	Yield stress 0.2% set (psi)	Elongation % in 2 in.	Reduction of area (%)	Charpy impact (ft.-lbs.)
85	64,100	32,500	37.0	62.7	39
750	68,100	23,500	28.5	61.7	45
1,000	50,400	22,800	32.5	77.6	26
1,200	28,100	15,100	56.0	88.6	—
1,400	11,700	5,900	82.5	89.0	—

Carbon-molybdenum steel possesses sufficient resistance to general attack at 1000° F., but is subject to pronounced intergranular attack at this temperature. At 1200° F. it undergoes pronounced general attack as well as intergranular attack.

Chromium-Molybdenum Steel. This steel,[15] analyzing 0.15 max. C, 0.30–0.60 Mn, 0.30 max. Si, 0.80–1.10 Cr, 0.45–0.65 Mo, 0.04 max. P, 0.045 max. S, is a substitute for carbon-molybdenum steel where greater creep strength and somewhat better corrosion and oxidation resistance is necessary. It is used for cracking-furnace tubes at temperatures up to 1100° F. where corrosion and oxidation are not serious, and for high-pressure boiler tubing, superheater tubing and high-temperature steam piping.

The tensile properties of the annealed steel are practically unchanged by long heating under stress at temperatures up to 1100° F. (see Table 129). There is a slight decrease in strength at 1200° F. as a result of spheroidization. This steel possesses a high degree of hot ductility under the combined influence of time and stress at 1100 and 1200° F., and a low ductility at 1000° F. The decreased ductility at 1000° F. is caused by the marked strain-hardening of this steel at this temperature under the higher

TABLE 129. *High-temperature Properties of Cr-Mo Steel*

Temp. (° F.)	Tensile strength (psi)	Yield strength 0.2% set (psi)	Elongation % in 2 in.	Reduction of area (%)	Charpy impact (ft.-lbs.)
85	62,500	42,250	34.5	73.7	56
750	63,500	24,350	33.8	70.3	45.5
1,000	51,250	20,750	33.3	78.9	26–32
1,200	32,100	17,000	52.0	88.2	53.5
1,400	11,350	6,500	94.0	97.8	——

stresses. Chromium-molybdenum steel possesses a high degree of surface and structural stability at temperatures up to 1100° F.

Similar steels with silicon increased to 1.0 per cent and chromium increased to 1.5 per cent show good stability up to 1200° F., and have higher creep strength and higher short-time high-temperature properties.

Silicon-Molybdenum Steel. A silicon-molybdenum steel,[15] analyzing 0.15 max. C, 1.15–1.65 Si and 0.45–0.65 Mo, was designed for applications in which a good combination of high-temperature strength and oxidation resistance is required. In the temperature range of 1000 to 1200° F. it has about twice the strength of carbon steel and oxidation resistance comparable to the 4 to 6 per cent chromium-molybdenum steel. It is recommended for use in cracking-furnace tubes, pipe still heater tubes, and tubing for high-pressure boilers and superheaters.

Silicon-Chromium-Molybdenum Steel. A silicon-chromium-molybdenum steel, analyzing 0.15 max. C, 0.50 max. Mn, 1–2 Si, 4–6 Cr, 0.45–0.65 Mo, is recommended for applications where best oxidation resistance is required for temperatures up to 1500° F.

Chromium Steels. Chromium steels,[10] in addition to exhibiting remarkable corrosion resistance and mechanical properties at room temperature, are very resistant to the destructive elements encountered at elevated temperatures when the correct grade is intelligently used.

Steels containing 4 to 6 per cent chromium resist excessive oxidation up to 1000° F. Those containing approximately 12 per cent chromium resist excessive oxidation up to 1300° F. With 16 per cent chromium, excessive oxidation is resisted up to 1500° F., while with 27 per cent chromium excessive oxidation is not encountered until temperatures in excess of 2150° F. are reached in an atmosphere of normal air.

With sufficiently high chromium content excessive scaling does not occur. Protection is obtained at high temperatures also by adding silicon or aluminum to iron.

One condition that has contributed in many instances to shortening the life of heat-resistant chromium steel equipment at elevated temperatures is the presence of materials capable of carburizing the steel. At temperatures over 1300° F. carbonaceous materials or gases can cause carbon to diffuse into the steel and alter its composition and constitution. It has been shown that as the carbon content of chromium steel increases, resistance to scaling at a given temperature decreases, as does overall corrosion resistance.

The high-temperature strength of the 4 to 6 per cent chromium steels is little if any greater than that of plain-carbon steels, but the corrosion resistance is superior.

The straight 12 per cent chromium steels are subject to temper embrittlement, that is, loss of room-temperature shock resistance after service at elevated temperatures within the range of 800 to 1100° F.; but this embrittlement can be eliminated by adding 0.50 per cent molybdenum or 1.0 per cent tungsten.

In the presence of a suitable proportion of chromium, both silicon and aluminum are more effective than chromium alone in imparting a high degree of oxidation resistance. The addition of 1.5 per cent silicon to the 4 to 6 per cent chromium-molybdenum type steel produces high resistance to oxidation at temperatures up to 1500° F., while further addition of 0.50 per cent aluminum to this same steel greatly improves the resistance even at 1750° F.

Oxidation resistance is very important[4] in high-temperature service. For instance the 4–6 per cent Cr-Mo (Type 502) steels show higher creep and rupture resistance above 1000° F. than other straight chromium-iron alloys with higher chromium content, but they cannot be exposed to oxidizing conditions for more than a few hundred hours at temperatures above 1150° F. without being seriously weakened by loss of section thickness (see Table 130).

TABLE 130. *Short-time High-temperature Tensile Properties of 4 to 6 Per Cent Chromium-Molybdenum Steel*

Temperature (° F.)	Ultimate strength (psi)	Yield strength* (psi)	Proportional limit (psi)	Elongation % in 2 in.	Reduction of area (%)
85	66,600	26,250	19,000	39.0	80.5
750	51,800	21,050	14,000	30.5	76.7
900	48,400	19,600	11,500	28.5	76.9
1,000	44,450	17,300	7,500	28.5	73.5
1,100	34,400	15,400	6,000	38.5	87.3
1,200	25,800	11,300	1,500	46.0	91.0
1,300	19,100	9,500	1,500	65.0	94.6
1,400	13,300	7,250	1,500	65.0	95.9

* Yield strength values are for 0.2 per cent permanent set.

The main applications of the 12 per cent chromium steels have been for turbine blading, valve trim liners for pressure vessels, and in oil-cracking units. They are used when corrosion resistance is the primary requisite and the use of the austenitic type is not justified. The 12.0 to 14.0 per cent chromium wrought alloys are the only straight-chromium steels which are not subject to temper embrittlement during service, although this is not necessarily true for castings.

For temperatures up to 700° F. the regular 12 per cent chromium grade of stainless steel,[5] when properly hardened, will maintain a hardness of approximately 300 Brinell when tested at room temperature, and will not temper below this figure. However, for continuous service above 700° F., this steel will gradually soften through tempering. Above 900° F. the regular grades of chromium stainless steel, if in the hardened condition, temper slowly and their strengths approach that of the annealed condition. For this reason for service at temperatures of 1000° F. or higher, the material is usually used in the annealed condition.

The addition of tungsten to 12 per cent chromium steel increases its strength so that up to approximately 1100° F. such a steel has creep strength slightly higher than 18–8 austenitic stainless steel. However, above 1150° F. this steel loses its strength more rapidly than does austenitic steel.

These alloys,[12] containing from 10 to 30 per cent chromium and little or no nickel, are useful chiefly for their resistance to oxidation and have low strength at elevated temperatures. Their use is dictated by conditions involving very low static loads under oxidizing or reducing conditions and uniform heating. The amount of chromium depends on the temperature to which they are exposed in service.

The 11.5 to 14.0 per cent chromium alloys are heat-treatable ferritic-martensitic steels. The mechanical properties at room temperature depend on the type of heat treatment received. For service at elevated temperatures they are usually given a full anneal.

The 18 per cent chromium alloys with low carbon content are only slightly hardenable and are ferritic. These alloys are also used in the annealed condition and are largely confined to applications in which oxidation resistance is the main requirement. With 1 per cent carbon, an 18 per cent chromium steel responds readily to hardening by quench and temper.

The 28 per cent chromium type is used primarily for heat-resistant applications where strength is not a consideration, in high-sulphur atmospheres, and in some services where the presence of sulphur cannot be tolerated. These alloys may be used up to 2000° F. Castings are supplied in two carbon ranges: (a) 0.35 per cent carbon, used for normal high-temperature service, and (b) 3.00 per cent carbon, used where a hard material resistant to abrasion is required for high-temperature service. The ductility and ultimate strength of the 0.35 per cent carbon grade are improved by the addition of nitrogen in excess of 0.15 per cent when the nickel is in excess of 2 per cent. Steels of this type are subject to grain-coarsening at temperatures in excess of 1600° F., and also to temper embrittlement.

The creep data and stress-to-rupture data[4] for a 1000-hour test indicated the superiority of 5 per cent chromium steel above 1000° F. to such alloys as 12 per cent chromium, 18 per cent chromium and 28 per cent chromium steels in spite of its relatively poorer oxidation resistance. However, due to loss of metal section in time caused by surface scaling, failure at higher temperatures would eventually occur, and would be chargeable to oxidation rather than to low strength of the sound remaining metal.

The foregoing statements indicate why the factors of stress, strain, time and temperature must be taken simultaneously with many other considerations in high-temperature design and metallurgy.

High-chromium ferritic steels are of more restricted utility and are less widely used than austenitic stainless steels. They lack the ambient temperature ductility of austenitic steels, are notch-sensitive, and are subject to grain growth on welding or other heating to high temperature. Nitrogen, an austenite former, is commonly added to the 27 per cent chromium alloy for grain refinement and improvement in workability.

Chromium-Nickel Austenitic Steels. There are two groups[12] of austenitic ferrous alloys.

(1) Those which contain more than 18 per cent chromium and more than 5 per cent nickel, and as a general characteristic have the chromium content higher than the nickel content. These alloys are used ordinarily under oxidizing or reducing conditions such as are withstood by the straight-chromium alloys, but in service they have greater strength and ductility. They are used, therefore, to withstand greater loads and moderate changes of temperatures. These alloys are used in reducing gases containing sulphur.

(2) Those which contain more than 10 per cent chromium and more than 25 per cent nickel, and in which the nickel content is usually higher than the chromium content. These alloys are used to withstand a reducing as well as an oxidizing atmosphere, except where sulphur content is appreciable. They do not carburize rapidly or become brittle, and do not take up nitrogen in a nitriding atmosphere. These properties become enhanced as the nickel content increases. These steels are used extensively under conditions of severe temperature fluctuation.

It has been shown that austenitic alloys retain their ductility better after heating to high and intermediate temperatures and have high strength at elevated temperatures; they also have much better load-carrying capacity at elevated temperatures, as determined by short-time tension and creep tests, than partly ferritic alloys.

Table 131 shows the typical short-time high-temperature tensile properties for a low carbon 18/8 (Type 304) stainless steel.

TABLE 131. *Short-time High-temperature Tensile Properties of Type 304 Steel*
(0.07 max. C, 17-19 Cr, 8-10.5 Ni)

Temperature (° F.)	Ultimate strength (psi)	Yield strength* (psi)	Proportional limit (psi)	Elongation % in 2 in.	Reduction of area (%)	Young's modulus x10^6
685	82,500	30,500	12,500	61.5	70.0	27.5
750	60,000	16,000	7,500	46.0	69.0	21.4
900	56,000	14,500	7,500	45.0	69.0	23.4
1,000	53,000	14,000	7,500	44.0	70.0	22.2
1,100	48,500	12,000	7,500	39.0	58.0	21.7
1,200	43,000	11,000	6,000	37.0	44.0	21.7
1,300	35,000	11,000	5,500	35.0	36.0	19.6
1,400	27,000	10,500	5,000	31.0	28.0	18.3
1,500	20,500	10,000	2,000	30.0	28.0	13.3

* Yield strength values are for 0.2 per cent permanent set.

Hardening of austenitic steels is accomplished by working the metal below its recrystallization temperature. Strain-relief annealing is generally done at approximately the operating temperature and eliminates those peak strains which would be relieved in service. The chief advantage of strain-relief annealing is dimensional stability.

Some of the austenitic alloys for high-temperature application have been designed to include elements which cause age-hardening. After quenching from a temperature high enough to cause solution of carbides and intermetallic compounds (segregated due to forging or rolling of the metal), the part is reheated to a lower temperature, which causes them to precipitate from this supersaturated solution in a fairly homogeneous pattern. The amount of precipitation is dependent both on the temperature and the length of the time at which the metal is heated or "aged" at this temperature.

Although higher strengths are obtainable by cold-working most of these age-hardenable austenitic alloys, it is generally more desirable for some parts to eliminate cold work, as this is hard on forging equipment, increases machining difficulties, reduces the ductility and does not produce as consistent results as solution treatment followed by age-hardening.

The well known 18 per cent chromium-8 per cent nickel composition is widely used for corrosion-resistant applications. It is also suitable for use at temperatures up to 1600° F. When it is used for resistance to oxidation at elevated temperatures, it is not necessary to keep the carbon content at the low level specified for corrosion-resistant alloys. Additions of columbium, titanium, molybdenum and tungsten are sometimes made to the normal type composition to impart greater strength at elevated temperatures.

Difficulties are experienced in welding these alloys. Some of the stainless alloys, when heated to temperatures of 800 to 1600° F., are subject to intergranular corrosion and embrittlement caused by precipitation of chromium carbide at the grain boundaries. In the Type 347 stainless alloys, columbium is added because of its greater affinity for carbon than chromium, thereby preventing depletion of the chromium at the grain boundaries. However, this causes a slight hot-short condition which may result in cracking during cooling. Rapid cooling will lessen the difficulties arising from this cause, and in addition will tend to anneal the joint. Table 132 shows its typical properties at elevated temperatures.

TABLE 132. *High-temperature Tensile Properties*[15] *of Columbium Type 18–8 Stainless Steel*

Temperature (° F.)	Tensile strength (psi)	Yield stress 0.2% set (psi)	Proportional limit (psi)	Elongation % in 2 in.	Reduction of area (%)
85	91,750	41,500	22,500	46.0	66.3
1,100	55,500	27,500	10,500	36.0	63.8
1,200	48,750	25,500	10,000	44.0	66.8
1,300	41,500	24,000	9,000	52.0	74.1

Columbium stainless steel is superior to standard 18–8 in its resistance to certain types of corrosion an doxidation attack and is immune to intergranular attack.

The stabilizing grades, Types 321 and 347, containing columbium or titanium, are used widely for applications that are in the range 900 to 1300° F. The carbides are stabilized so that those harmful intergranular carbides do not form which decrease the impact resistance of the compositions within the temperature range mentioned.

The strength of 18–8 stainless steel containing molybdenum is considerably greater at elevated temperatures as a result of the molybdenum than the standard 18–8 grade. The other grades of 18–8, with additions such as titanium and columbium, have strengths slightly above those of Type 304 stainless steel but considerably below that of Type 316.

Type 16–13–3 stainless steel, analyzing 16–18 Cr, 11–14 Ni, 2.5–3.25 Mo, is an austenitic, non-magnetic alloy used for temperatures up to 1500° F. At elevated temperatures it possesses greater creep and rupture strength than does standard 18–8. It is generally recommended for use in high-temperature applications in which greater strength is required than can be obtained with 18–8 and where increased resistance to certain acids and salts is desired, especially for valves in reciprocating aircraft engines. Its typical properties[15] are shown in Table 133.

In alloys of the 25 per cent chromium-12 per cent nickel type which are not wholly austenitic, ferrite is the stable phase at 1800° F, while sigma is the stable phase at 1600° F. and lower. Ferrite is weak but not brittle at 1800° F., whereas sigma is both weak and relatively brittle at or below 1600° F. In a few installations this alloy has been reported to have given

TABLE 133. *High-temperature Tensile Properties and Impact Resistance*

Temperature (° F.)	Tensile strength (psi)	Yield stress 0.2% set (psi)	Proportional limit (psi)	Elongation % in 2 in.	Reduction of area (%)	Charpy impact ft.-lbs	
						1 hr.*	1,000 hrs.*
85	103,900	36,750	21,000	59.5	77.0	78	—
1,000	73,500	20,250	11,500	46.0	64.8	68	68
1,100	69,100	19,600	11,000	48.5	65.1	67	56
1,200	60,500	20,500	11,000	40.5	50.8	59	50
1,300	50,200	18,750	9,500	43.0	49.9	60	43
1,400	39,000	17,900	9,000	49.5	57.8	60	36
1,500	31,500	17,500	8,000	54.5	63.0	54	37

* At temperature either 1 hr. or 1000 hrs., as indicated, prior to breaking at temperature.

unsatisfactory service because of excessive embrittlement and/or low load-carrying capacity. It was shown that wide variations in the chemical composition of this alloy—particularly high percentages of ferrite-promoting elements compared with austenite-promoting elements—may result in substantial proportions of ferrite, which has low strength at elevated temperatures, and may become embrittled at intermediate temperatures or on repeated heating and cooling in certain temperature ranges. On the other hand, the high chromium-low nickel alloy is generally considered to have good resistance to oxidation and to sulphidation, and also to have very good surface stability against the hot products of combustion and many other reagents. Table 134 summarizes the properties of this type of alloy in which the carbon content varies from 0.30 to 0.60 per cent.

TABLE 134. *Summary of Average Mechanical Properties of Cast Commercial 25 Cr-12 Ni Alloy*

Tensile strength (psi)	
As cast	75,000
Aged (1400° F.)	85,000
At 1800° F.	12,000
Yield strength (psi)	
As cast	40,000
Aged	47,000
At 1800° F.	8,000
% Elongation in 2″	
As cast	9.0
Aged *	4.0
At 1800° F.	27.0
% Reduction of area	
As cast	16.4
Aged	4.4
At 1800° F.	44.4
Modulus of elasticity	
As cast	24,300,000
At 1800° F.	2,800,000

* Tests for room-temperature properties after ageing at 1400° F. for 24 hours showed elongation values as high as 30 per cent.

The 29 Cr-10 Ni alloy has excellent resistance to corrosion at elevated temperatures and is suitable for applications up to 2000° F. The material is stronger and more ductile than the straight-chromium type.

The 25 Cr-20 Ni stainless steel is an austenitic alloy recommended for temperatures of 1500° F. and even up to 2100° F. It possesses greater creep and rupture strength than 18–8 and also increased scaling and high-temperature corrosion resistance. However, like 18–8, under certain conditions this alloy is subject to intergranular carbide precipitation with the subsequent detrimental effect on certain of its characteristics. The high-temperature load-carrying capacity of 25–20 can be greatly influenced by heat treatment and grain size control. Table 135 shows its typical high-temperature properties.[15]

TABLE 135. *High-temperature Tensile Properties of 25 Cr-20 Ni Stainless Steel*

Temperature (° F.)	Tensile strength (psi)	Yield stress 0.2% set (psi)	Proportional limit (psi)	Elongation % in 2 in.	Reduction of area (%)
85	87,400	36,000	10,000	54.0	76.0
1,000	73,000	20,500	17,500	46.0	52.0
1,100	65,500	19,250	16,000	32.0	37.0
1,200	58,000	20,000	12,500	21.0	25.0
1,300	44,500	20,000	12,500	17.0	22.0
1,400	36,750	20,000	11,000	19.0	24.0
1,500	26,250	20,000	10,000	15.0	22.0
1,600	19,700	——	——	28.0	26.0
1,800	10,250	——	——	24.0	24.0

The high-temperature properties of 25 Cr-20 Ni austenitic steel are greatly influenced by the heat treatment employed. For optimum creep properties the steel should be heat-treated for maximum grain size. On the basis of the stress required for a creep rate of 0.10 per cent per 1000 hours, the solution-heat-treated material is more than twice as strong at 1000° F. as normalized steel, at 1200° F. ten times as strong, and at 1300° F. about thirteen times as creep resistant. These differences are considerably greater than can be attributed to grain size alone. However, the structure of fine-grained steel is unstable, with a phase precipitating under the combined influence of time, temperature and stress, and it is the appearance of this sigma phase which greatly decreases the creep resistance.

At elevated temperatures[1] ferrite is weak, but very ductile. It is not necessarily detrimental to performance, since under some circumstances the attendant ductility is known to be beneficial. In contrast, the undersirable sigma phase, probably induced by chromium segregation, is weak and brittle. Embrittlement resulting from small proportions of sigma phase, however, may be no more serious than that associated with carbide precipitation. Molybdenum is a sigma phase stabilizer in these alloys.

Special Age-hardening-Alloys

Recently a series of alloys has been developed for service where high strength is required in the range of temperature from 1000 to 1600° F. These steels, known as "S-495," "S-497," "S-590," and "S-816," are age-hardening alloys that can be solution-treated and aged to hardness in excess of 300 Brinell. They retain this hardness even when treated to temperatures in excess of 1500° F., and show strengths at elevated temperatures considerably above those that can be obtained with the heat-resistant alloys previously available. The compositions of these steels are shown in Table 136.

Table 136. *Composition of Age-hardening Alloys*

	C	Cr	Ni	CO	Mo	W	Cb	Fe
"S-495"	0.40	14	20	—	4	4	4	bal.
"S-590"	0.40	20	20	20	4	4	4	bal.
"S-816"	0.40	20	20	43	4	4	4	bal.

The "S-816" alloy is solution-treated at 2150–2300° F. and aged at 1300–1500° F. Its stress-strain data[8] are given in Table 137.

Table 137. *Stress to Rupture in Time Indicated of Alloy S-816*

Hours	1200° F.	1350° F.	1500° F.
100	63,000	41,500	23,500
1,000	51,000	32,500	19,400
10,000	40,000	25,500	14,500
*100,000	31,500	19,700	10,900

* Extrapolated.

Another excellent heat-resisting material is "Alloy 16–25–6." It has high creep resistance at elevated temperatures and is used for gas turbine and turbosupercharger applications. Its nominal composition is 16 per cent chromium, 25 per cent nickel, 6 per cent molybdenum, 0.1 per cent carbon and balance iron. As this alloy is an austenitic material,[6] it does not undergo any phase changes on heating and, therefore, cannot be hardened by standard thermal treatments. Its physical properties, however, are materially affected by cold work. Cold-working is effective to different degrees at temperatures exceeding 1700° F. Finishing temperatures in rolling and forging, therefore, greatly affect the final strength of the product. Tempering at 1200° F. after cold-working increases the hardness regardless of the amount of cold work given. At higher temperatures, an equilibrium is reached at different amounts of cold work where the increase in hardness due to precipitation-hardening is counterbalanced by the softening effect of stress relief and precipitate coagulation. The maximum hardness values for a given amount of cold work shift to lower temperatures of tempering with increasing amounts of cold work.

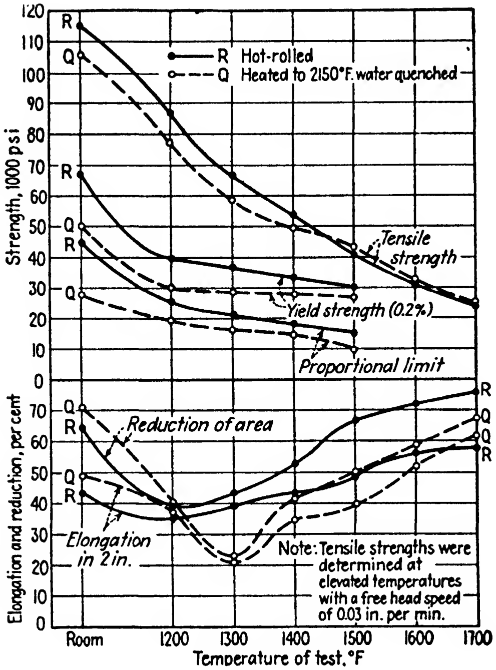


Figure 126. Short-time tensile properties of 16–25–6 alloy at indicated temperatures, 1-in. round bars.

(Courtesy Timken Roller Bearing Co., Canton, Ohio)

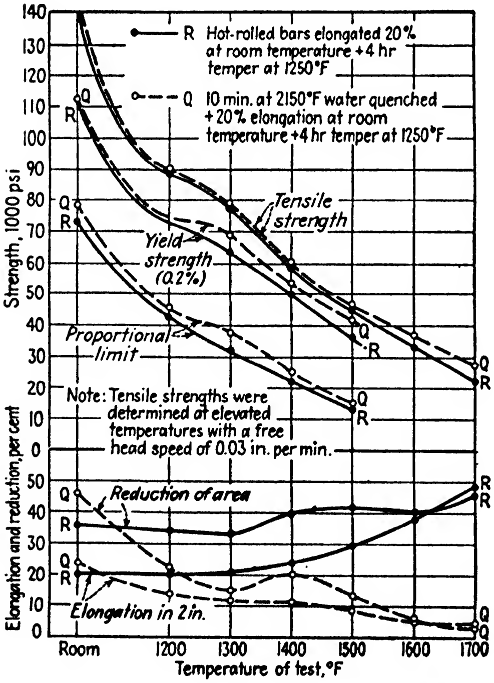


Figure 127. Short time tensile properties of 16–25–6 alloy at indicated temperatures, 1¼-in. round bars.

(Courtesy Timken Roller Bearing Co., Canton, Ohio)

The ready response to cold work, as well as the precipitation-hardening characteristics which have been shown to influence markedly the room-temperature properties of "Alloy 16–25–6" also affect its high-temperature properties. Figure 126 illustrates the short-time tensile values [6] of hot-rolled as well as solution-quenched material up to 1700° F. These graphs indicate that the hot-rolled alloy possesses superior strength values at least up to 1450° F. It appears significant that a pronounced dip in the ductility curves of the solution-quenched material occurs at 1300° F., which could not be observed for the alloy in the "as-rolled" condition. Precipitation-hardening explains this phenomenon.

The short-time tensile values [6] of the cold-worked alloy are shown in Figure 127. Up to 1450° F. the cold work imparted a marked increase to the proportional limit, yield strength and tensile strength of the material. The solution-quenched alloy seems superior in these strength values to the hot rolled material, although the difference is of small magnitude. However, the bars solution-quenched before cold work lack the high ductility values associated with "as-rolled" material.

Special Alloys for Ultra-high Temperatures

War developments [9] have given great impetus to the so-called "super-alloys" for application at temperatures from 1000 to 1500° F. Postwar developments in military aircraft and guided missiles are placing emphasis upon the best of these, particularly for applications at ranges from 1400 to 1800° F.

They are chromium-base, nickel-base, cobalt, and other special types of high alloy content. The applications of the super-alloys at such high temperatures are primarily in highly stressed turbine blading and in high-temperature sheet for cobustion chambers and exhaust systems.

Chromium-base Alloys. The very high strength exhibited by chromium-base alloys [10] (55 chromium, 25 iron, 20 molybdenum, and 60 chromium, 25 iron, 15 molybdenum) in rupture tests at 1350° F. indicates that they are potentially among the most promising known for bucket service in gas turbines. Some chromium-base alloys tested had rupture strengths as high as 73,000 and 54,500 psi for fracture in 100 and 1000 hours, respectively. The highest similar values published for other alloys are of the order of 50,000 and 40,000 psi. A strong precipitation reaction occurs at 1350° F. which is stable at that temperature and is probably responsible for the high strength.

The chromium-base alloys have certain rather severe limitations in their present state of development. The most serious of these are brittleness at room temperature and the necessity for melting and casting under high vacuum to avoid the detrimental effects from atmospheric oxygen and nitrogen. Considerable progress has been made in overcoming these difficulties, and further improvement seems quite possible.

At the present time the alloy most promising for service at 1350° F. appears to be a 60 per cent chromium, 25 per cent iron, 15 per cent molybdenum alloy with less than 0.05 per cent carbon and 0.5 to 0.7 per cent silicon. It has the best combination of strength at 1350° F. and engineering properties at room temperature. With care it can be machined and processed in the normal manner. Higher strengths can be obtained from alloys with higher molybdenum content, but at the present time their inferior properties at room temperature offset their higher strength.

Nickel-base Alloys. Both nickel and "Inconel" qualify as good heat-resisting materials. Under reducing and sulphur-free conditions and at very high temperatures, where resistance to scaling is more important than creep strength, nickel is preferred to "Inconel" because of its higher melting point; useful service has been obtained at 2300° F. When high creep strength is the more important property, "Inconel" is superior to nickel and is recommended for use up to 2100° F. For most purposes, under oxidizing conditions, "Inconel" is superior to nickel at the highest temperatures. If sulphur-containing gases are present, "Inconel" can be used up to 1500° F. and nickel up to 1000° F. A nickel-manganese alloy, containing 4.5 per cent of manganese and known as "D Nickel," is used for certain high-temperature purposes in moderately sulphidizing atmospheres. Other nickel alloys ("Monel," "K Monel" and "S Monel") serve usefully at temperatures up to about 1500° F.

"Inconel B" is a modification of "Inconel" in which the chromium content is increased from 12–14 per cent up to 16–18 per cent in order to provide increased oxidation resistance.

For sulphidizing atmospheres at temperatures over 1000° F., the wrought nickel-chromium-iron alloys (types 330, 311, 310 and 309 stainless steel) and the corresponding cast grades are used.

"Inconel W" and "Inconel X" respond to age-hardening in which an artificial ageing, after cold work, gives an increase in strength properties. They can be used in work for temperatures up to 1500° F. Precipitation-hardening characteristics are obtained by the addition of aluminum and titanium.

The "Hastelloy" alloys contain more than half nickel, up to one-third molybdenum, and minor percentages of chromium, tungsten and iron. "Hastelloy C" is an age-hardenable material and can be heat treated to give maximum physical properties at high temperature.

"Inconel X" has a high rupture strength at all temperatures up to 1500° F., and shows low creep rates under high stresses at 1200, 1350 and 1500° F. "Inconel W" is of almost the same composition, except that it contains no columbium. It has about 80 per cent of the strength of "Inconel X" at room temperature and up to 1200° F. However, at 1500° F. it has less than half this strength. Typical compositions of the nickel-base alloys are given in Table 138.

TABLE 138. *Compositions of Nickel-base Alloys*

	C	Fe	Cr	Mo	Cu	Ti	Al	Cb	Ni
"Monel"	0.15	1.4	—	—	30	—	—	—	Bal.
"K Monel"	0.15	0.9	—	—	29	—	2.7	—	Bal.
"S Monel	0.10	2.0	—	—	30	—	4 Si	—	Bal.
"Inconel"	0.08	6.5	14	—	0.2	—	—	—	Bal.
"Inconel B"	0.15	9.0	17	—	0.5	-	—	—	Bal.
"Inconel W"	0.03	6	14	—	—	2.7	0.6	—	Bal.
"Inconel X"	0.08 Max.	7	15	—	—	2.5	0.7	1.0	Bal.
"Hastelloy C"	0.15	6	15	17	—	—	—	5_w	Bal.

The limiting service temperatures of some of these alloys[14] in different atmospheres are shown in Table 139; while the creep strengths at various temperatures are shown in Table 140.

Cobalt-base Alloys. The cobalt-base alloys maintain their physical properties and their resistance to creep at elevated temperatures by reason of progressive ageing in a temperature range from 1300 to 2100° F. They are difficult to machine because of the rapidity with which they work-harden. Consequently, where machining operations are used, it is generally necessary to give a softening anneal of 2100° F. or higher to put the alloy in the best condition for fabrication and assembly.

The use of cast in preference to forged alloys is indicated by the superior physical properties in both stress-to-rupture and creep tests over long periods and at higher temperatures, as compared with the similar properties of wrought materials under these conditions. The short-time, high-temperature properties of the cast materials, however, are definitely lower than those of wrought materials.

"Vitallium" is a high-cobalt alloy having high stress-to-rupture properties. Its typical composition is 0.2–0.3 per cent carbon, 28 per cent chromium, 2 per cent nickel, 6 per cent molybdenum, balance cobalt. Such alloy parts are usually made by the precision-casting process.

"Alloy X–40" containing 0.48 per cent carbon, 25 per cent chromium, 10 per cent nickel, 7 per cent tungsten and about 56 per cent cobalt, has high stress-to-rupture values at 1500 to 1600° F. At 1500 hours the stress necessary to fracture is 32,000 psi in 10 hours, 28,000 psi in 100 hours, and 26,000 psi in 1000 hours. This alloy is generally used for forgings.

"Haynes-Stellite" Alloys No. 21, No. 23, No. 30 and No. 31 are cobalt-base alloys containing 23 to 30 per cent chromium and 4 to 9 per cent of either tungsten or molybdenum, the balance being cobalt plus varying

TABLE 139. *Limiting Service Temperatures of Nickel-base Alloys*

Material	Sulphur-free atmospheres			Steam	Sulphurous atmospheres			
					Temperature (° F.) below which these materials may be used		Temperatures (° F.) above which these materials cannot be used	
	Oxidizing	Reducing H_2	Reducing CO		Oxidizing	Reducing	Oxidizing	Reducing
"Monel"	1,000	2,000	1,500	700–800	up to 600	Up to 500	1,000	650
Nickel	1,900	2,300	2,300	800–900	up to 600	Up to 500	1,000	700
"D Nickel"	1,650	2,100	2,100	——	600	——	1,000	——
"Inconel"	2,000	2,100	2,100	1,100	1,500	1,000	1,500	1,000

Table 140. *Creep Strength of Monel, "K Monel," Nickel and "Inconel"*

Material	Condition	Temperature (° F.)	Stress, psi., to produce an elongation of	
			0.10 per cent in 10,000 hr.	1.00 per cent in 10,000 hr.
"Monel"	Hot-rolled	750	20,000	31,000
		800	15,000	23,500
		900	—	13,000
"K Monel"	Cold-drawn, age-hardened	750	67,000	—
		800	48,000	—
		900	25,000	45,000
		1,000	8,500	21,000
Nickel	Hot-rolled	650	15,000	—
		750	—	10,000
	Cold-drawn, as-drawn	800	—	24,000
"Inconel"	Hot-rolled	800	48,000	—
		900*	28,000	39,000
		1,000	14,000	22,000
		1,100	6,000	11,000

* Below 900° F. the creep exceeds the yield strength, 0.20 per cent offset, as determined by the short-time tensile test.

amounts of nickel up to 17 per cent. Alloy No. 27 contains 30 per cent minimum cobalt plus 5 to 7 per cent molybdenum, the balance being nickel. The chemical composition of these alloys are shown in Table 141.

TABLE 141. *Chemical Composition of "Haynes-Stellite" Alloys*

	C	Cr	Ni	Mo	Cb	W	Fe	Co
H. S. #21	0.20–0.35	25–30	1.50–3.5	4.5–6.5	—	—	2 max.	Bal.
H. S. #23	0.35–0.50	23–29	1.50 max.	—	—	4–7	2 max.	Bal.
H. S. #27	0.35–0.50	23–29	Bal.	5–7	—	—	2 max.	30 Min.
H. S. #30	0.35–0.50	23–29	13–17	5–7	—	—	2 max.	Bal.
H. S. #31	0.45–0.60	23–28	9–12	—	—	6–9	1.50 max.	Bal.

It is not necessary to heat-treat or pre-age high-temperature alloys based on cobalt, since they have excellent elevated-temperature properties as-cast, which are maintained and supplemented by ageing in service in the range from 1300 to 2000° F.

Variations in ultimate tensile and yield strength at temperatures from room to 1800° F. for the cobalt-base alloys,[9] both as-cast and after ageing at 1350° F., are shown in Table 142. Short-time strength in the temperature range of 1000 to 1200° F. is considerably increased by ageing; however, the ductility (elongation in 2 inches) is greatly reduced. The beneficial effect of ageing on the yield strength of these alloys is known to be quite marked.

TABLE 142. *Short-time Tensile Tests of Precision-cast Specimens*

Alloy	Condition		70° F. psi	1,000° F. psi	1,500° F. psi	1,800° F. psi
"Vitallium"	As-cast,	T.S.	101,500	69,000	——	33,300
		Y.S.	82,000	39,000	——	——
	Aged,	T.S.	86,000	90,000	60,000	32,500
		Y.S.	74,700	71,500	49,000	——
"X–40"	As-cast,	T.S.	101,000	80,500	——	——
		Y.S.	74,000	50,200	——	——
	Aged,	T.S.	——	——	——	——
		Y.S.	——	——	44,700	——

Table 143 shows the average stress-rupture data for four of the Haynes-Stellite Alloys.[17] It is to be noted that Alloy No. 21 is similar in composition to "Vitallium" and that Alloy No. 31 is similar to "Alloy X–40."

Other Alloys. "K42B" is a nickel-cobalt-chromium-iron corrosion- and heat-resistant alloy analyzing about 42 per cent nickel, 22 per cent cobalt, 18 per cent chromium, 14 per cent iron, 2.2 per cent titanium, 0.7 per cent manganese, 0.6 per cent silicon, 0.3 per cent aluminum and 0.05 per cent carbon. It responds to age-hardening heat treatment by additions of aluminum and titanium, and its service temperature ranges from 1250 to 1450° F. depending on the character of heat treatment.

TABLE 143. *Average Stress Rupture Data for Precision-cast H. S. Alloys*

H. S. No.	Test temp. (° F.)	Stress (psi) for rupture in 10 hrs.	100 hrs.	500 hrs.	1,000 hrs.
21	1,200	70,000	51,900	——	44,200
	1,300	54,000	43,000	——	27,000
	1,400	42,000	24,000	——	15,000
	1,500	——	22,000	15,800	14,200
	1,600	——	16,700	13,400	13,200
	1,700	17,000	13,000	10,700	10,000
	1,800	12,500	9,400	7,700	7,000
	2,000	4,200			
23	1,200	——	58,000	50,000	47,000
	1,300	50,000	39,000	32,300	30,000
	1,400	——	36,000	28,000	25,000
	1,500	——	27,200	22,500	21,800
	1,600	——	16,000	13,000	12,000
	1,700	17,000	14,000	12,200	11,500
	1,800	12,500	8,600	6,200	5,400
27	1,200	58,000	55,000	49,000	46,000
	1,300	45,000	37,000	31,500	29,000
	1,400	35,000	28,000	——	——
	1,500	29,200	23,400	19,700	18,400
	1,600	——	16,000	12,900	12,000
	1,700	16,000	12,000	9,700	8,600
	1,800	12,500	9,300	7,500	6,800
30	1,350	——	47,000	——	——
	1,500	33,000	28,600	24,100	21,700
	1,600	24,200	18,800	15,500	14,800
	1,700	19,000	16,000	12,300	11,500
	1,800	14,000	10,000	7,900	7,100
	2,000	5,500	3,000	——	——

The elevated-temperature properties of "K42B" compared to "Inconel" are shown in Table 144.

TABLE 144

	"K42B"			"Inconel"		
	70° F.	1,000° F.	1,600° F.	70° F.	1,000° F.	1,600° F.
Tensile strength (psi)	158,000	135,000	30,000	85,000	80,000	24,000
Yield strength (psi)	90,000	90,000	28,000	35,000	22,000	18,000
% Elongation	29	26	45	49	21	32

"Refractalloy 70" is a cobalt-chromium-nickel-iron high-temperature alloy analyzing about 30 per cent cobalt, 20 per cent chromium, 20 per cent nickel, 15 per cent iron, 8 per cent molybdenum, 4 per cent tungsten, 2 per cent manganese and 0.1 per cent carbon. This alloy is also strengthened by precipitation-hardening. Typical stress-rupture values at 1500° F. are shown in Table 145.

Table 145

Stress (psi)	Time (hours) for rupture	Elong. (%)	Time in hours for deformation of 1%	2%	5%
25,000	8.2	17.0	0.8	1.7	4.3
20,000	62	22.1	—	—	—
16,000	562	12.3	188	342	498
15,000	1,016	11.8	430	680	857

"Alloy ATV3" has a typical composition of 0.35 per cent carbon, 15 per cent chromium, 28 per cent nickel, 4 per cent tungsten, and balance iron; it has high stress-to-rupture values at 1500° F.

"Kovar," containing 54 per cent iron, 18 per cent cobalt and 28 per cent nickel, is an excellent heat-resistant alloy recommended for high-temperature applications.

There are many other special composition alloys which have been developed for extreme high-temperature applications. Some have proved their commercial value, while others are still being tested in service.

Selection of Alloys

The problem of selecting proper and economical material for use at elevated temperatures requires a knowledge not only of the strength and stability of the materials under stress at high temperatures, but also of their resistance to oxidation and corrosion. High creep strength alone is not sufficient; it must be associated with good corrosion and oxidation resistance for service at the expected high operating temperatures. Therefore, metals and alloys which are suitable for high-temperature uses must have two principal characteristics, both are equally important; *viz.*, good resistance to oxidation and high strength at elevated temperatures.

In many cases the selection of promising materials has been based on creep and rupture results alone. However, the development of materials in use requires knowledge of all properties of each material and extensive laboratory testing, including behavior under vibration, stress or temperature variation, heat shock, notch sensitivity, ductility and stability, in addition to galvanic corrosion and corrosion by hot gases. Other useful characteristics are high endurance limit, impact strength and hardness.

Test data have shown that it is not chemical composition alone that determines the properties; fabrication procedure and heat treatment also are potent factors. The ready response to cold work as well as the precipitation-hardening characteristics of many alloys, which have been shown to exert marked influence on room-temperature properties, also affect high-temperature properties.

Except in age-hardening alloys[12] of the "Inconel W" type, high yield strengths of these super-alloys at room temperature are obtained only by so-called hot-cold working the alloy about 20 per cent or more at a temperature below 1700° F., usually near 1200° F. While this working of the alloy serves to accelerate precipitation, its major function is to raise the low-temperature yield strength without affecting the ultimate strength. Hot-cold worked materials have better load-carrying ability under high stresses and for short periods, while annealed or solution-treated materials are better under low stresses for longer periods.

At about 1350° F. alloys given a solution treatment with or without ageing treatments usually develop the best properties. At 1500 to 1600° F. either hot or cold work develops properties inferior to those obtained from solution-treated and aged materials.

Comparison of properties of wrought and cast alloys indicates that the alloys have better rupture strengths above 1350° F. in the cast than in the forged condition.

In the design of high-temperature equipment it is desirable to have a working picture of both the creep and the rupture properties of a material at the temperature in question before arriving at safe working stresses. Depending upon the particular application, either creep or rupture after the long periods may be the criterion of successful operation. Where close tolerances are required, creep is usually the limiting factor. In the case of materials which fail by intergranular cracking after long periods, it has been found that the amount of elongation preceding fracture may be greatly reduced. In such cases, the relation of the long-time rupture strength to the long-time creep strength of the material assumes added importance.

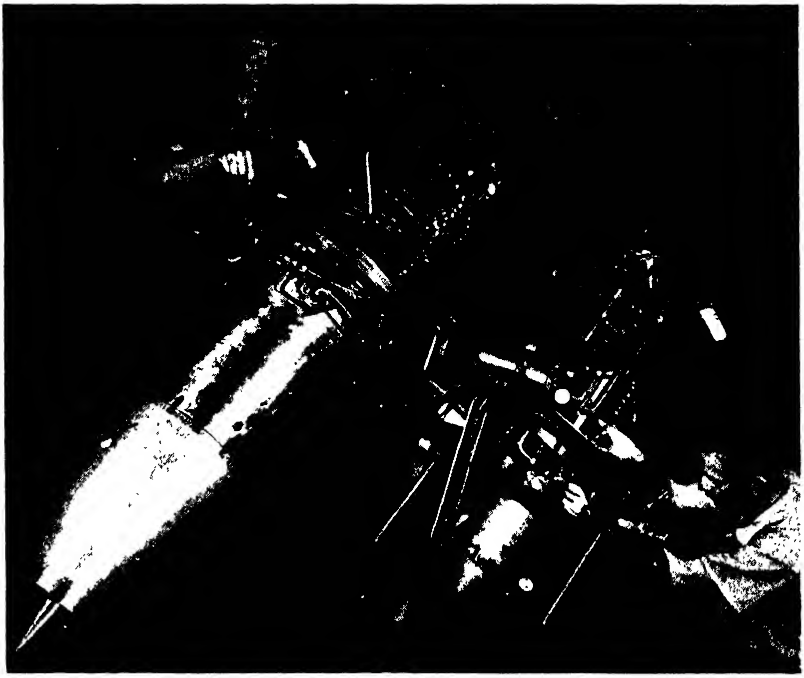
With some materials there is good reason to believe that the amount of elongation accompanying long-time fractures will be very small indeed. Usually these materials possess high creep strengths and fail by a process of intergranular cracking. On the same basis, materials that do not fail by intergranular cracking in tests of long duration normally show much larger factors of safety against failure.

Materials which are free from scaling at high temperatures and high enough in creep strength do not deform under load. Consequently they retain a constant size during service and the same area of metal is available at all times to support the required load. The safe working load is the maximum stress in pounds per square inch which could be supported at any temperature.

The field of dynamic loading,[3] with combined radial and transverse forces, is quite different from the ordinary sphere of application of heat-resistant materials, which involves the selection of oxidation- and/or corrosion-resistant alloys to withstand fairly simple static stress systems (furnace parts, oil refinery stills, etc.). Although dynamically loaded high-temperature equipment has been in successful service for many years (blowers, steam turbines, etc.), it has been possible to keep both temperatures and stresses within the capabilities of materials which are relatively weak at high temperatures. In contrast, the newer equipment, such as aircraft turbosuperchargers, diesel engine exhaust superchargers, gas turbines and jet engines, will not perform this function successfully unless they can operate at much higher stresses and/or temperatures than heretofore believed possible.

The four vital factors which must be considered simultaneously in selecting the proper alloy for a particular design and application are temperature, stress, strain and time. The following illustrations show the commercial applications of these high-temperature alloys.

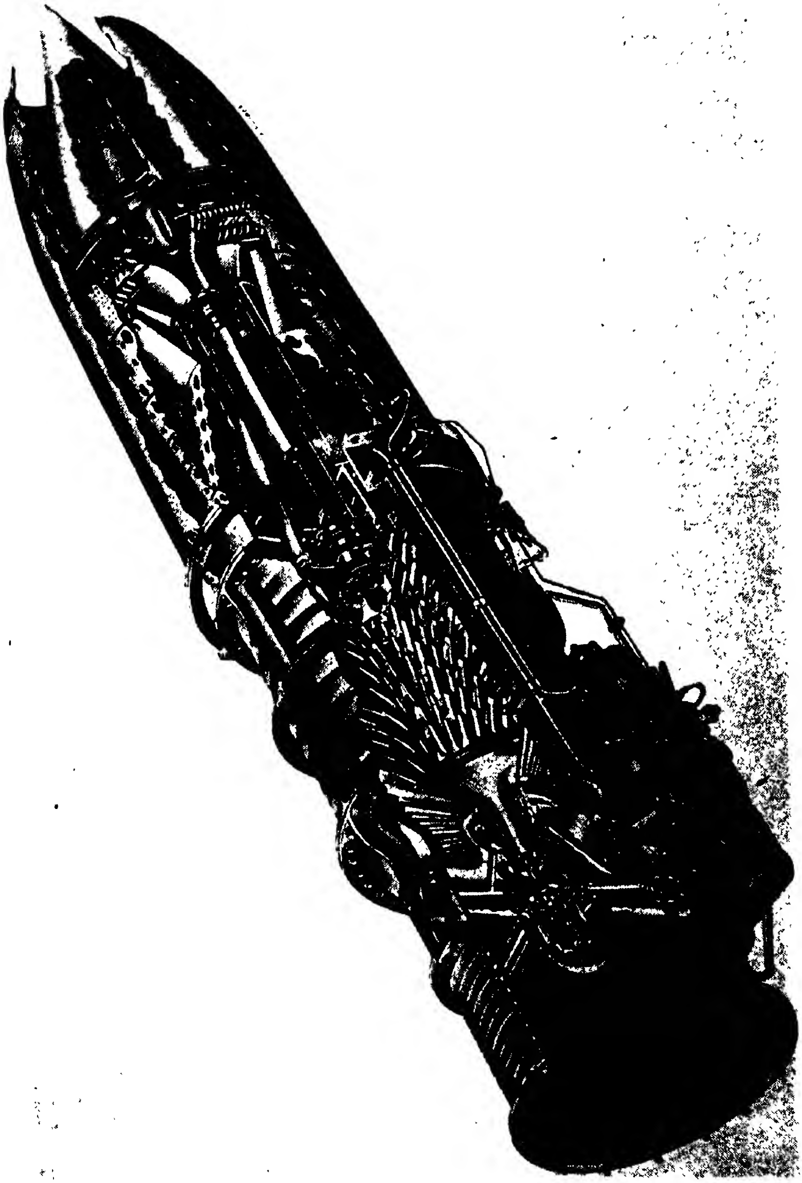
Figure 128 shows a 9.5" Westinghouse Jet Engine and a 19–XB Westinghouse Jet Engine; the latter was used in guided missiles. It is the type used in the carrier-operated Navy airplane. Figure 129 shows a cut-away of the Westinghouse 19–XB Jet Engine shown in Figure 128.



(*Courtesy Westinghouse Electric Corp., Philadelphia, Pa.*)

Figure 128. Westinghouse jet engine.

Figure 130 shows a Westinghouse 2000 horsepower locomotive gas turbine (from the left, two 100-hp. generators, the reduction gas, air inlet, compressor, combustion, gas turbine, and exhaust.)

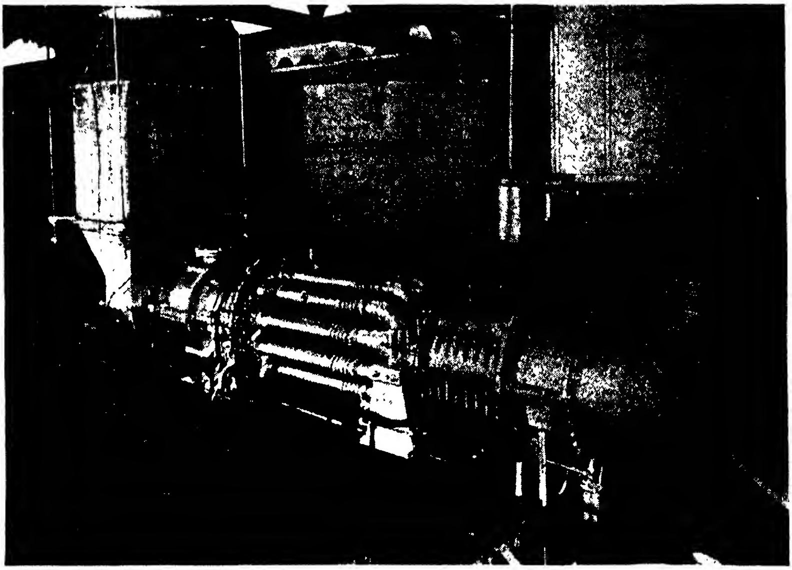


(Courtesy Westinghouse Electric Corp., Philadelphia, Pa.)

Figure 129. Westinghouse 19–X–B jet engine.

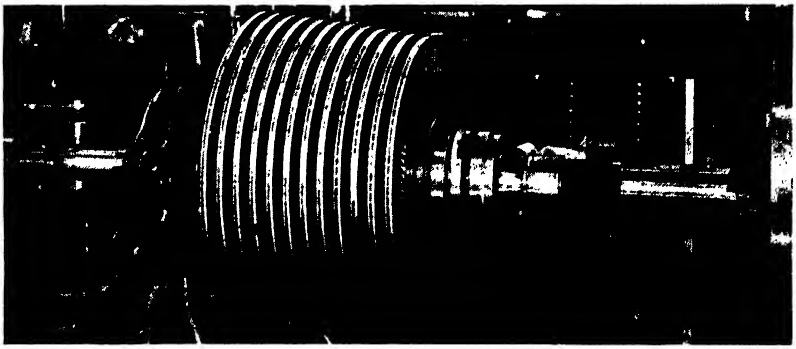
Figure 131 shows the rotor for the Elliott gas turbine, which operates up to 1400° F. This rotor is made of 19–9W–Mo heat-resisting alloy. Figure 132 is a schematic layout of the Elliott gas turbine showing the grade of alloy used for the different high-temperature parts.

Figure 133 shows the "Thermoflex" blanket for jet engines. The asbestos is sandwiched between two layers of "Inconel" mesh. Outside this is a sheet of metallic foil held in place by another layer of mesh. The "Thermoflex" blanket laces neatly around the red-hot engine cones of the new jet engines.



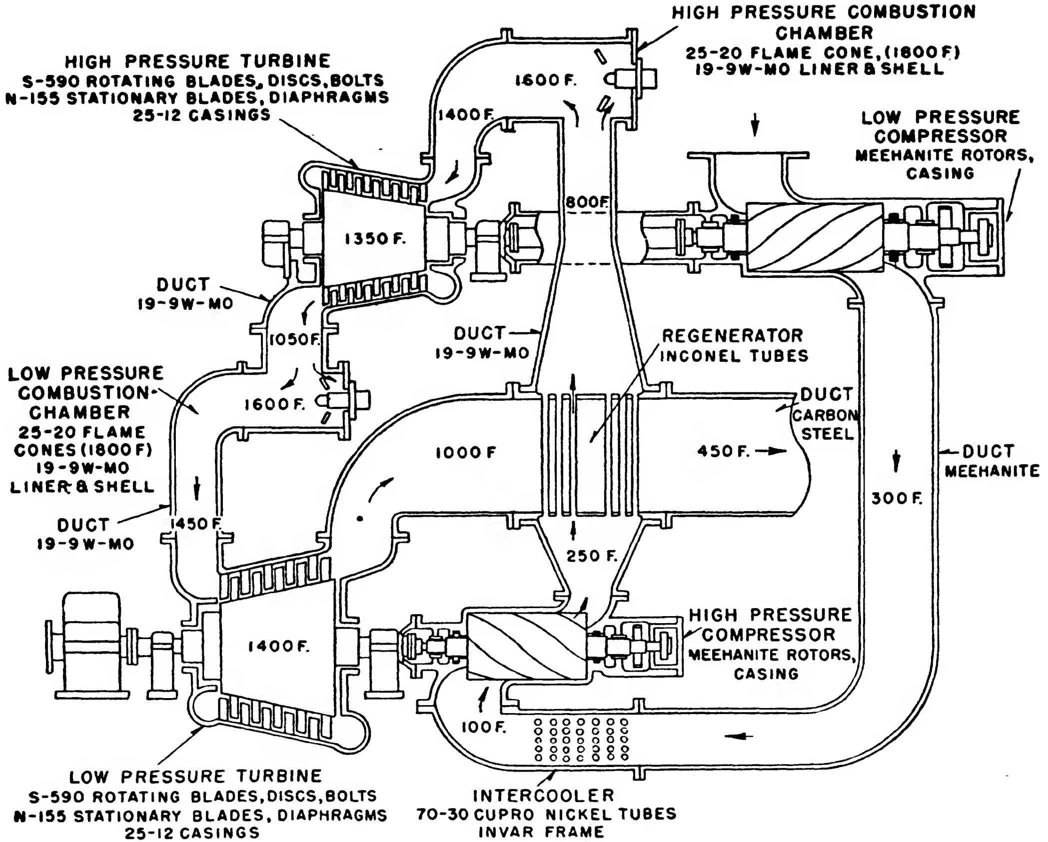
(Courtesy Westinghouse Electric Corp., Philadelphia, Pa.)

Figure 130. Westinghouse 2000 HP locomotive gas turbine.



(Courtesy Elliott Company, Jeannette, Pa.)

Figure 131. Gas turbine rotor.



(Courtesy Elliott Company, Jeannette, Pa.)

Figure 132. Elliott gas turbine.

Its ½" to ¾" thickness protects the surrounding air-frame from these excessive temperatures, which would literally burn it up.

Figure 134 shows "Inconel" exhaust manifolds made by the Pollak Manufacturing Co. for Eastern Airlines.

Figure 135 shows a stack of carburizing boxes and covers made from "Amsco F-6" (60% Ni-12% Cr-bal. Fe).

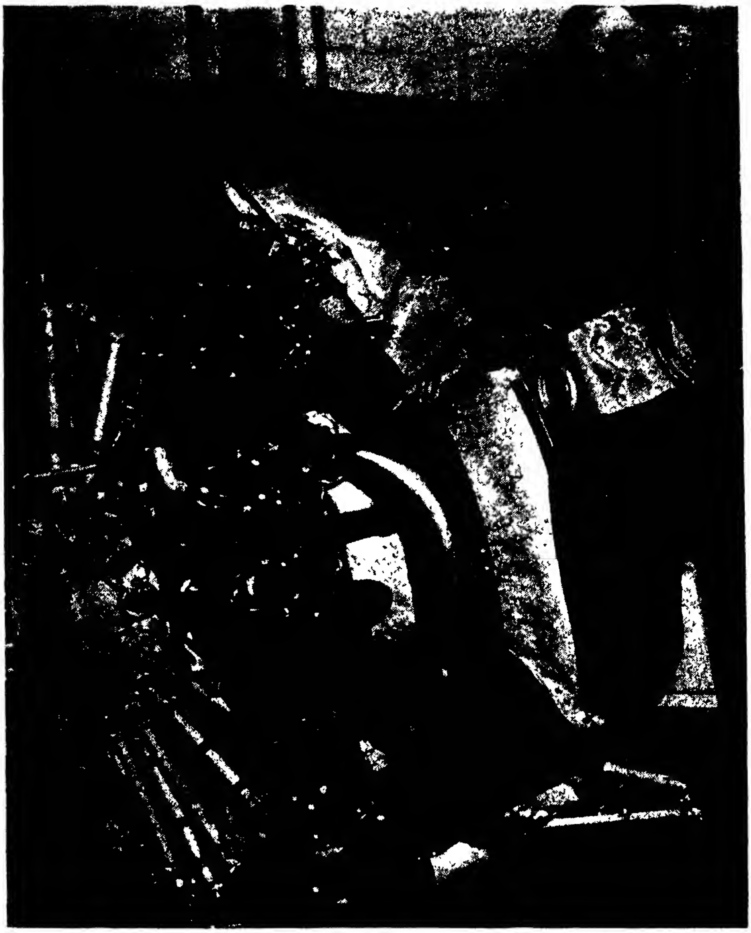
Figure 136 (top) is a photograph of the cast blading made of the highly heat-resistant alloy "Vitallium" for the Houdry type gas turbine; below is a photograph of the machined gas turbine blading with integral root for the same type gas turbine but made of a tungsten-molybdenum "Alloy 19-9."

(Courtesy International Nickel Co., New York, N. Y.)

Figure 133. "Thermoflex" blanket for jet engines.

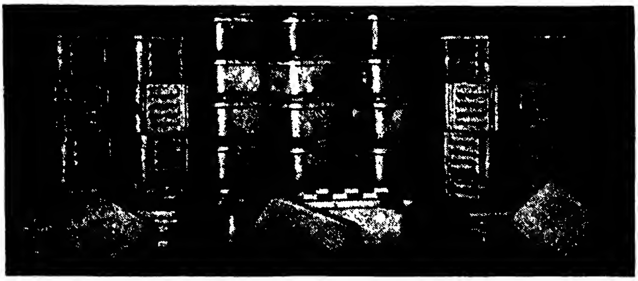
Figure 137 shows a typical petroleum-refining furnace at the fluid catalytic cracking installation of The Texas Company at Port Arthur, Texas. Interior view shows wall, roof and convection bank tubes supported by 25 Cr-12 Ni steel cast brackets. The tubes in this particular furnace are carbon steel; however, similar furnaces are tubed with C-Mo, Cr-Mo and 18-8 steel. Design and construction were by the M. W. Kellogg Company.

Figure 138 shows the interior of the regenerator of Gulf Oil Corporation's fluid catalytic cracking unit with insulating block (bottom) and 12 per cent chromium steel shingles protecting insulation on top head. The six



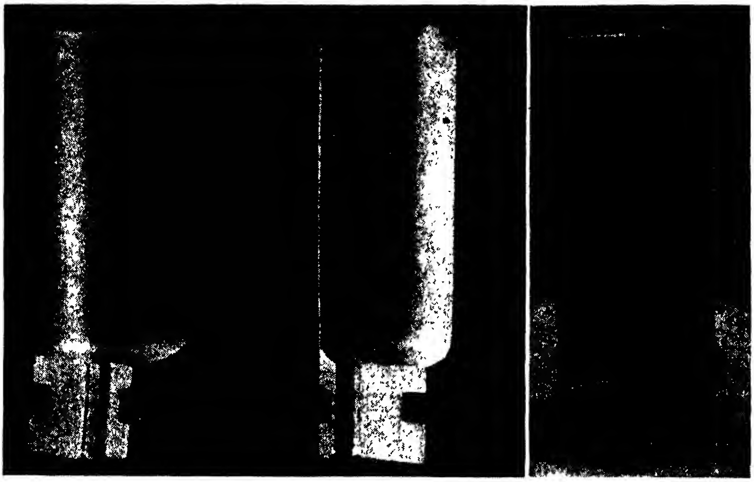
(Courtesy International Nickel Co., New York, N. Y.)

Figure 134. Inconel exhaust manifold.



(Courtesy Electro-Alloys Div., American Brake Shoe Co., Elyria, Ohio)

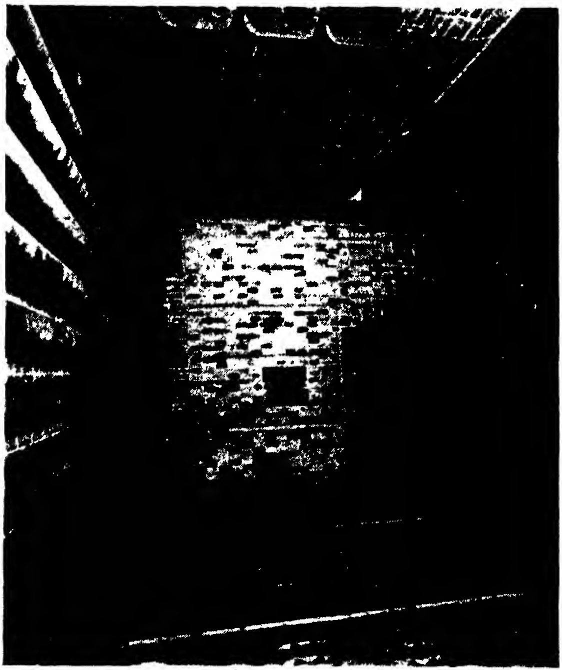
Figure 135. Carburizing boxes and covers.



Cast Cast Machined

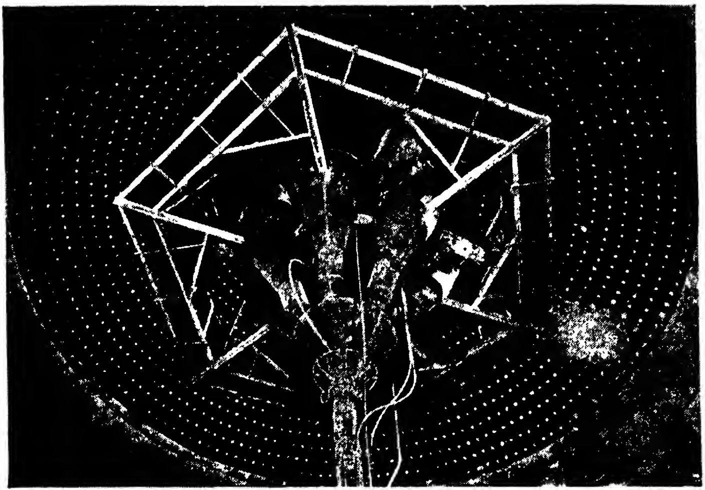
(*Courtesy Allis-Chalmers Mfg. Co., Milwaukee, Wis.*)

Figure 136. Gas turbine blading.



(*Courtesy M. W. Kellogg Co., Jersey City, N. J.*)

Figure 137. Petroleum Refining furnace.



(Courtesy M. W. Kellogg Co., Jersey City, N. J.)

Figure 138. Interior of regenerator of fluid catalytic unit.

cyclone separators are of 12 per cent chromium steel; the structural members are 18 Cr–8 Ni and the gratings for the walkway are carbon steel. The spot of light at the right is an open manhole. Working temperature for the regenerator is 1060° F. Design and construction of this unit was by the M. W. Kellogg Company.

The various proprietary alloys mentioned in this chapter are registered trade names of the following manufacturers:

- Allegheny-Ludlum Steel Co.
  - "S-495 Alloy"
  - "S-590 Alloy"
  - "S-816 Alloy"
- Austenal Laboratories
  - "Vitallium"
- General Electric Co.
  - "X-40 Alloy"
- Haynes-Stellite Co.
  - "Hastelloy C"
  - "Stellite"
  - "Haynes-Stellite" Alloy Nos. 21, 23, 27, 30, 31
- International Nickel Co.
  - "D Nickel"
  - "Monel"
  - "K Monel"
  - "S Monel"
  - "Inconel"
  - "Inconel B"
  - "Inconel W"
  - "Inconel X"
- Midvale Steel Co.
  - "ATV3 Alloy"
- Timken Bearing Co.
  - "Alloy 16–25–6"
- Westinghouse Electric Corp.
  - "K-42-B Alloy"
  - "Kovar"
  - "Refractalloy 70"

REFERENCES

1. Avery, H., Cook, E., and Fellows, A., "Engineering Properties of Heat-resistant Alloys," AIME Tech. Pub. No. 1480 (August, 1942).
2. Gow, J., "Balancing the Composition of Cast 25% Chromium–12% Nickel Type Alloys," *Trans. Am. Soc. Metals* (Dec., 1942).
3. Evans, C., "High Temperature Alloys for Dynamic Loading," *Iron Age* (June, 1944).
4. Evans, C., "Wrought Heat-Resisting Alloys for Gas Turbine Service," *Metal Progress* (Nov., 1945).
5. Lincoln, R., "Heat-resistant Steel," *Iron Age* (Nov. 8, 1945).
6. Fleischman, M., "16–25–6 Alloy for Gas Turbines," *Iron Age* (Jan. 24, 1946).
7. Agnew, J., "High-temperature Strength," *Trans. Am. Soc. Mech. Eng.* (May, 1946).
8. Wilson, T., "High Strength High Temperature Alloy S–816," *Materials and Methods* (October, 1946).
9. Badger, F., "Cobalt-Base and Nickel-Base Alloys for Ultra-high Temperatures," *Metal Progress* (Sept., 1947).
10. Freeman, "Chromium-base Alloys for High-temperature Service," National Advisory Committee for Aeronautics, Tech. Paper No. 1314, 1946.
11. Stewart, K., private communications.
12. Anon., "Heat-resistant Alloys," ASM Committee on Heat-resistant Alloys (1947).
13. "Metals Handbook," American Society for Metals.
14. International Nickel Co. publications.
15. "Digest of Steels for High-temperature Service," Timken Roller Bearing Co.
16. Clark, C., "High-temperature Properties of Steel," Steel and Tube Division Timken Roller Bearing Co. bulletin.
17. Haynes Stellite Company publications.

Section V

Testing

Chapter XVII

Mechanical Testing

It has been stated that the testing of materials is doubtless as old as man's use of materials for his weapons, tools and machines. In early times such testing was an incident in the manufacture of the weapon or tool; later it was a test before construction began.

In order to use engineering materials in design, fabrication and construction, a knowledge of their mechanical properties is necessary. These are obtained by mechanical tests such as those for hardness, tension, impact, torsion, fatigue, bend, creep, and so forth. The mechanical properties are used in evaluating the quality of a material and in determining its conformance or nonconformance to specifications. Further, they furnish a basis for the determination and the selection of engineering design values. In addition, manufacturers of metal products use such data for control of manufacturing methods as well as for guidance in the development of new materials.

Strength with plasticity is the most important combination of properties a metal can possess. Strength is the ability of a material to resist deformation, while plasticity is its capacity for withstanding deformation without breaking.

In mechanical testing, the significance of the results depends upon three things: the accuracy and sensitivity of the testing machine and the instruments used; the care used in preparing the samples; and the exactness and skill of the operator.

Errors of the testing equipment naturally result in errors in the values obtained; therefore, adequate calibration of all mechanical testing equipment is necessary. This involves determination of both the accuracy and the sensitivity of the equipment. A sensitive instrument or machine is not necessarily accurate, but the accuracy is, in general, limited by the sensitivity.

Many methods of testing have been conceived and pursued. Tensile and hardness testing procedures at room temperature have been well standardized throughout the world and direct comparison of these properties, regardless of who determines them, may be made with some degree of confidence. However, impact, shear, and many other mechanical tests have not been thoroughly standardized in all countries. The validity of comparing such values obtained by different investigators for various metals is therefore uncertain. Consequently, the methods standardized by the American Society for Testing Materials are accepted by the engineering profession and by industries in the United States.

The character, method and equipment used in the various tests to obtain the mechanical properties of metallic materials are herewith given in the order of apparent importance or relationship. The reader is advised to refer to the "Standards of the American Society for Testing Materials" or to those of similar societies in other countries for more detailed and more exact information on the standardized design of the test specimens and on the specified procedures for each mechanical test.

Hardness[8]

Hardness testing plays an important role in determining the properties of metals.[7] Penetration hardness, which is the most common hardness designation, may be defined in general as that inherent property of a metal which offers resistance to deformation or penetration by another material having a greater hardness. The hardness of a metal may be manifested by its resistance (1) to cutting operations, (2) to abrasive wear, (3) to strike and rebound, (4) to indentation, and (5) to deformation. A number of different types of hardness testing machines are available, each designed to operate under one of these principles.

Hardness testing, which may be applied to parts of any metal of any shape, is the most widely used specification test. The general trend in production hardness testing leans toward testing the semi-finished and finished products with light loads, such as are used with the Rockwell machine. On hard steels, the depth of indentation with the Rockwell Superficial tester is less than 0.001″ when using 30-kg load against a depth of indentation of 0.0035″ under "C" scale conditions of test on the normal Rockwell tester, using 150-kg load. Testing raw material such as bars, rods, plates, forgings and castings is usually done with the Brinell hardness tester.

The Brinell Test. The sample is indented with a 10-mm hardened steel ball, or carbide ball, under a load of 3000 kg for 30 seconds. The impression diameter is measured under a microscope and the Brinell Hardness Number is read from the table. This hardness number is equal to P/A, where P is the load on the ball in kilograms, and A is the spherical area of the impression in square millimeters. The area A is obtained from

$$A = \frac{\pi D}{2} (D - \sqrt{D^2 - d^2})$$

in which D is the ball diameter and d is the measured diameter of the impression in millimeters.

For softer metals, or from about 100 Brinell down, a load of 500 kg is used, and the hardness numbers are also included in the table. In exceptional cases a different ball diameter and load are used; thus, to secure comparable hardness readings, the same ratio of P to D^2 should be used, or 3000 ÷ 100 = 30. The actual hardness number is obtained from P/A by using the foregoing formula for A.

As soon as the hardness of the sample exceeds about 400, an error in the

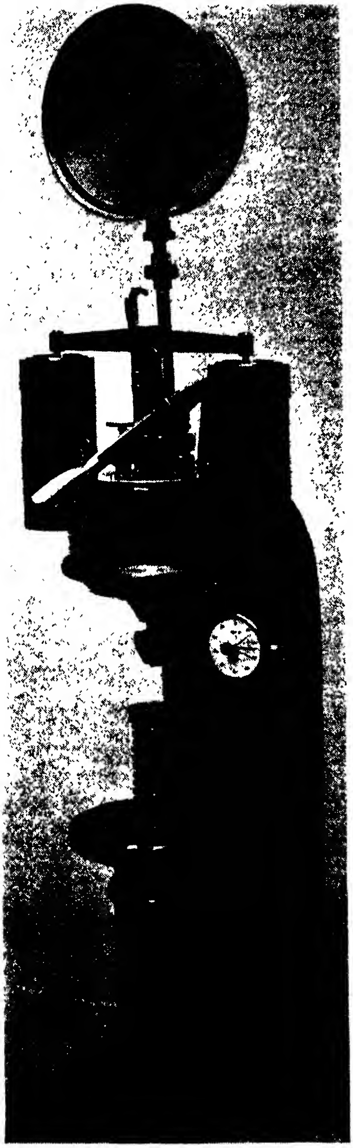


Figure 139. Brinell hardness tester.

(Courtesy Tinius Olsen Testing Machine Co., Philadelphia, Pa.)

determination is introduced owing to the flattening of the steel ball. Better hardness determinations of such materials can be made with a Hultgren ball up to 62 Rockwell C, or a tungsten carbide ball up to 67 Rockwell C, or by means of a test which uses a super hard diamond penetrator.

Figure 139 is a photograph of one model of a Brinell hardness tester.

The Rockwell Test. The sample is indented with a small, hardened steel ball or a diamond cone. The depth of penetration is determined as a measure of the hardness, while the corresponding Rockwell number is read from a reversed dial scale on the instrument. A minor load of 10 kg is first applied on the indenter to set the zero point. With the 1/16" ball, a load of 100 kg is applied, and upon releasing the load, the hardness number is read from the "B" scale. With the diamond cone indenter for the harder materials, the zero point is set as before; a load of 150 kg is applied, and the hardness number is read from the "C" scale. The reading is made while the minor load is still on the penetrator. Other scales have been devised to cover a wider range of hardness and thinner samples. These are given in Table 146.

TABLE 146. *Rockwell Scales*

Scale	Load (kg)	Penetrator	Dial readings
A	60	Diamond cone	Black
B	100	1/16" ball	Red
C	150	Diamond cone	Black
D	100	Diamond cone	Black
E	100	1/8" ball	Red
F	60	1/16" ball	Red
G	150	1/16" ball	Red
S	60	1/8" ball	Red

The "A" scale is useful for hard carbides, cold-rolled steel strip, case-hardened steel, and nitrided steel. On hard carbides the lighter load minimizes breakage of the diamond. In any case a chipped point should be guarded against, for it produces an error. Figure 140 is a photograph of the standard Rockwell Hardness tester.

Superficial Rockwell Test. The Superficial Rockwell test is used for very thin samples (thin rims and cases, etc.) where only a very shallow penetration can be tolerated or where heavier loads are likely to break

TABLE 147. *Superficial Rockwell Hardness Designations*

Load (kg)	Diamond cone	1/16-in. Ball
15	15-N	15-T
30	30-N	30-T
45	45-N	45-T

$$\text{D.P.H.} = \frac{2L \sin \frac{a}{2}}{d^2}$$

D.P.H. = diamond pyramid hardness
d = length of average diagonal in mm
a = apex angle = 136°
L = load in kg

the diamond point. The principle is the same as before, though the minor load is 3 kg and the major load is either 15, 30, or 45 kg. The reading of the hardness number is given a designation in accordance with the penetrator and load used, as shown in Table 147.

The Tukon Tester. The Tukon hardness tester is by far the most sensitive and the most satisfactory for determining either superficial hardness or the hardness of microconstituents of metals and alloys. This machine resembles the standard Rockwell tester. The indenter and loads, as well as the mode of operation, constitute the principal differences. The testing loads may be varied from 25 to 3600 grams, according to the requirements of the situation, thus causing penetrations of minute depths and areas.

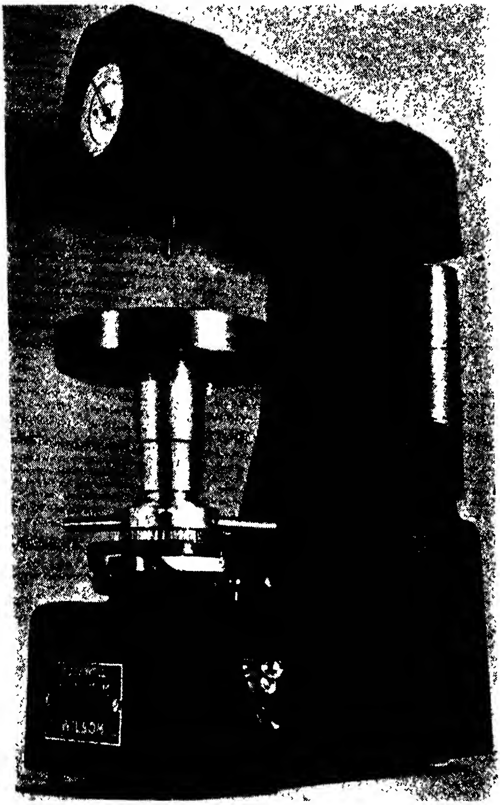


Figure 140. Standard Rockwell hardness tester.

(Courtesy Mechanical Instrument Co., New York, N. Y.)

The indenter is pyramidal in form, giving a diamond-shaped (rhombic) indentation, of which the length of the long diagonal is approximately 7 times that of the short one. Measurement of the long diagonal provides a sensitive indicator of the penetration. The Tukon hardness is expressed in the same manner as the Brinell hardness.

In another model of the Tukon tester the loads can be varied from 25 to 50,000 grams. For macrohardness testing, loads up to 50 kg may be applied and the instrument used for general hardness test purposes.

Vickers Hardness Test. The Vickers hardness test uses a diamond pyramid penetrator with a load which varies from 5 to 120 kg, depending on the thickness and hardness of the sample. The diagonal dimension of the square impression is measured under a microscope and the Vickers hardness number is obtained from a table or by use of the calculation

$$H = 1.8544\ P/d^2$$

where P is the load in kg and d is the diameter in mm.

This is a very satisfactory test, especially when used on thin samples and on hard surfaces up to over 1000 Brinell or Vickers hardness number.

Monotron Hardness Test. The Monotron hardness test uses a diamond ball penetrator, 0.75 mm in diameter. The hardness reading corresponds to the load in kg required to penetrate the surface to the standard depth of 9/5000 in. When the depth gage shows this penetration the pressure gage gives the hardness reading directly.

Scleroscope Hardness Test. The scleroscope determines the hardness of the sample by measuring the height of rebound of a diamond-tipped tup. The tup falls from a fixed height and, as it rebounds, the height is secured from an arbitrary scale reading which gives the hardness number. This is a shop test which finds considerable use in spite of its shortcomings and arbitrary nature. Hollow parts and thin sheet stock give incorrect values.

Mohs' Scale of Hardness. Mohs' scale of hardness is based on the scratch hardness of minerals as shown in Table 148. Talc is the softest and diamond the hardest.

TABLE 148. *Mohs' Hardness Scale*

Mohs' hardness	White mineral	Black mineral	Equivalent
1	Talc	Graphite	
2	Gypsum	Stibnite	Fingernail = 2.5
3	Calcite	Galena	Copper coin = 3.5
4	Fluorite	Chalcopyrite	
5	Apatite	Niccolite	Knife blade = 5.5
6	Feldspar	Magnetite	
7	Quartz		
8	Topaz		
9	Corundum		
10	Diamond		WC = 9±

Any mineral on this list will scratch any mineral of lower hardness and, in turn, will be scratched by any mineral of greater hardness. An unknown mineral will scratch and will be scratched by the mineral of equal hardness.

To distinguish between the true scratch and a chalk streak, the minerals on the left can be used for the dark minerals and those on the right for the light minerals. In terms of the absolute hardness, each mineral of this series is roughly twice as hard as the mineral next below it in hardness, though the diamond undoubtedly exceeds this materially.

The File Test. A hardened steel file is commonly used to test quenched or quenched and tempered steel for "file hardness" by the scratch method. Special files may be secured for the purpose. File hardness usually corresponds to about 62 to 65 Rockwell C, though variations from this are reported. A handy set of files can be prepared by tempering one each to different temperatures after quenching to produce about the range in hardness which it is desired to cover.

Table 149 is a conversion table of hardness numerals as furnished by the Wilson Mechanical Instrument Co. The accuracy of the conversion will depend on the material tested. However, it is an excellent working table and guide for commercial practice.

Tensile Tests

Essentially, a tensile-testing machine consists of four parts or groups of parts: namely, (1) the grips for holding the specimen; (2) a mechanism for applying the stress load, which may be a screw operated by a motor through a system of gears or a hydraulic cylinder actuated with oil under high pressure; (3) a device for measuring the load, which for motor-driven machines is usually a system of levers, with the last arm forming a graduated beam, and for hydraulic machines a dial or dials connected through small tubes to the pressure cylinder; and (4) a frame of suitable design and strength for supporting and holding these parts together. In general, testing machines vary in size from 100 to 2,000,000 pounds capacity, the smallest being used for fine wires, etc. Figure 141 shows the 60,000-pound capacity tensile testing machine (hydraulic type).

The test is carried out in machines which vary widely in detail, but all consist of two essential members: (1) a device for straining the specimen, and (2) a device for measuring the resistance of the specimen to this straining. A strain gage or extensometer is used to measure the strain over the 2-inch gage length.

From the tension test there may be obtained the following tensile properties: the proportional elastic limit, the elastic limit or set elastic limit, the yield point, the yield strength or yield stress, Johnson's apparent elastic limit, the ultimate strength, the modulus of elasticity, the per cent elongation, and the reduction of area.

The ultimate strength of a material is the load per square inch of cross-section required to fracture it; but a metal may be rendered useless with-

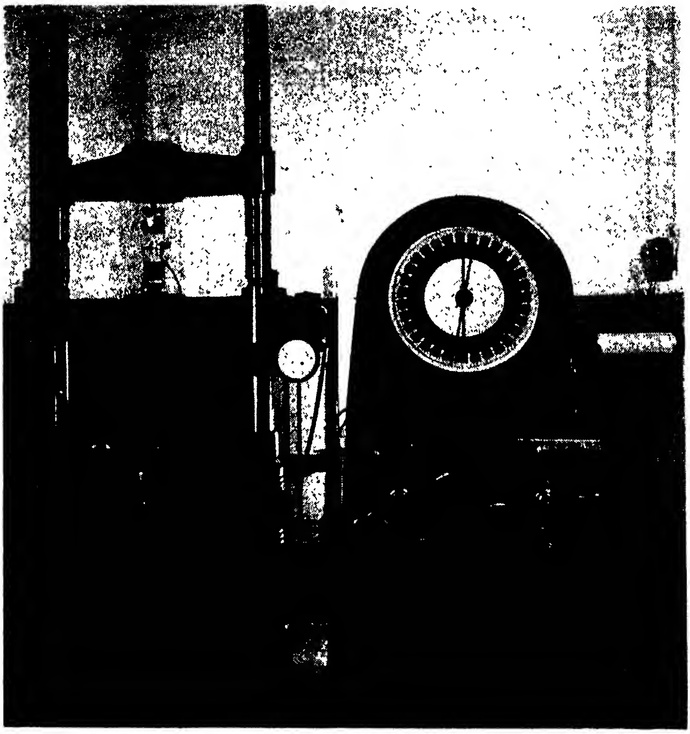
TABLE 149. *Conversion Table of Hardness Numerals*

Vickers or Firth	Brinell			Rockwell									Durometer	Monotron		Drop hardness mm. kg.	Hebert pendulum		Scleroscope	Duroscope	Moh.
	Diameter mm.	Standard ball	Tungsten carbide ball	150 kg. C	100 kg. D	60 kg. A	1/16-in. ball B	1/8-in. ball E	15-N	30-N	45-N	30-T		Cons. dia.	Diam. Brin.		Time S	Time D			
1,224	2.20	780	872	—	—	—	—	—	—	—	—	—	28	130	1,200	—	90	64	106	—	
1,116	2.25	745	840	—	—	—	—	—	—	—	—	—	31	122	1,130	—	85	59	102	—	8.5
1,022	2.30	712	812	—	—	—	—	—	—	—	—	—	32	111	1,030	—	80	56	98	—	
941	2.35	682	794	65	73	84.5	—	—	92.5	82	72	—	34	103	956	—	76	52	94	—	
868	2.40	653	760	64	72	83	—	—	92	81	71	—	37	96	894	—	72	49	91	54	
804	2.45	627	724	62	71	82.5	—	—	91	79	69	—	40	91	850	—	67	47	87	53	8.0
746	2.50	601	682	60	70	81.5	—	—	90	77.5	66.5	—	43	86	804	—	63	45	84	52	
694	2.55	578	646	58	68	80.5	—	—	89	76	64.5	—	45	82	767	1,400	60	42	81	51	
650	2.60	555	614	56	67	79.5	—	—	88	74	62	—	46	78	727	1,300	56	40	78	50	
606	2.65	534	578	54	65	78.5	—	—	87	72.5	60	—	48	74	690	1,225	53	38	76	49	
587	2.70	514	555	52	64	77.5	—	—	86	70.5	57.5	—	49	71	660	1,160	51	37	73	49	
551	2.75	495	525	50	63	76.5	—	—	85	69	55	—	50	68	630	1,095	48	36	71	48	
534	2.80	477	514	49	62	76	—	—	84.5	68	54	—	51	66	610	1,050	47	35	68	48	
502	2.85	461	477	48	61	75.5	—	—	84	67	53	—	52	63	586	1,005	44	34	66	47	
474	2.90	444	460	46	60	74.5	—	—	83	65.5	51	—	53	61	566	950	41	33	64	46	7.0
460	2.95	429	432	45	59	74	—	—	82.5	64.5	49.5	—	55	59	548	910	39	32	62	46	
435	3.00	415	418	43	58	73	—	—	81.5	62.5	47.5	—	56	57	530	880	37	30	61	45	
423	3.05	401	401	42	57	72.5	—	—	81	62	46.5	—	58	55	510	840	35	29	59	45	
401	3.10	388	388	41	56	72	—	—	80.5	61	45	—	59	53	490	810	34	28	57	44	
390	3.15	375	375	40	56	71.5	—	—	80	60	44	—	60	51	471	780	33	27	56	44	6.5
380	3.20	363	364	39	55	71	—	—	79.5	59	43	—	62	50	462	750	32	26	54	43	
361	3.25	352	352	38	54	70.5	—	—	79	58	42	—	63	48	453	725	30	26	53	43	
344	3.30	341	341	36	53	69.5	—	—	78	56.5	39.5	—	64	47	433	700	29	25	51	42	
334	3.35	331	330	35	52	69	—	—	77.5	56	38.5	—	65	45	414	675	28	24	50	42	
320	3.40	321	321	33	50	67.5	—	—	76.5	54	36	—	66	44	408	650	27	24	49	41	
311	3.45	311	311	32	50	67	—	—	76	53	35	—	68	42	390	630	26	23	47	41	
303	3.50	302	302	31	49	66.5	—	—	75.5	52	34	—	69	41	380	610	24	23	46	40	6.0
292	3.55	293	—	30	48	66	—	—	75	51.5	33	—	70	40	370	590	24	22	45	40	
285	3.60	285	—	29	47	65.5	—	—	74.5	50.5	31.5	—	71	39	360	570	23	22	44	40	
278	3.65	277	—	28	47	65	—	—	74	49.5	30.5	—	72	38	350	550	23	21	43	39	
270	3.70	269	—	27	46	64.5	—	—	73.5	48.5	29.5	—	73	37	340	535	22	21	42	39	

261	3.75	262	—	26	45	64	—	—	73	48	28.5	—	75	36	331	520	22	20	41	38	
255	3.80	255	—	25	45	63.5	—	—	72.5	47	27	—	76	35	322	505	21	20	40	38	
249	3.85	248	—	24	44	63	—	—	72	46.5	26	—	77	34	313	490	21	19	39	37	5.5
240	3.90	241	—	23	43	62.5	102	—	71.5	46	25	85	78	33	304	475	20	19	38	37	
235	3.95	235	—	21	42	61.5	101	—	70.5	44	23	84	79	32	295	460	20	19	37	37	
228	4.00	229	—	20	41	61	100	—	70	43	22	83	81	31	286	450	19	18	36	36	
222	4.05	223	—	19	40	102	99	—	—	—	—	82	82	30	277	440	19	18	35	36	
217	4.10	217	—	17	39	—	98	110	—	—	—	82	83	29	268	430	19	18	34	36	
213	4.15	212	—	15	38	—	97	110	—	—	—	81	84	29	268	415	18	17	34	35	
208	4.20	207	—	14	37	—	95	110	—	—	—	81	86	28	259	405	18	17	33	35	
201	4.25	201	—	13	37	—	94	109	—	—	—	80	87	28	259	395	18	17	32	35	
197	4.30	197	—	12	36	—	93	109	—	—	—	79	88	27	250	385	17	16	31	34	
192	4.35	192	—	11	35	—	92	108	—	—	—	78	89	26	—	375	17	16	30	34	5.0
186	4.40	187	—	9	34	—	91	108	—	—	—	78	90	26	—	365	17	16	30	34	
183	4.45	183	—	8	34	—	90	108	—	—	—	77	92	25	—	360	17	16	29	33	
178	4.50	179	—	7	33	—	90	107	—	—	—	77	93	25	—	350	16	16	29	33	
174	4.55	174	—	6	33	—	89	107	—	—	—	76	94	24	—	340	16	15	28	33	
171	4.60	170	—	4	32	—	88	106	—	—	—	76	95	23	—	335	16	15	28	32	
166	4.65	167	—	3	32	—	87	106	—	—	—	75	96	23	—	330	16	15	27	32	
162	4.70	163	—	2	31	—	86	105	—	—	—	74	97	22	—	320	16	15	27	32	
159	4.75	159	—	1	31	—	85	105	—	—	—	73	99	22	—	315	16	15	26	31	
155	4.80	156	—	0	30	—	84	104	—	—	—	73	100	21	—	310	16	15	26	31	
152	4.85	152	—	—	—	—	83	104	—	—	—	72	102	21	—	300	16	15	25	31	
149	4.90	149	—	—	—	—	82	103	—	—	—	71	104	20	—	295	15	14	24	30	4.5
146	4.95	146	—	—	—	—	81	103	—	—	—	71	105	20	—	290	15	14	24	30	
143	5.00	143	—	—	—	—	80	102	—	—	—	70	106	19	—	285	15	14	24	30	
140	5.05	140	—	—	—	—	79	102	—	—	—	69	108	19	—	280	15	14	23	29	
138	5.10	137	—	—	—	—	78	101	—	—	—	68	109	19	—	275	15	14	23	—	
134	5.15	134	—	—	—	—	77	101	—	—	—	68	111	18	—	270	15	14	23	—	
131	5.20	131	—	—	—	—	76	100	—	—	—	67	113	18	—	265	14	13	22	—	
129	5.25	128	—	—	—	—	75	100	—	—	—	67	115	18	—	260	14	13	22	—	
127	5.30	126	—	—	—	—	74	99	—	—	—	66	116	17	—	255	14	13	22	—	
123	5.35	123	—	—	—	—	73	99	—	—	—	66	117	17	—	250	14	13	21	—	
121	5.40	121	—	—	—	—	72	98	—	—	—	65	119	17	—	245	14	13	21	—	
118	5.45	118	—	—	—	—	71	98	—	—	—	64	121	16	—	240	14	13	21	—	
116	5.50	116	—	—	—	—	70	97	—	—	—	63	122	16	—	235	—	—	20	—	
115	5.55	114	—	—	—	—	68	97	—	—	—	63	123	16	—	233	—	—	20	—	
113	5.60	111	—	—	—	—	67	96	—	—	—	62	124	15	—	230	—	—	20	—	
110	5.65	110	—	—	—	—	66	95	—	—	—	61	126	15	—	228	—	—	20	—	
109	5.70	109	—	—	—	—	65	95	—	—	—	60	127	15	—	225	—	—	19	—	
108	5.75	107	—	—	—	—	64	94	—	—	—	59	128	14	—	223	—	—	19	—	

out being actually broken if it is stressed to the point where it yields or deforms permanently.

Tensile strength is the maximum tensile stress which a material is capable of withstanding. It is measured by dividing the maximum lead carried during a tension test conducted to rupture under definite prescribed conditions by the original cross-sectional area of the specimen. It is expressed in pounds per square inch. English practice uses tons per square inch and Continental practice kilograms per square millimeter.



(Courtesy Baldwin Locomotive Works, Philadelphia, Pa.)

Figure 141. Tensile test machine.

Yield point is the stress in a material at which there occurs a marked increase in strain without an increase in stress. For material that has a "sharp-kneed" stress-strain diagram and consequently exhibits at a certain stress the special characteristic of yielding without increase in stress, the yield point may be obtained from the load determined by the "drop" of the testing machine beam, or by use of dividers on the gage length. For material whose stress-strain diagram in the region of yield is a smooth curve of gradual curvature, the "yield strength" is preferred. It is expressed in the same units as the tensile strength.

Yield strength is the stress at which a material exhibits a specified limiting permanent set or specified elongation under load, generally from 0.1 to 0.2 per cent of the gage length. For material possessing the special characteristic of yielding without increase in stress the yield strength and yield point are substantially the same. It is expressed in the same units as the tensile strength, but the specified value of "set" used is stated after the term "yield strength."

Elastic limit is the maximum stress to which a material may be subjected without permanent deformation or set upon complete release of the stress. It is the maximum stress at which a material exhibits a slight deviation from the straight line (proportional limit), but will return to the original length on release of the load. It is expressed in the same units as the tensile strength.

Proportional limit is the stress upon a material beyond which the strain ceases to bear a constant direct relation to the stress. It is expressed in the same units as tensile strength.

Johnson's elastic limit is the point on the stress-strain diagram at which the rate of deformation is 50 per cent greater than it is at the origin. It is expressed in the same units as tensile strength.

Elongation is the difference in the gage length before the tensile test specimen has been subjected to any stress and after rupture, expressed in percentage of the original gage length. The gage length usually taken is either 2 inches or 8 inches. The latter is used for wire.

Reduction of area is the difference between the original cross-sectional area and the least cross-sectional area after rupture, expressed as a percentage of the original cross-sectional area.

The per cent elongation and the per cent reduction of area obtained in a tensile test of a material are an indication of the ductility of the material.

For most applications yield strength data are sufficient to act as a basis of design. However, there are many other applications which require that we know just how far a metal may be stressed without taking any permanent set or even without varying from a straight line relation of stress to strain.

Such applications require a knowledge of the proportional limit or the elastic limit of the material. The proportional limit is a maximum stress under which a material will maintain a perfectly uniform rate of stress to strain. This is illustrated by the lower portion (from 0 to about 4000 psi) of the stress-strain curve shown in Figure 142. Such a curve is drawn from stress and strain measurements taken during a tensile, compressive, shear or torsional test.

Most materials can be stressed slightly above the proportional limit without taking any permanent set. That is, the material will exhibit a slight deviation from the straight line, such as would occur at a stress of about 42,000 or 44,000 psi on the chart, but will return to the same original length when the load is released. The maximum stress from which a material can recover completely is the elastic limit.

Elastic limit determinations are quite lengthy, because the process entails alternate loading and unloading of the specimen, each time using a slightly greater load, until the specimen fails to return to its original position. The stress corresponding to the last previous load is then taken as the elastic limit.

Different metals yield differently,[5] as illustrated in Figure 142. Curve A is typical for mild steel and for almost all soft steels. It shows a distinct dip, indicating that when a certain stress is reached the metal stretches rapidly, even if the load is slightly reduced. Thus, a material of this type shows a sharply defined yield point. Hard steels and some non-ferrous metals have a characteristic as shown in Curve B. There is no actual dip in the curve, but there is a definite break which may be noticed during testing. Most non-ferrous metals show a curve similar to Curve C. There is no definite break, but a gradual curvature. Here it becomes impossible to measure a yield point, since there is no point which can be picked out during the test. For such materials the yield strength is measured as the stress required to produce a certain permanent set, usually 0.2 per cent of the gage length.

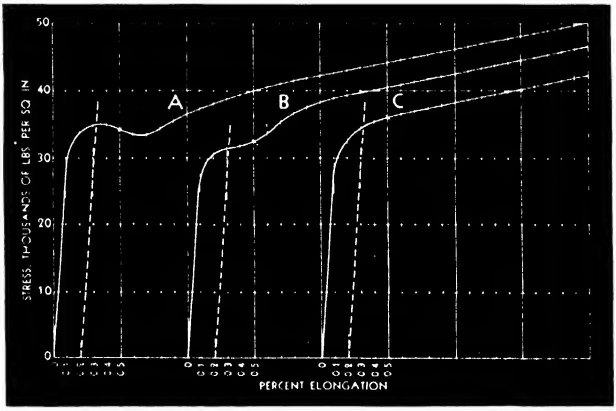


Figure 142. Stress-strain curves.

Young's modulus or *modulus of elasticity* is defined as the ratio of the unit stress to the unit strain. It is the slope of the straight-line part of the stress-strain curve below the proportional limit. The modulus of elasticity is a measure of the stiffness of a material; it measures the resistance of a material to elastic deformation. The higher the modulus, the stiffer the material. Metals and alloys of high moduli must be more heavily loaded to produce a given sag or deflection.

Compression Tests

It is usually tacitly assumed[6] that materials are equally strong in tension and compression, or that if any difference exists, the compression strength is the greater of the two. With metals compression tests are much less commonly used than tension tests.

From the compression test there may be obtained the following compressive properties: the proportional limit, the elastic limit, the yield point and the ultimate strength. *Compressive ultimate strength* is the maximum compressive stress to which a material may be subjected without failure. It is expressed in pounds per square inch. *Compressive yield point* is the stress in compression at which a marked deformation continues without failure in load. The *compressive yield strength* is the maximum stress that a metal, subjected to compression, can withstand without a predefined amount of deformation. Both are expressed in pounds per square inch. *Compressive elastic limit* is the maximum compressive stress to which a material may be subjected without permanent deformation or "set" upon complete release of the stress. It is expressed in pounds per square inch.

In compression, the ultimate strength is easily determined in brittle materials which shatter at failure, but in ductile materials there is no definite value for it. For materials that do not fail by shattering fracture, the value obtained for compressive strength is an arbitrary one, dependent upon the degree of distortion regarded as indicating complete failure of the material. In many ductile materials the maximum usable compressive strength is the compressive yield strength. If it is desired to compare two ductile materials in compression, a definite limit for the deformation may be set and the loads required to cause this deformation compared.

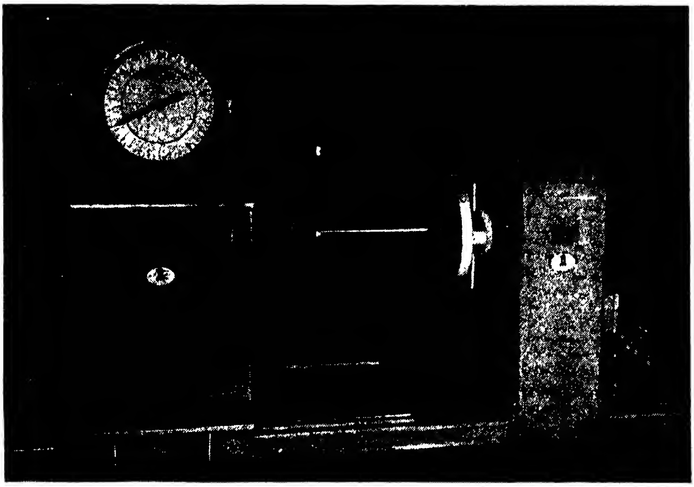
In the compression test the movable cross-head of the machine should move in a straight line at right angles to the stationary crosshead, without appreciable lateral motion and without wobbling.

Torsion Test

The suitability of a material for parts which must withstand twisting and wrenching stresses is judged by measuring its properties as it is twisted in the torsion test. Torsional properties evaluate the character of materials for engineering uses which involve lateral as well as longitudinal stresses.

From this test there may be obtained the following torsional properties: the proportional limit, the elastic limit or possibly the shearing yield strength, the ultimate shearing strength or the modulus of rupture, and the modulus of elasticity in shear (sometimes called the modulus of rigidity). *Torsional strength* is the ultimate shear strength in torsion expressed in pounds per square inch. *Torsional yield strength* is generally defined as the maximum stress developed by a torque producing an offset of 0.2 per cent from the original modulus line, analogous to the method used for determining tensile yield strength. It is expressed in pounds per square inch. *Torsional elastic limit* is the elastic limit in torsion, expressed in pounds per square inch, and is analogous to the elastic limit in tension. *Modulus of rupture* is the maximum stress, expressed in pounds per square inch, in the extreme fiber tested to rupture, as computed by the empirical application of the flexural formula to stresses above the transverse proportional limit. *Modulus of elasticity in shear* is the ratio of stress within the proportional limit to the corresponding angular strain in radians. It is obtained by unit shearing deformation, and is expressed in pounds per square inch.

The torsion test actually is used to determine the physical constants of materials in shear. A torsion-testing machine applies a twisting moment to a specimen in a plane at right angles to the axis of the specimen. This is accomplished by a rotating head arranged with a set of jaws to hold one end of the specimen so that its axis will coincide with the axis of rotation. The other end of the specimen is held by similar jaws in the fixed or weighing head of the machine where, as the head is rotated, the twisting moment can be measured by a suitable weighing system. The displacement of a



(Courtesy Riehle Testing Machines Div., American Machine & Metals, Inc., East Moline, Ill.)

Figure 143. Riehle torsion test machine.

point on the surface of the specimen is measured with respect to some other point in the same element to give the angle of twist (Figure 143).

In plotting a stress-strain diagram for a torsion test it is customary to plot torque in inch-pounds on the vertical axis and unit deformation on the horizontal axis.

Shear Strength Test

Shear strength is the stress, expressed in pounds per square inch, required to produce fracture when impressed vertically upon the cross-section of a material. The amount of energy which must be supplied to shear a unit volume of metal increases with increasing tensile strength of the material which is being deformed. Shear stress is the component of stress acting on the plane of shear.

Shear yield point, expressed in pounds per square inch, is the stress at which deformation in shear occurs with little increase in stress. In ductile materials, the yield point in shear is considered the maximum shear strength for practical purposes. Since the stress and strain are proportional up to the elastic limit, there is a modulus of elasticity in shear as there is in tension or compression. It is known as the *modulus of rupture* or the *modulus of rigidity.*

In practice, nearly all parts which are subjected to shear are also stressed in tension or compression at the same time, and the combination of these stresses may be considerably in excess of either of the primary stresses.

The shear fracture is quite distinct from either the tension or compression fracture. There is no reduction of area or elongation, and the fracture has a distinct texture which shows the twisting effect.

For single shear tests, any convenient jig which will hold one end of the test specimen securely can be used. The cutter is attached preferably to the movable head of the tensile machine and pressed vertically on the specimen.

Notch Impact Test

The impact test, which is an indication of the shock resistance or notch sensitivity of a material, consists usually of the determination of the energy absorbed in breaking a notched specimen by a single blow. The results of the test are stated only in terms of impact value, indicative of the total energy to break a standard specimen by a single blow under standard conditions, and should not be generalized and applied quantitatively to other sizes of test specimens or other conditions. Although there are a number of methods of performing the impact test, those in general use are (a) simple-beam test (Charpy), and (b) cantilever-beam test (Izod).

In the Charpy or Izod machine the pendulum acquires a certain energy during its fall from the starting position. A definite portion of this energy is used in rupturing the test bar. The energy remaining in the pendulum causes it to rise to a height dependent on the remaining energy, of which it is a measure. The energy of rupture is therefore determined by the difference in energy in the pendulum before and after the rupture.

For the Charpy test, the specimen is broken by a blow at the center on a face opposite the notch with the ends supported on an anvil. In the Izod test, the specimen is broken by a blow at one end of the notched face, the other end being held rigidly in a vise for one-third of its total length. In both tests, the pendulum striking the blow is released from a height sufficient to break the specimen. Swinging downward in a vertical plane, the tup on the pendulum contacts the specimen at the lowest point in the arc of swing, breaks it, and continues in an arc till the pendulum stops. From the weight of the pendulum and the angle of fall, the total energy in foot-

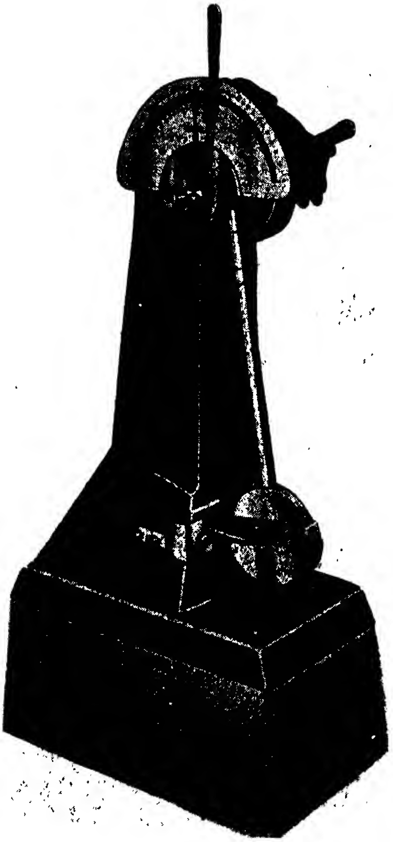


Figure 144. Riehle impact tester.

(Courtesy Riehle Testing Machines Div., American Machine & Metals, Inc., East Moline, Ill.)

pounds it contains at the instant of impact can be calculated, and from the angle of rise, the energy remaining in the pendulum after the contact can be found in the same units. With the machine illustrated in Figure 144, results for all tests are read directly in foot-pounds on a uniformly graduated scale. The greater the amount of energy absorbed by the specimen during impact, the less will be the upward swing of the pendulum.

Generally speaking, the shock-resisting power of a material may be estimated by considering both its strength and ductility. These properties are measured by applying loads at a very slow rate. However, materials which exhibit good strength and ductility under such conditions may not necessarily possess good resistance to shock and impact loads.

Impact strength evaluates the toughness of a material better than any other single test. Both the Charpy and Izod tests are affected somewhat by the susceptibility of the material to failure due to localized stresses near a sharp notch.

Tension Impact Test

Tension impact is the energy, in foot-pounds, absorbed in rupturing a specially prepared specimen by allowing a moving weight to strike the specimen in such a manner that the specimen is parted suddenly in tension. Both the Izod and Charpy impact machines are equipped for such impact tension tests. In the Charpy machine the specimen is held by one end in a threaded socket on the back of the pendulum and the other end carries an auxiliary cross arm which contacts the anvil on the downward swing. In the Izod machine the specimen is clamped in an auxiliary anvil attached to the regular anvil and also carries a cross arm which is struck by the pendulum in its downward swing.

In the Riehle Impact Tester (Figure 144) two anvils of equal length are provided to perform the test. They are mounted as illustrated after the Charpy and Izod anvils have been removed. The standard tension specimen is threaded on both ends, one being screwed into the rear of the bob, the other into the impact crosshead. As the bob swings through the lowest point in its arc, the crosshead strikes the anvils, causing the entire inertia of the bob to be exerted axially upon the specimen.

Torsion Impact Test

Torsion impact is the energy, in foot-pounds, absorbed in rupturing a specially prepared specimen by allowing a moving weight to strike the specimen in such a manner that the specimen is ruptured suddenly by torsion. The torsion impact machine consists of three parts: (1) the momentum unit, (2) the sliding unit carrying one end of the specimen, holding it against rotation, and (3) a substantial base.

A test is made as follows: The specimen is clamped in the sliding head with a steel strike-bar attached to its free end. The sliding member is pulled entirely to the right so the strike-bar clears the bosses on the wheel. The momentum unit is brought up to a predetermined speed indicated on the tachometer, a small motor providing the turning effort through a friction drive. The "bomb-proof" cover is then closed by moving the handle from right to left. The knob on the end of the sliding member on the far right is then sharply pushed home; this brings the strike-arm within the "bomb-proof" cover into the path of the hammers, so the specimen suffers sudden fracture in torsion impact. The residual speed is then read on the tachometer (Figure 145).

(Courtesy Baldwin Locomotive Works, Philadelphia, Pa.)

Figure 145. Torsion impact testing machine.

The kinetic energies for various wheel speeds are given in a table accompanying the machine. The energy in foot-pounds absorbed in breaking the specimen is the difference between initial and residual energies, corresponding to initial and residual speeds. One operator can mount the specimen and complete a test in less than two minutes.

A method of obtaining approximate stress values from work deformation data has been developed.

$$W = \frac{\alpha S}{158{,}800} + 0.185 \times 10^{-9}S^2$$

W = torsion impact value
α = twist of the total deformation in degrees
S = shearing strength in pounds per square inch

This equation may be reduced to the following form:

$$S^2 + 34{,}200\alpha S + (-5.4 \times 10^9 W) = 0$$

which reduces to

$$S = 10{,}000(-1.71\alpha + \sqrt{2.9\alpha^2 + 54W})$$

Figure 146 shows the relation between torsion impact and Rockwell hardness for a hardened chromium ball-bearing steel.

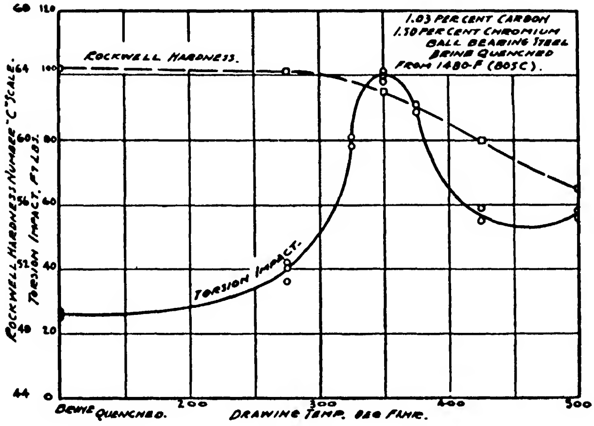


Figure 146. Torsion impact results. Chromium ball-bearing steel.

Ductility Test

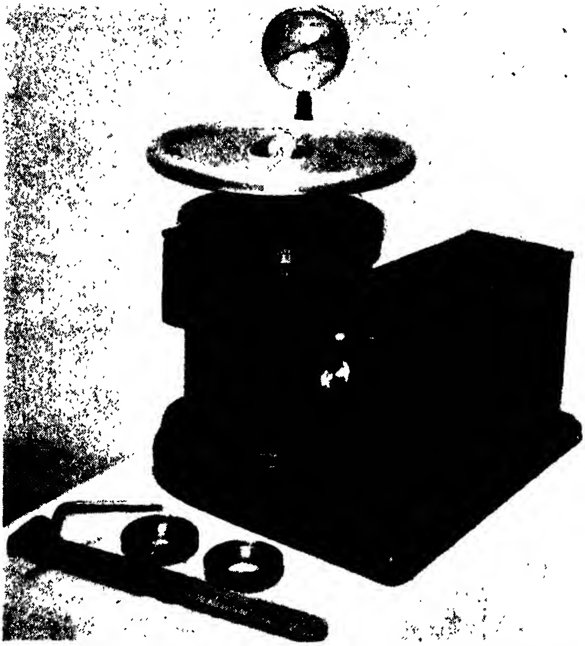
Ductility is that property of a material which allows it to be deformed without rupture; in other words, the ability to be manipulated by cold-working methods (bending, deep-drawing, spinning, cold heading) without undue effort. The lack of ductility is commonly called brittleness.

Ductility can be determined[5] by measuring the per cent elongation and reduction of area in a tensile test, by the increase in diameter resulting from a compression test, by the deflection at maximum strength in a shear test and by the depth of cup in the Ericksen or Olsen test.

Most ductility tests are made by the cupping method. This method is the depth of impression, or cup, coinciding with the fracture of sheet metal when tested using a ⅞-inch diameter ball and a 1⅝-inch vertical-sided die. The value is expressed in inches or millimeters, with the fracture load in pounds or kilograms.

Figure 147 is a photograph of the Olsen ductility testing machine for testing sheet metal. The load is applied hydraulically through a piston to the test sample. A direct-connected, motor-driven rotary pump gives the utmost in smoothness of operation. The automatic stop, which is particularly useful in the determination of the load at ¼-inch depth of cup is provided. The test is then continued by throwing the small hand lever below the handwheel. The maximum load and maximum depth of cup can be noted. The depth of cup measured in thousandths of an inch is taken as the measure of ductility.

These machines are exceptionally fast in operation. Once the valve is set for the testing speed, all that is required of the operator is to remove the



(*Courtesy Tinius Olsen Testing Machine Co., Philadelphia, Pa.*)

Figure 147. Olsen ductility testing machine.

handle shown to its uppermost position to apply the load. The specimen is placed in the opening between the grips, the load is applied uniformly to grip the specimen, and this is immediately followed by the penetrator forming the cup. After the test is completed, the handle is moved to its lowest position, which quickly returns the piston with the ball support to its original position. After the specimen is removed from the machine, another is placed in the head; the operator then repeats the above sequence of operations.

Various capacities of machines are made depending on the thickness and the material under test: 12,000-pounds capacity will take materials up to $\frac{1}{16}$-inch thick; 24,000-pounds capacity will take materials up to $\frac{1}{8}$-inch thick; 50,000-pounds capacity will take materials up to $\frac{5}{16}$-inch thick; and 60,000-pounds capacity will take materials up to $\frac{3}{8}$-inch thick.

In the Ericksen test, the specimen of the sheet or strip is clamped between two ring-shaped dies and held in such a way that the metal can flow, while a tool having a rounded end (hemispherical) is moved gradually forward under the influence of a ram, actuated by a micrometer screw, until fracture occurs. The test piece is under permanent observation of the operator, so that the point of fracture can be determined with great accuracy (0.01 mm). The depth of impression, that is, the height of the dome, required to obtain fracture, can be read off directly from a micrometer scale or dial gage and represents the "Ericksen Value" in hundredths of a millimeter. This cupping method of test determines in a simple and rapid manner the actual workability of metal sheets to the point of fracture.

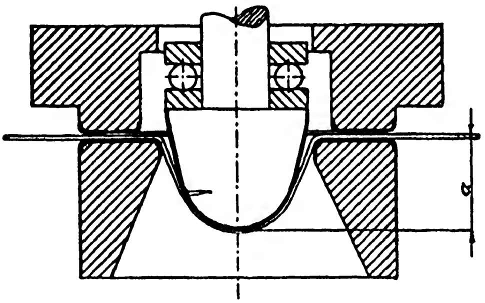


Figure 148. Tools for Ericksen ductility test.

Figure 148 is a diagrammatic sketch of the Ericksen standard tool for testing metal sheets.

While the Olsen and Ericksen machines differ in many respects, they are similar in the manner of applying the test. However, the test results are sensitive to variations in gage

Bend Test

A large part of all structural members in service is subject to bending, which produces tension, compression and shear stresses in the member. The stress caused by bending is not uniform over the cross-sectional area, but varies from a maximum compression on one side to a maximum tension on the opposite side.

Various tests are used to determine the ductility of sheet or plate that is subject to bending. These tests may include determination of the minimum radius or diameter required to make a satisfactory bend, and the number of repeated bends that the material can withstand without failure when bent through a given angle and over a definite radius.

The bend number is the number of reversed bends through a specified angle (usually 90°) about a specified radius to which a specimen can be subjected without fracture.

From the bend test there may be obtained: unit stresses in tension and compression, modulus of rupture for brittle materials and modulus of elasticity. Ductile material produces no fracture in the bend test; therefore it has no modulus of rupture.

Transverse Strength Test

Transverse strength tests are actually bend tests. They are used for the evaluation of strength and toughness of hard and brittle material such as cast iron, sintered carbides and hardened tool steels. The test is made by placing the prepared specimen horizontally on cylinders or knife edges as beam supports. The load is applied at the center of the span through a ball or cylindrical surface, which usually has the same radius as the supports, until rupture occurs. The rate of loading is unimportant in brittle materials as long as it remains lower than the speed of shock-loading.

This test is not applied for the purpose of determining the actual working strength of the material, but only for comparative purposes. Consequently the results are usually stated in terms of the breaking load applied in pounds and the deflection in inches.

Therefore, *transverse strength* may be defined as the ultimate strength in bending for brittle materials when tested to the point of rupture, as a beam on simple supports with concentrated central load. *Transverse deflection* is the specified deflection of the material, tested in the transverse test, produced by some specified load, dependent upon the size of the specimen. It is the maximum deflection to rupture.

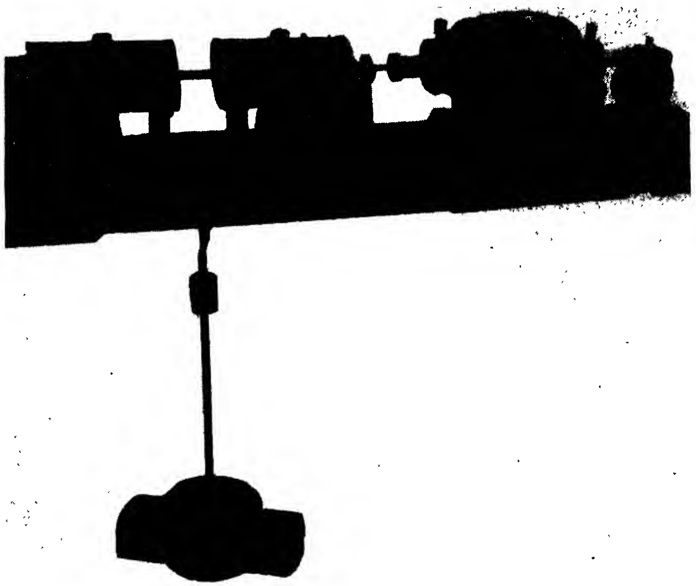
The amount of flexure of the beam under load may be utilized as a measure of the ductility of the material. In addition, the modulus of rupture for cast iron can be calculated from this test with the formula $R = \frac{2.546LS,}{D^3}$ in which R is the modulus of rupture, L is the span length or distance between supports in inches, S is the breaking load in pounds, and D is the diameter of the test bar in inches.

Fatigue Test

In many structures, certain members are required to withstand repeated or fluctuating stresses. Many machine parts are subject to vibration. The behavior of metals when they are subjected to such alternating stress is therefore extremely important. Under such conditions of repeated stresses metals are likely to break under loads much less than the static loads they are capable of supporting. It has been shown that the repeated application of such stresses may cause failure even when the stresses are below the elastic limit of the material. Failure by such alternating stress is called *fatigue*.

The *fatigue limit* or *endurance limit* is that unit stress a metal can withstand for an indefinitely large number of cycles of stress. It is the maximum stress to which a material can be subjected an indefinitely large number of times without causing failure and is expressed in pounds per square inch.

Values of endurance limit are usually obtained by using a machine of the rotating simple-beam type, in which the outermost fibers of a solid cylindrical specimen are subjected to cycles of completely reversed stress from tension to compression.



(Courtesy Baldwin Locomotive Works, Philadelphia, Pa.)

Figure 149. R. R. Moore fatigue testing machine.

To determine the maximum number of stress cycles that can be applied without breaking the specimen, it is customary to start the test with relatively large stresses, say two-thirds of the yield strength in tension, and repeat the test with smaller loads until the load the specimen can withstand indefinitely is reached. To find this load, the results of the several tests are plotted with the stress as ordinate and the number of repetitions of the stress as abscissa, the latter on the logarithmic scale.

Of prime importance for high fatigue life are the smoothness and lack of stress-raising imperfections on the metals used. Fatigue limit increases with the tensile strength, and in ductile steels is approximately 50 to 60 per cent of the tensile strength. However, corrosive conditions on the surface of the metal greatly decrease the fatigue strength even at low stresses.

A number of types of fatigue-testing machines are available. In the most common type, a round test bar is rotated horizontally with a load applied by means of a weight hung on one end, and the stresses are calculated from the applied load and the dimensions of the test specimen. In such a test, the load varies from a tensile stress to a compressive stress of equal magnitude.

Figure 149 shows the R. R. Moore high-speed fatigue-testing machine, which incorporates a special design based on the rotating-beam principle. In this machine the specimen functions as a simple beam symmetrically loaded at two points. The machine consists essentially of two housings, each of which supports a rotating spindle. The tapered ends of the test specimen are drawn into tapered holes in the end of each spindle by bolts which lock the specimen firmly in place. The housings are supported on trunnions which permit deflection of the housings in a vertical plane when the load is applied. Knife-edge seats mounted on opposite sides of each housing receive the knife edges mounted in the ends of the hanger yokes which carry the load weights. The machine is driven by an electric motor through a flexible drive link which offers no restraint to the required deflections of the housings.

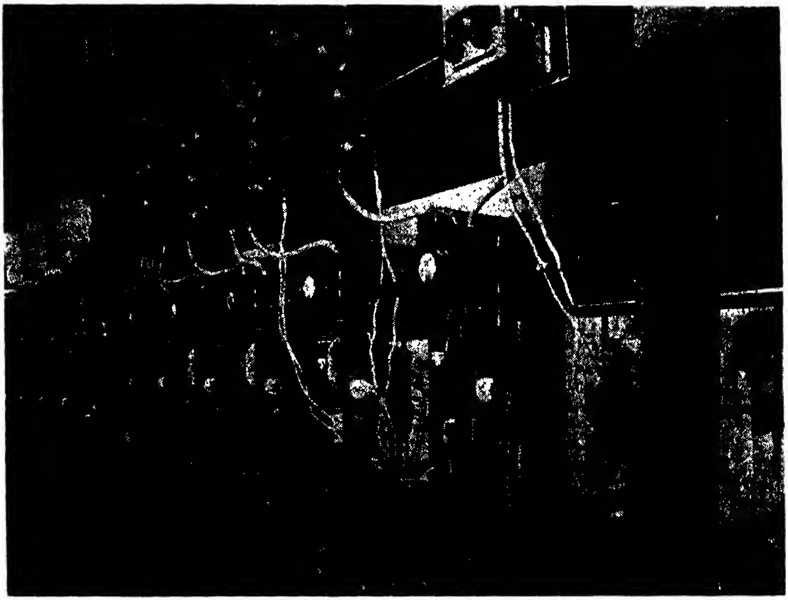
Creep Strength Test

Creep is the gradual plastic flow (permanent elongation) of a metal induced by a combination of high temperature and a steady stress below that required to produce a permanent set, as determined by short-time tests at the same temperature.

The creep strength or limiting creep stress of a metal is its ability to withstand creep, expressed as the maximum stress that may be applied at a given temperature to cause plastic flow of the material at a given rate, or not exceeding a certain amount in a specified number of hours, *e.g.*, 1.0, 0.1, or 0.01 per cent elongation in 1000 or 10,000 hours. It is generally expressed as pounds per square inch to produce a 0.10 per cent elongation in 10,000 hours.

In making a creep test, a specially prepared specimen is heated to the desired temperature in an electric furnace, usually under a small load, and a predetermined load is applied under conditions that will permit accurate measurement of the elongation of the specimen with an extensometer scaled to permit readings to 0.0001 inch per inch of gage length. Readings are taken just before and immediately after the load is applied, then at intervals of 24 hours or more for the duration of the test (Figure 150).

The creep test is used to determine the combined effects of time, temperature, and stress on the flow of a material. As usually conducted, the rate of flow is determined for a constant temperature and stress. A strain-time curve plotted for most metals shows three stages: an initial rapid but decreasing creep rate is followed by a period of approximately constant rate, which eventually increases until failure occurs. In general, the rate during the second period is used to determine the "creep rate" for a given stress, and the test is usually discontinued after this rate has been established.



(Courtesy University of Michigan, Engineering Research Institute, Ann Arbor, Mich.)

Figure 150. Battery of creep test units.

Creep rates are commonly reported as percentage elongation per thousand hours based on a secondary period of at least several hundred hours.

The first period is known as the initial creep, and the second as the secondary creep or period of constant creep, though it is not certain that the flow is constant for the whole of this period.

Creep may be an effect of consequential magnitude at normal temperatures as well as at elevated temperatures, depending on the material under consideration.

Stress-Rupture Test

For high-temperature applications materials are given the stress-rupture test. This short-time test differs from the long-time creep test in that the specimens are carried to actual fracture and the deformation rate is not necessarily determined. The results obtained are of value not only in indicating the actual load-carrying ability of the material but also in yielding important information with respect to the influence of time, temperature and stress on the hot ductility, as well as on the surface and structure stability.

In the rupture tests the stresses at each temperature are selected so that the fracture time varies from a few minutes up to at least 1000 to 1500 hours. The specimen, of modified threaded tensile variety, is suspended in a furnace and dead weight-loaded through a lever system. The furnace temperature is automatically maintained. Strain measurements are made periodically (Figure 151).

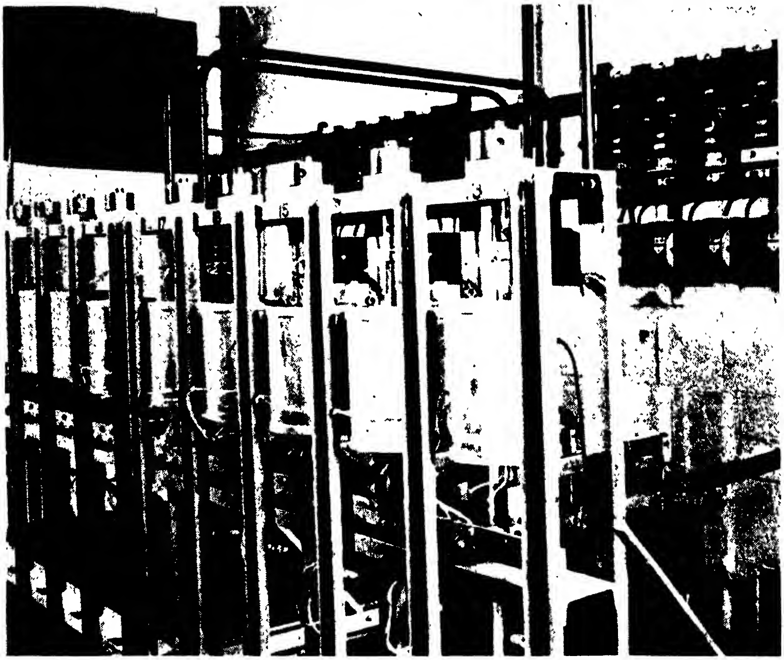

(Courtesy University of Michigan, Engineering Research Institute, Ann Arbor, Mich.)

Figure 151. Battery of stress-rupture test units.

When the stresses and corresponding fracture time periods are plotted to logarithmic coordinates, a single straight-line relationship results over the entire time range, provided the material possesses a sufficient degree of surface and structural stability under the given test conditions.

Because of the definite relationship which exists between stress and fracture time, it is possible to obtain, from the logarithmic plot, stresses corresponding to fracture time periods well beyond those actually used in the tests. It is customary to express these findings in terms of the stresses required for fracture in either 10,000 or 100,000 hours.

For relatively rapid evaluation of elevated temperature properties, the so-called stress-rupture or time-to-rupture test is valuable. It is intermediate between a short-time tensile test (which gives no measure of creep characteristics) and a long-time creep test.

REFERENCES

1. Riehle Bros. Testing Machine Co., Philadelphia, Pa.
2. Baldwin-Southwark Corporation, Philadelphia, Pa.
3. Steel City Testing Laboratory, Detroit, Mich.
4. Churchill, H., "Physical Testing of Metals," American Society for Metals, 1936.
5. "The Technical Editor Speaks," International Nickel Co. bulletin.
6. "Metals Handbook," American Society for Metals, 1948.
7. Hoyt, S., "Metals & Alloys Data Book," Reinhold Publishing Corp., 1943.
8. Lysaght, V. E., "Indentation Hardness Testing," New York, Reinhold Pub. Corp., 1949.

Chapter XVIII

Non-destructive Testing and Inspecting

In the manufacture of industrial products, accessories, apparatus and machinery, inspection and tests of various types are required. These tests may be for the quality of the material, quality of assembly and/or quality of performance of the finished unit. Raw material going into a product can readily be tested by the inspection department or by the laboratory by destructive or non-destructive methods, depending upon the particular item. However, finished products requiring 100 per cent inspection must be tested by non-destructive methods to avoid damaging the part or the completed assembly.

There are a number of methods and types of equipment for non-destructive testing and inspection of material, parts, and assemblies. The equipment and apparatus herewith cited under proprietary trade names are typical and do not necessarily mean that they are the only ones of their type available or the only methods used for the particular test or inspection.

Magnetic Particle Inspection. "Magnaflux" is a rapid visual inspection[10] of magnetic parts to locate defects by a technique of applying magnetization and ferromagnetic particles. When a suitable magnetic field is set up by means of an electric current in the part in the proper direction, sudden interruptions to this magnetic field, such as cracks, inclusions or seams occurring at or near the surface of the part so magnetized, crowd some of the magnetic flux outside the surface of the part. These so-called leakage fields attract and hold finely divided ferromagnetic particles.

The powder of fine particles of magnetic material, either dry or suspended in a liquid, is applied over the surface, and some of the powder in the vicinity of such a leakage field will be attracted and held by the leakage field, thus setting up a magnetically held pattern outlining the discontinuity. The inspector in examining these parts sees in the accumulation of particles a definite indication of the exact location, extent and shape of the discontinuity.

For more sensitive indication of the defects in parts, fluorescent particles are used ("Magnaglo") which glow brilliantly in darkness under black light. Figure 152 is a photograph showing the "Magnaflux" inspection of an aviation engine crankshaft.

Fluorescent Penetrant Inspection. Fluorescent penetrant inspection (frequently referred to as "Zyglo" inspection) is used to locate discontinuities open to the surface in all solid materials, particularly non-ferrous metals, ceramics, plastics, and glass. By this method significant discontinuities are revealed by black light as fluorescent indications.

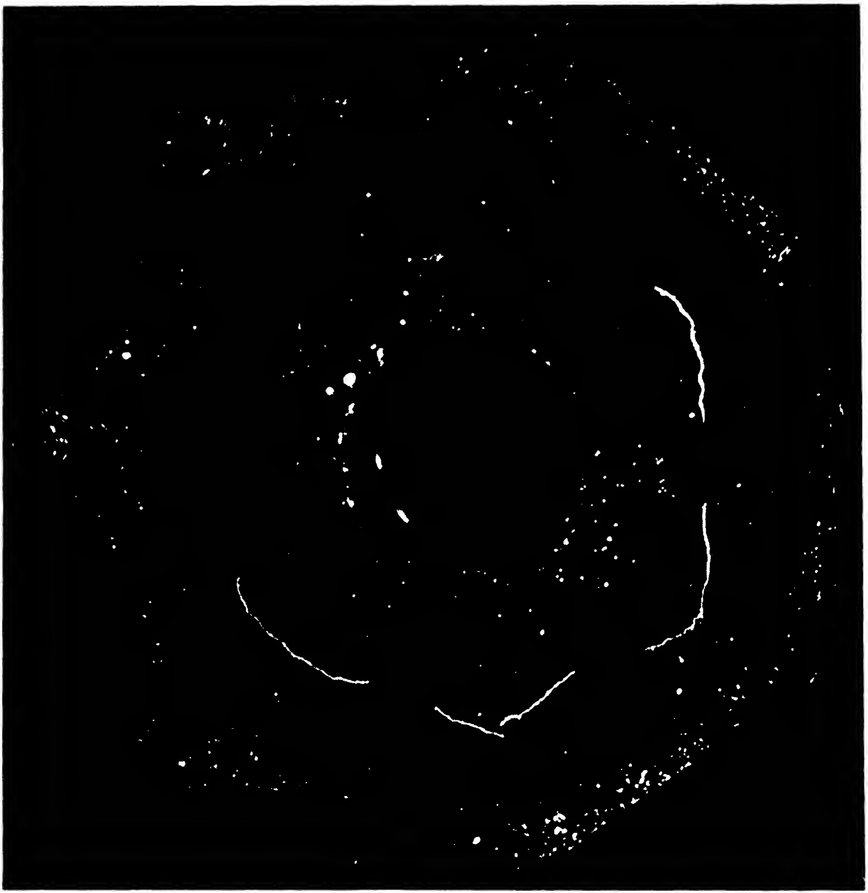
Parts to be inspected are wetted by dipping, brushing or spraying with a special fluorescent, penetrating liquid which is allowed to seep into discontinuities. The excess liquid is then drained from the surface of the parts and a developing agent is applied to draw the fluorescent liquid back out of the discontinuities by capillary action. Upon examination under suitable near-ultraviolet light, discontinuities are revealed by a line of bright, greenish-yellow fluorescence. Figure 153 is an aircraft engine crankcase nose section casting showing "Zyglo" indications of service cracks (white) between holes and also surface pin-hole porosity (white).

(Courtesy Magnaflux Corp., New York, N. Y.)

Figure 152. Magnetic particle inspection. Wet method being applied to crankshaft.

Magnetic Analysis. A purely magnetic test[2] is applicable for discontinuities in material of uniform cross-section, such as bar stock. The magnetic disturbance to a longitudinal field is usually recorded on an oscillograph, or by means of suitable amplification and relays is caused to indicate its presence as the bar is carried longitudinally through a constant or alternating magnetic field. This equipment detects in bars flaws like cracks, seams, laps, slivers, pin-holes, weak welds; and also mix-ups in analysis, grades, processing, heat treatment, hardness and structure.

"Cyclograph." The operating principle of the cyclograph utilizes the fact that correlation exists between the physical, electrical, and magnetic properties of metals. To compare these properties rapidly, the parts to be tested are made the core of a test coil. The coil characteristics, which are governed by the core properties, influence the operation of the oscillator and can be visually evaluated by observation of a simple amplitude change in the pattern on a cathode-ray tube indicator screen.



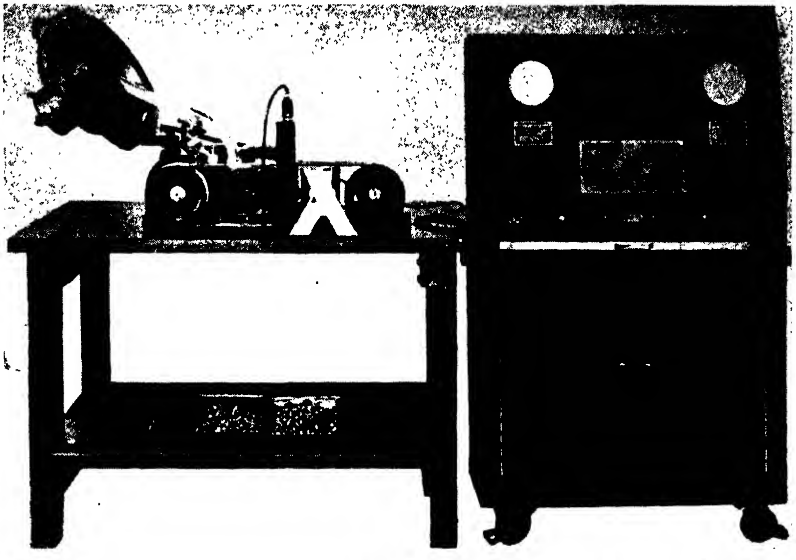
(*Courtesy Magnaflux Corp.*)

Figure 153. Zyglo indications of cracks and porosity.

Since the "Cyclograph" is a comparator, known standard parts must be used to set up the instrument. The instrument then indicates which parts do or do not conform to the selected standards. It is found that different physical properties predominate at certain frequencies. For example, at low or medium frequencies (3000 to 12,000 cycles) correlation is usually obtained with analysis or structure. Higher frequencies (over 12,000 cycles) provide information on the surface layers of the metal part and may be successfully used to classify parts according to case depth, decarburization and plating thickness.

This instrument, therefore, is recommended by the manufacturer to easily determine, by comparing the luminous shape of the cyclogram with the reading of a predetermined standard piece, whether or not the sample possesses a desired metallurgical characteristic, such as certain case depth, depth of decarburization, amount of cold work, brittleness (stress gradients) or structure, and also to easily sort magnetic or non-magnetic material according to chemical analysis, heat treatment, structure, internal stresses or thickness of plating or cladding.

Figure 154 shows the "Cyclograph" being used to control an automatic sorting device to separate bolts of mixed analyses with a speed of approximately ninety per minute. Each bolt, as it passes through the field of the test coil, produces a definite core loss, the magnitude of which depends on the analysis of the steel in the bolt. The core loss produced by each bolt is used as a signal to operate the relay system; at a pre-determined level the relay will produce a 110-volt signal which operates the solenoid controlled gate on the feeder. Since one analysis level can be so set as to give a signal



(Courtesy Allen B. DuMont Laboratories, Inc., Passaic, N. J.)

Figure 154. DuMont cyclograph.

for one analysis only, the solenoid-controlled gate will cut out one analysis and pass the others.

Radiography. Radiography is used for the examination of both metallic and also non-metallic materials by x-rays or gamma rays to locate defects, that is, interruptions in the continuity of the material. Defects and voids in the material will absorb the rays to a less extent than the adjacent areas and the rays passing through will strike the film with varying intensities. The developed negatives, or radiographs,[6] serve as shadow pictures, wherein changes in density or thickness are revealed by dark and light areas. Voids, cracks and holes appear as dark areas because they permit readier passage of the x-ray to the film. The colors will be reversed on prints made from these negatives.

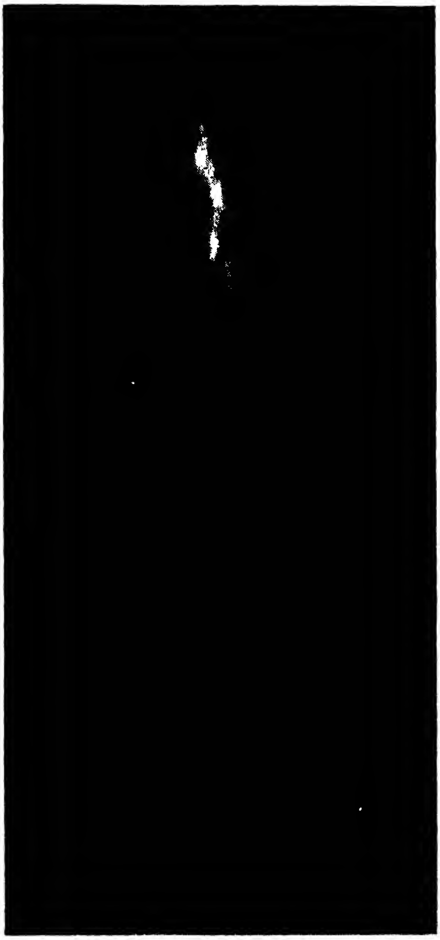
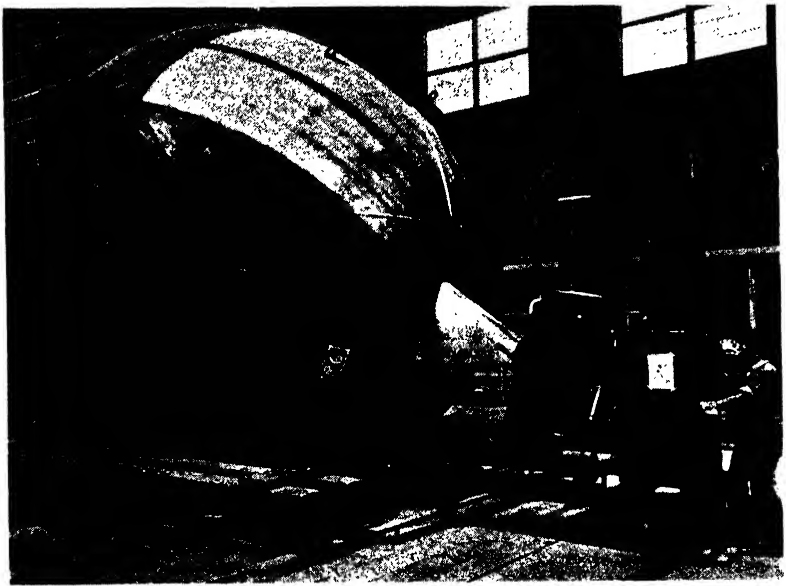


Figure 155. Cracks in a steel casting.

The radiograph produced is really a shadow picture of the object that has been placed in the path of the rays. The appearance of the image thus recorded is materially influenced by the relative position of the object in the beam. The density of any radiographic image depends upon the amount of radiation reaching the sensitive emulsion on the film. The amount of radiation in turn is influenced by the distance from the source of the rays to the film, the ray-emitting power of the source, and the time of exposure to the rays.



(Courtesy General Electric X-Ray Corp., Milwaukee, Wis.)

Figure 156. G. E. Industrial 200KV x-ray unit.

The sharpness of the image of a defect obtained increases linearly with the distance from the source to the defect and decreases linearly with the distance from the defect to the film.

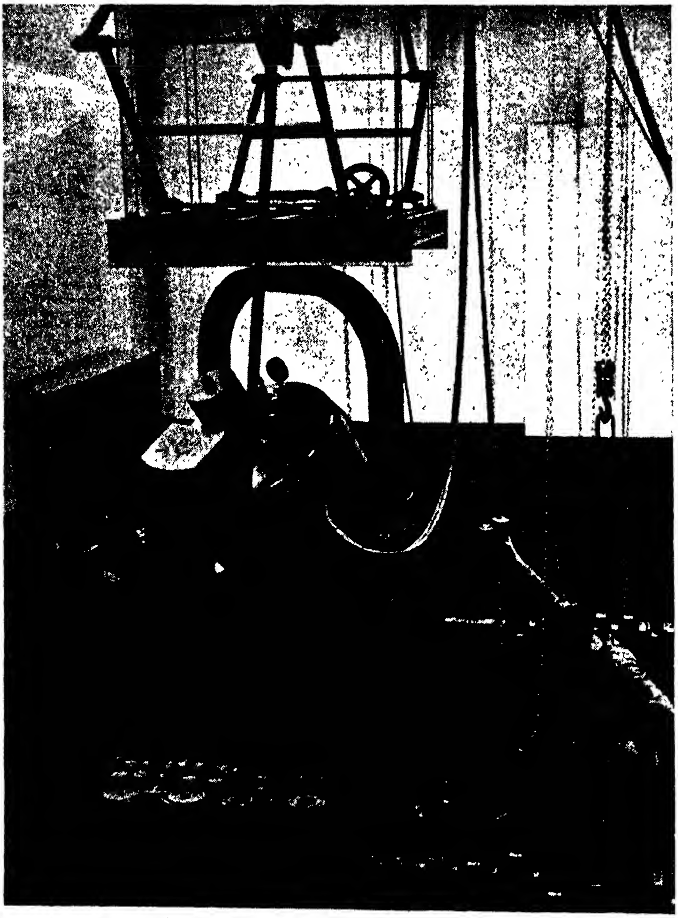
The thickness of the section through which x-rays may penetrate is limited by the capacity of the machine and will vary with the metal being examined. X-ray equipment rated at 220 kv is suitable for up to 3 inches of steel. Rays from one million-volt equipment can be used up to 6 inches of steel.

Radiography using radium depends upon the emission of penetrating gamma rays given off by radium. These rays are similar to x-rays, but have shorter wave lengths and higher penetrating power.

Fluoroscopic radiography is used for quick inspection, a fluorescent screen being used in place of the film. By means of this screen the observer can examine the shadowgraph produced on the screen when the x-ray beam is passing through the object.

Figure 155 is a print made from a radiograph ("Exograph") of a steel casting approximately 1¼″ thick showing cracks (white).

Figure 156 shows an industrial 200-kv x-ray unit, mounted on a flange wheel truck, radiographing the welds in a steel plug at the Grand Coulee Dam in the state of Washington.

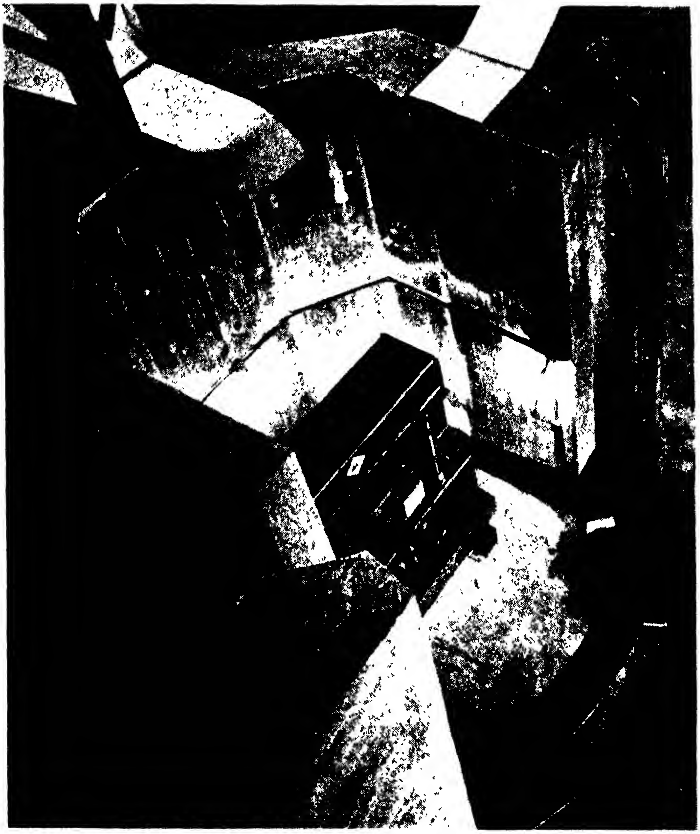


(Courtesy General Electric X-Ray Corp., Milwaukee, Wis.)

Figure 157. G. E. 1,000,000 volt x-ray unit.

Figure 157 shows a 1,000,000-volt x-ray unit positioned for radiography of steel crankshafts.

Betatron. A 20-million-volt betatron has been constructed generating x-rays ten times more powerful than any before used in practical industrial radiography. With this machine, penetration of metal has been extended to as deep as 20 inches with great accuracy and high speed. It enables radiographing entire assemblies, individually or on a continuous line basis. Through higher-energy x-radiation, it has greatly reduced the time required for exposure. A flaw of $\frac{1}{32}$ inch is detectable in steel thicknesses from 2 to 12 inches, and from 12 to 30 inches the minimum detectable flaw is $\frac{1}{16}$ inch.



(Courtesy Allis-Chalmers Mfg. Co., Milwaukee, Wis.)

Figure 158. 20 million volt Betatron.

Figure 158 is a photograph of an installation of a 20-million volt betatron, showing the concrete wall for personnel protection from x-rays. The top of the power unit is visible at top center.

X-ray Photometer. X-ray photometry[11] is a new branch of non-destructive testing utilizing a combination of x-rays and phototubes for measuring x-ray absorption of materials. The method uses a divided x-ray beam; half the beam is passed through a standard absorber and the other half through the test specimen. The two beams then impinge upon a fluorescent screen; the light created by fluorescence is picked up by a phototube and amplified. A calibrated wedge-type variable attenuator disk rotates in the beam, which passes through the test specimen in such a fashion as to insert a known absorption, depending upon the angular position of the disk. Thus, the position of the disk gives a direct indication of the difference in absorption of the two samples.

Many applications are possible for an instrument of this nature. It opens a band above the ultraviolet spectrum and in the lower end of the x-ray spectrum to industrial inspection and test methods. It can reach up into the normal radiographic range and find applications such as control of thickness of hot-rolled steel. It has wide application in quantitative chemical analysis.

It is particularly desirable in those measurements where the controlling component is of considerably higher atomic number than that of the other constituents of the product being measured. It has the unique advantage that the absorption of x-rays is independent of the physical state of the matter being transversed. The material to be tested is not harmed in any way, since there is no physical contact.

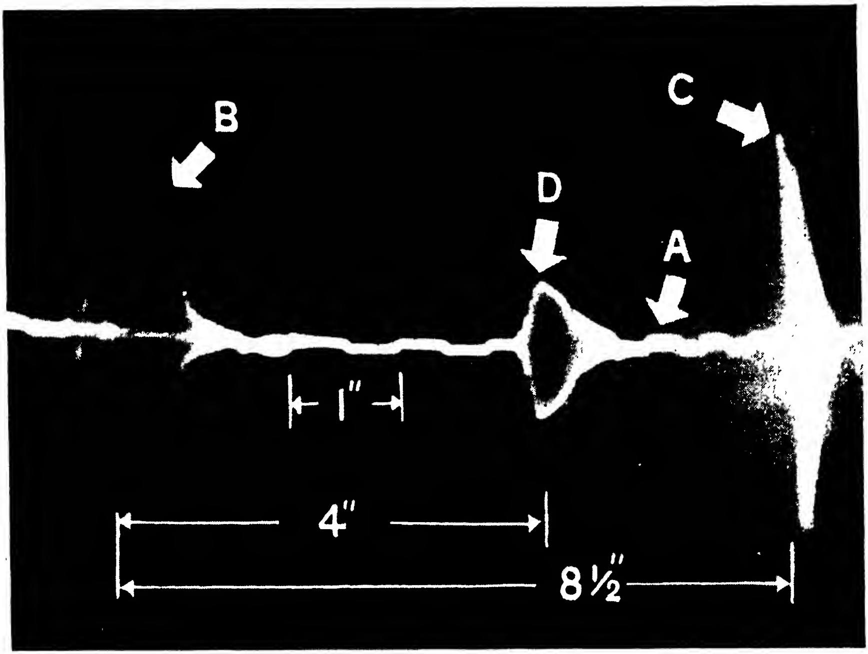
To illustrate the applications of x-ray photometry, the following are a few possible uses: the copper content of aluminum sheets can be checked; lead glass can be distinguished from soda glass, or the percentage of lead in glass determined; the thickness of silver deposit on glass mirrors may be determined; and the thickness of silver emulsion on films may be measured.

Sonic Tests. Vibration tests have been used to locate cracked car wheels by tapping the wheels with a hammer. The major effect of a crack is to change the damping capacity and, therefore, the length of time the metal will sound after having been struck. The result is a difference in sound or ring. The minor effect is the change in the harmonic content of the resulting sound. Both effects are quite evident to the trained ear.

Sound or percussion tests are performed in this manner, thus producing a characteristic tone which will be changed by the presence of discontinuities. They can be used only to detect very large defects, and even then are not always dependable tests. Methods such as these are only qualitative. They can tell only whether a piece is good or bad and can indicate nothing about location or size of flaws.

Supersonic Inspection. Supersonic inspection methods[9] are used as a means of detecting flaws in materials. Supersonic waves are able to penetrate thick sections of materials and can examine the interior to locate accurately any discontinuities present. There are two principal supersonic methods: (1) the reflection method and (2) the through-transmission method.

(1) "Supersonic Reflectoscope" utilizes the reflection or echo principle. Sound waves are sent into the part and measurement is taken of the length of time required for these vibrations to penetrate the material, reflect from the opposite side or from an internal flaw, and return to the sending point. The essential parts of the "Reflectoscope" are: a generator which creates the supersonic waves, the quartz crystal which radiates the sound waves into the material and also receives the back reflections, an electronic amplifier, and a cathode-ray oscilloscope which measures the round trip of the waves. It can be calibrated for each type of material to indicate visually the thickness of the material and the location of the flaws.

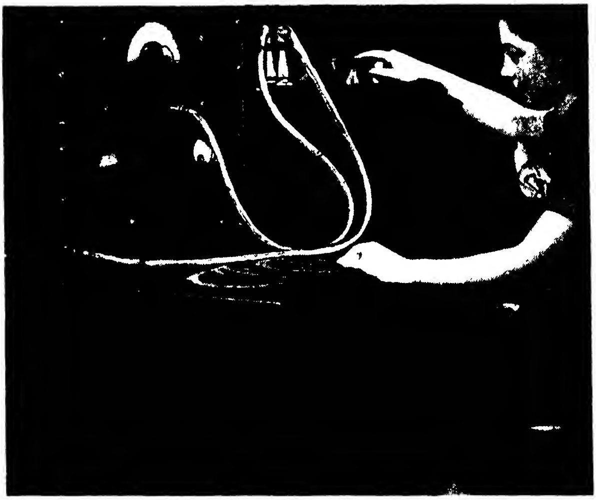


(Courtesy Sperry Products, Inc., Danbury, Conn.)

Figure 159. A typical reflection pattern on the Reflectoscope oscilloscope. A—base line graduated in inches of thickness; B—indication of the initial sound pulse; C—reflection of sound wave from opposite side; D—reflection of sound wave caused by a defect.

In operation, if the piece has no flaws, the two peaks in the pattern which shows on the oscilloscope indicate the two edges of the piece. If discontinuities are present they will be indicated by additional peaks between the normal peaks (Figure 159). This method is generally not good for thicknesses of material below ½ inch. The shape and form of the material to be inspected must be such as to provide an intimate contact between the crystal and the surface. It is best suited for detecting deep-seated defects which present a reflecting surface to the beam. It is not particularly adapted for surface or near surface defects.

(2) "Hypersonic Analyzer" and "Thruray" (Figure 160) utilize a through-transmission method which measures the change in energy level of the sound beam when it passes through the material. When a beam of sound energy is directed through a piece of material some of the energy is dissipated. If a discontinuity such as a crack is also encountered during the passage, the energy pattern is further weakened. This difference, in addition to the normal losses between the energy of the sound wave entering one side of the material and that picked up on the other side, indicates the presence of discontinuities in the specimen.



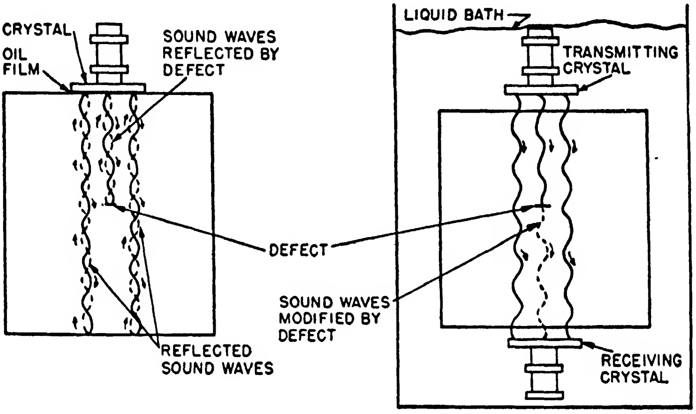
(Courtesy Sperry Products, Inc., Danbury, Conn.)

Figure 160. Sperry Thruray.

The equipment for the "Hypersonic Analyzer" consists of an electronic supersonic generator which creates a signal, a piezoelectric crystal transducer which converts the supersonic signal into mechanical supersonic energy, another piezoelectric crystal transducer which serves as a receiver of the transmitted sound and converts the mechanical energy into an electrical signal, an electronic amplifier, and an indicating device for signalling the presence of flaws. The forms or shapes inspected must have a uniform cross-section so that the sound beam goes through the same thickness of material at all points. This equipment can examine material from 0.001

inch to 5 inches thick. Figure 161 is a schematic sketch of the reflection and through-transmission methods of supersonic inspection, showing the principles of operation.

Brittle Lacquer Coating. Brittle lacquer coating is used for studying local strain distribution. Essentially, this is an extension to the elastic field of the method of loading structures until the local yield point is reached, the latter being located by the production of Lüders lines, usually shown by the detachment of scale at the point of local overload. The scale itself acts as a brittle coating, but only in the range beyond the elastic.



THROUGH-TRANSMISSION METHOD

Figure 161. Schematic sketch of reflection and through-transmission methods of supersonic inspection, showing the principles of operation.

The "Stress-Coat" method consists of spray-painting the surface of the part for which stress-distribution is to be determined with a coating of a brittle lacquer. The lacquer is allowed to harden and the load is then applied. The strain set up by loading will cause cracking of the lacquer at a stress well below the elastic limit of the material. By means of the crack pattern thus formed it is possible to determine the stress distribution not only in the regions of highest stress but also in other regions as well. Since the cracks always occur in the direction perpendicular to the algebraically larger principal strain, this provides a direct method for establishing the directions of the stresses in the structure. The number of cracks per inch of lacquer is proportional to the percentage of stretch.

This method is used to advantage on surfaces of odd-shaped bodies. It is not limited in respect to the kind of materials to which it can be applied, and it works satisfactorily on steel, brass, copper or cast iron. It can be used for both static and dynamic testing.

Figure 162. Straight tension loading on steel plate with hole. Enlarged 2.5X.

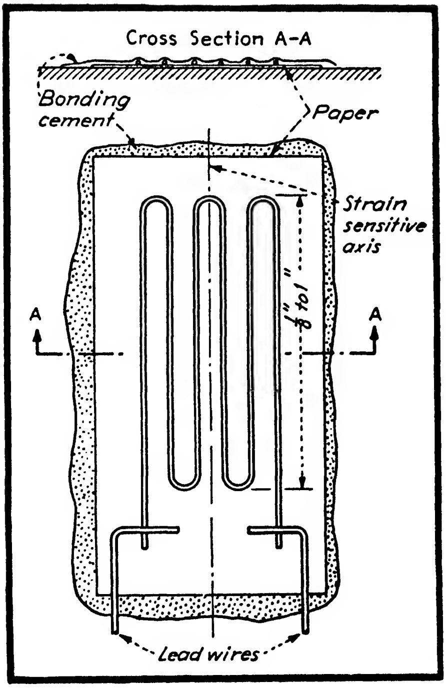
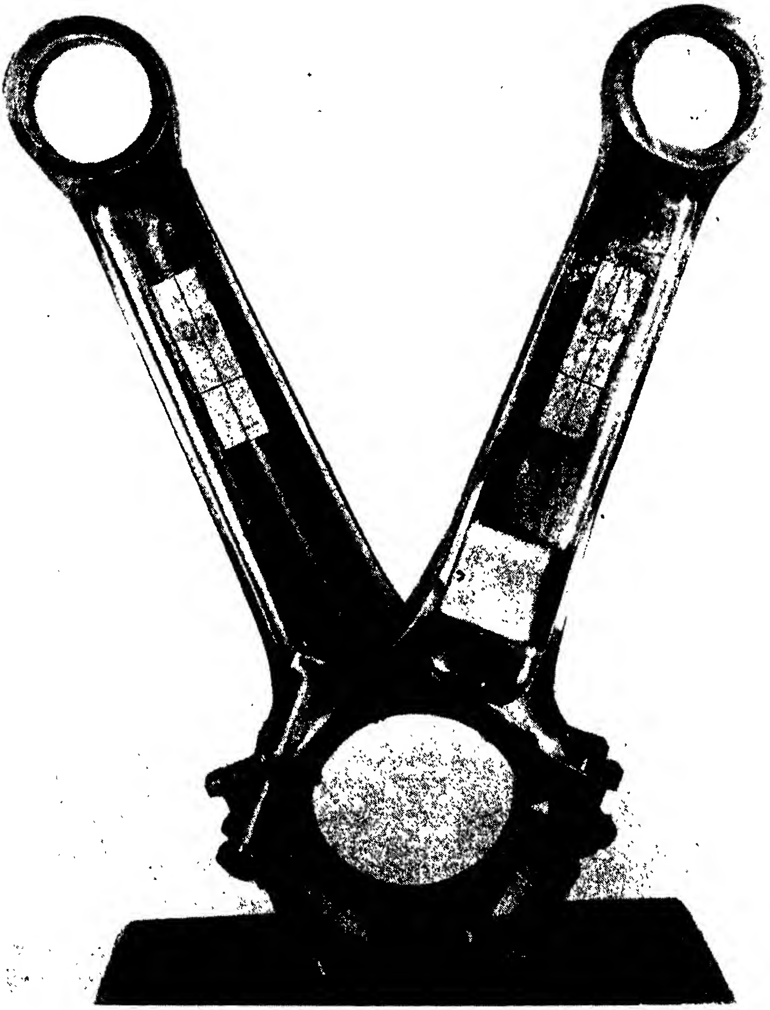


Figure 163. Plan and cross-section views showing construction of a typical wire resistance strain gage.

(Courtesy Baldwin Locomotive Works, Philadelphia, Pa.)

Figure 162 illustrates the principle of the "Stress-Coat" method in its application on straight tension loading on a steel plate with hole.

Strain Gage. Strain gages[4] of the "SR-4" type make possible the accurate, inexpensive indication of either static or dynamic loads of almost any nature. This electric strain gage depends on changes in the electrical resistance of metal when it is stretched or squeezed. It takes the form of a series of loops of very fine wire cemented to a thin paper membrane which in turn is cemented to the surface of the structural part to be analyzed. A



(Courtesy Baldwin Locomotive Works, Philadelphia, Pa.)

Figure 164. Strain gages on connecting rods.

surface deformation of 5 ten-thousandths of 1 per cent of the length is measurable, and instantaneous variations in strain can be observed.

These strain gages are used in place of the brittle lacquer method where greater analytical precision is needed.

Figure 163 shows the plan and cross-section views illustrating construction of a typical wire resistance strain gage.

Figure 164 shows "SR–4" strain gages mounted on the blades of two airplane engine connecting rods. Resistance wire gages of special construction are also mounted in the bore of the connecting rods.

Photoelasticity. The photoelastic method[5] is used for studying stresses in a finished part. In this method, models are made of some suitable transparent material and examined in polarized light. These models, upon being subjected to stress, show colored patterns when white light is used. An idea as to the appearance of a stressed photoelastic model in the polariscope can be obtained from Figure 165 which illustrates the photoelastic stress pattern found in regions of high stress in meshing gears. The heavy black lines in the picture of the stressed models are called *isochromatics.* Each line

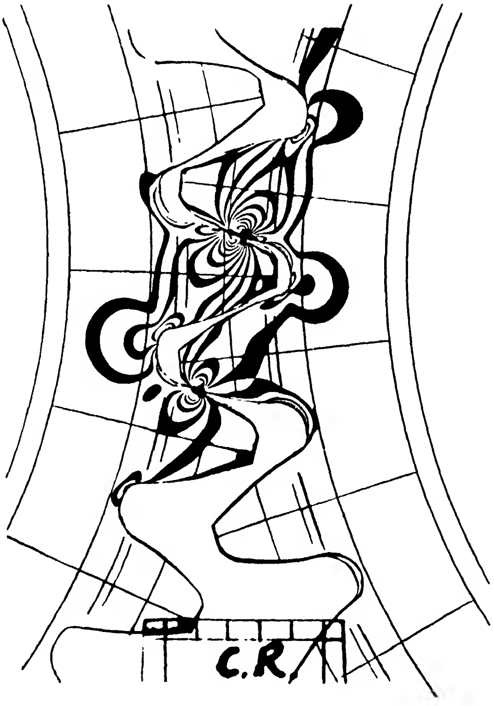


Figure 165. Photoelastic stress pattern showing regions of high stress in meshing gears.

represents a constant value of a stress. It is evident that two kinds of information can be gained from photoelastic stress diagrams: (1) the pattern of the stresses occurring in a structure can be studied and even from a very rough visual observation the locations of highest stress may be determined by noticing the regions in which the isochromatics are crowded closest together; (2) the magnitude of the stress at any point can be determined by merely counting the number of isochromatic lines from a reference point to the point at which it is desired to compute the stress. It is necessary, of course, to calibrate the model material so that the stress magnitude corresponding to each one of the lines can be evaluated.

Besides its use in determining stress-concentration factors the photoelastic analysis has a very definite advantage over some other methods because it shows the complete stress distribution in the model and gives a graphic representation of the entire distribution at once. On account of this characteristic it can be used to locate regions of both high and low stress with equal ease.

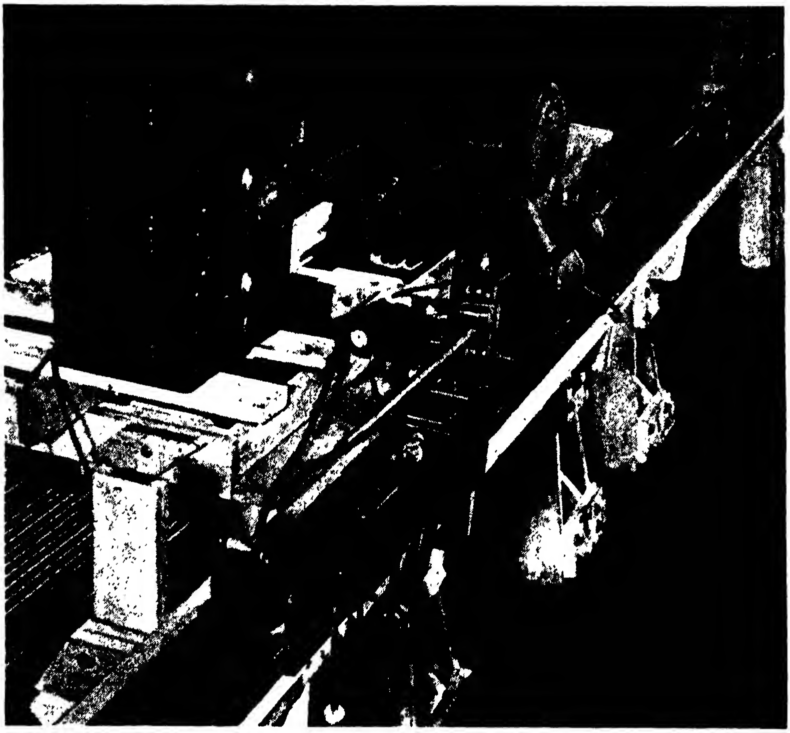
Electric Conductivity. The electric conductivity of a solid metal[2] is locally disturbed by the presence of a discontinuity, and the resistance factor offers excellent opportunity for test methods. This disturbance in conductivity is the basis of the Sperry rail test, in which transverse fissures are located by the local change in the conductivity of the rail. A generator aboard the detector car introduces current (4500 amperes at 2 to 3 volts) into the rails by means of sets of copper brushes. Each of these brush clusters carries a searching unit consisting of a pair of electrically operated coils. When a fissure in the rail is encountered current is forced to pass around the internal break and a change in the density of the flux occurs. The electromotive force produced operates automatic pens on recorders and a paint gun beneath the car. A bullet of white paint is shot onto the rail at the suspected point.

The Sperry Detector (Figure 166) is used to detect longitudinal defects in both ferrous and non-ferrous metals or magnetic and non-magnetic materials, since it is independent of and unaffected by magnetic properties. It detects surface and sub-surface defects which extend to within 1/16 inch of the surface, and indicates size and location.

The unit is based on the relationship between an electric current flowing in a metal and the resistance offered by the metal to the flow. By the application of electronic principles, the Detector also signals by a light the presence of a defect and stops the movement of the material. It is particularly applicable for the fast low cost, non-destructive production testing of tubing, bar stock and lead sheath.

Pressure Tests. Pressure tests are used to locate leaks in castings, fabricated units, and joined assemblies. Hydrostatic testing consists of filling the part with water under a specified pressure and examining the part for leaks. Steam and air may be used in pressure tests.

Chemical Reactions. Chemical reactions, such as etching, both macro and micro, are in extensive use to identify the material and also to show the presence of defects. An illustration of the use of spot testing to detect flaws is the application in the ball-bearing industry of a light, non-destructive etch to show extremely local soft spots and fine cracks.

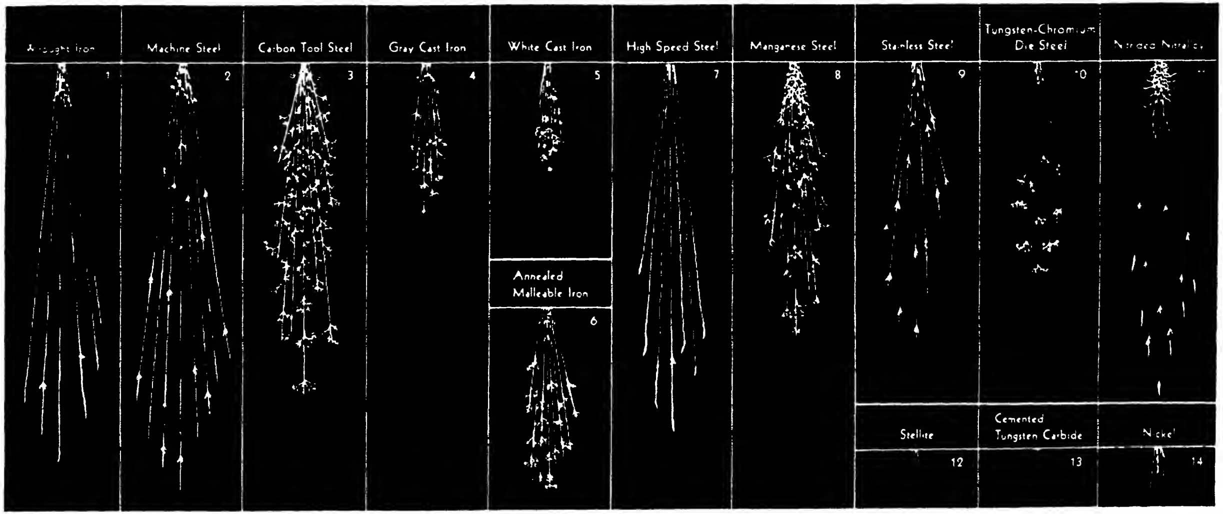


(*Courtesy Sperry Products Inc., Danbury, Conn.*)

Figure 166. Sperry magnetic detector.

Spot tests are applications of a few drops of a specific chemical reagent on the surface of the material to cause a desired chemical reaction or color change for the identification of certain elements present.

Spark Testing. Spark testing[1, 8] is a crude, yet simple and quick method of identifying and sorting material. The material is held against a high-speed abrasive wheel and the resulting sparks are examined with the naked eye. It may be said that spark testing is a means of separating different grades of steel when the chemical compositions are known, and of determining the grade of unknown steels. The steel held against the silicon carbide



Line	Metal	Volume of Stream	Length of Stream *(a)*	Color of Stream		Quantity of Spurts *(b)*	Nature of Spurts *(b)*	Line
				Close to Wheel	Near End			
1	Wrought iron	Large	65 in.	Straw	White	Very few	Forked	1
2	Machine steel	Large	70	White	White	Few	Forked	2
3	Carbon toolsteel	Moderately large	55	White	White	Very many	Fine, repeating	3
4	Gray cast iron	Small	25	Red	Straw	Many	Fine, repeating	4
5	White cast iron	Very small	20	Red	Straw	Few	Fine, repeating	5
6	Annealed malleable iron	Moderate	30	Red	Straw	Many	Fine, repeating	6
7	High speed steel	Small	60	Red	Straw	Extremely few	Forked	7
8	Manganese steel	Moderately large	45	White	White	Many	Fine, repeating	8
9	Stainless steel	Moderate	50	Straw	White	Moderate	Forked	9
10	Tungsten-chromium die steel	Small	35	Red	Straw *(c)*	Many	Fine, repeating *(c)*	10
11	Nitrided nitralloy	Large (curved)	55	White	White	Moderate	Forked	11
12	Stellite	Very small	10	Orange	Orange	None		12
13	Cemented tungsten carbide	Extremely small	2	Light orange	Light orange	None		13
14	Nickel	Very small *(d)*	10	Orange	Orange	None		14
15	Copper, brass, aluminum	None				None		15

(a) Figures obtained with 12-in. wheel on bench stand, and are relative only. Actual length in each instance will vary with grinding wheel and pressure.

(b) "Spurts" are the sparks (seemingly small explosions) that occur at intervals on the carrier lines.

(c) Spurts are blue-white.

(d) Some wavy streaks may be observed.

Figure 167. Spark test for metals. (Reprinted from "Grits and Grinds" (Norton Co.), June 1940.)

wheel, or *vice versa*, throws off a pattern of sparks known as a spark stream. This is made up of numerous carrier lines which are the visible trajectories of the incandescent particles thrown off by the grinding wheel. These carrier lines transport the effects of the various elements throughout the spark stream.

Spark characteristics are largely a function of the oxidation of the chemical elements present in the specimen. The color, shape and size of the sparks are greatly affected by the type and quantity of these elements (Figure 167). Carbon appears as bursts, and this effect intensifies as the carbon content increases. Silicon suppresses the carbon bursts and appears throughout the entire stream in the form of small beads of light. As the sulphur content increases, a candle flame swelling of increasing intensity appears throughout the entire spark stream. Phosphorus appears at the very end of the individual carrier lines in the form of spear heads. Molybdenum is seen as a well defined spear head at the very end of the stream. The molybdenum spear head is short and very distinct, while the phosphorus spear head is long and rather indistinct. Molybdenum imparts an orange color to the entire spark stream. Nickel manifests itself as definite blocks of light along the carrier lines. Chromium has the effect of whitening the carrier lines and making them more distinct throughout the entire stream.

Coating Thickness Measurement

Filmeter. The Filmeter is used to measure rapidly and non-destructively the thickness of non-conducting (insulating or non-metallic) coatings deposited on non-magnetic base metals. The coatings may be paint, varnish, shellac, lacquer, enamels, plastics, ceramics, and the like, and the base metal may be any non-magnetic material such as aluminum, magnesium, copper, brasses and bronzes.

The thickness that may be measured is from 0 to 0.005 inch with an accuracy of 3 per cent of full scale. The base metal must not be less than 0.011 inch thick for copper or aluminum, and not less than 0.020 inch thick for brass and bronze. There is no limitation on the maximum thickness of the base metal.

The Filmeter consists of a battery operated electronic beat-frequency oscillator. The inductance coil of one oscillator is mounted in the end of a tripod-mounted inductor and is connected to the instrument by means of a shielded, rubber-covered cable. Earphones enable the operator to determine when the two oscillators are set to the same frequency.

The principle of operation is based on the inductance effect which the coated base metal has on the coil in the inductor. The current flowing in the coil induces eddy currents in the base metal which have an intensity that varies with the distance between the coil and the base metal. These eddy currents produce a change in the inductance in the coil, causing a change in frequency of the oscillator to which it is connected. This change in frequency is measured by rotating the 4-inch diameter dial (which is coupled to a variable condenser) until the frequency returns to its original value. The fixed oscillator is used as a reference standard. Conversion of the dial reading to thickness is made by means of an adjustable calibration curve supplied with the instrument.

Film Thickness Gage. Thickness gages quickly measure the thickness of non-magnetic material on magnetic iron or steel. Measurements are made from one side of the coatings without marking the surface.

The Type A thickness gage consists of a gage head, and indicating unit, and suitable leads. This gage is used primarily for measuring the thickness of thin metallic or non-metallic, non-magnetic coatings on magnetic steel parts. The normal measuring range is 0.0001 to 0.010 inch of coating thickness. However, the sensitivity of the gage can be adjusted to permit measurements down to 0.00005 inch.

The gage head is made up of two magnetic poles, each pole being surrounded by a coil of wire. On the front panel of the indicating unit are mounted an indicating instrument, a power switch, two three-position switches—one for adjusting the electric circuit for the thickness of the coating to be measured, the other for adjusting the sensitivity of the electric circuit—a potentiometer for adjusting the zero position of the indicating instrument pointer, and a potentiometer for finer adjustment of the sensitivity of the electric circuit.

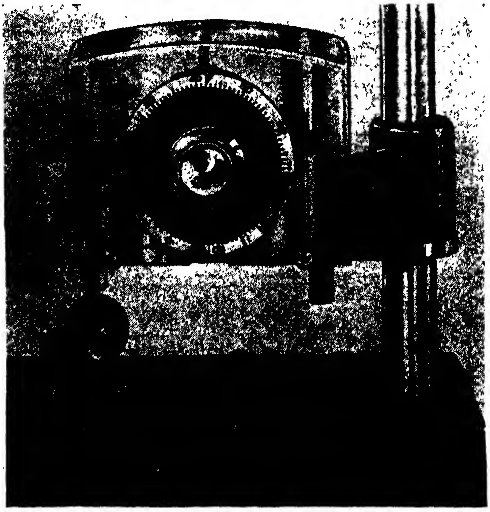
The Type B thickness gage (Figure 168) consists of a gage head, a control unit, and suitable leads. It is used primarily for measuring the thickness of paints, enamels, heavy platings, bearing linings, and other non-magnetic coatings on magnetic steel parts. The standard scale range is 0.0001 to 0.100 inch. However, it can be supplied with a special scale range which is extended to 0.300 inch for non-metallic coatings only. For metallic coatings, the range can be extended to a value somewhere between 0.100 and 0.300 inch, depending upon the resistivity of the metal.

The gage head consists of a steel spool wound with a coil of wire and fitted with a handle connected to the indicating unit. The gage head is placed on the coating and the instrument reading is noted. A suitable thickness standard is inserted between the coating and the gage head. If the new reading of the instrument is not equal to the original reading plus the thickness of the standard, the rheostat has to be adjusted until the instrument indicates the anticipated value of coating thickness plus standard. Repeating this procedure several times will adjust the gage correctly for the particular base metal.

The accuracy varies from approximately plus or minus 5 per cent to

(*Courtesy General Electric Corp., Schenectady, N. Y.*)

Figure 168. G–E thickness gage, Type B, being used to measure thicknesses of carbon deposit on head of removed automotive piston during engine tests.



(*Courtesy American Instrument Co.*)

Figure 169. Magne-Gage.

plus or minus 10 per cent of the thickness of the standard used to set the gage.

"Magne-Gage." The "Magne-Gage" consists essentially of a small, permanent bar magnet freely suspended from a horizontal lever. The latter is actuated by a spiral spring which is coiled by turning a graduated dial. The attractive force between the magnet and the specimen is indicated on the graduated dial, and the readings obtained are converted to thickness by reference to a calibration curve. The instrument is adapted to the different applications by means of four readily interchangeable magnets (Figure 169).

To measure thickness, the tip of the magnet is brought into contact with the specimen and the dial turned until the magnet is detached. The instrument may be calibrated to indicate coating thickness since the thinner the coating, the greater will be the force necessary to effect the separation.

It is used for measuring nickel coatings up to 0.001 inch thick on non-magnetic base metals such as copper, brass and zinc nickel coatings up to 0.002 inch thick iron or steel, and non-magnetic coatings up to 0.080 inch thick on iron or steel. These non-magnetic coatings may be electrodeposited copper, zinc, cadmium, tin, or chromium; and also non-metallic materials such as paint or enamel.

The kind of base metal on which the coating is placed does not affect the magnetic measurements, provided the base metal is non-magnetic. On non-magnetic coatings on magnetic bases, such as iron or steel, the method is based on the decrease in magnetic attraction resulting from the interposition of any non-magnetic material between the magnet and the steel base.

REFERENCES

1. Gordon, G., "Classifying Steels by Spark Testing," *Iron Age* (October 19, 1939).
2. De Forest, A., "Non-destructive Inspection of Metals," *Mining and Metallurgy* (July, 1940).
3. Lipson, L., "New Coating Thickness Gage," *A.S.T.M. Bull.* (August, 1945).
4. Knight, H., "Testing and Inspection," *Materials and Methods* (January, 1946).
5. Murray, W., "Stress Analysis Methods," *Materials and Methods* (April, 1946).
6. Le Grand, R., "Non-destructive Testing Methods," *American Machinist* (May, 1946).
7. Cavanaugh, H., "Non-destructive Testing of Metal Parts," *Steel Processing* (July, 1946).
8. Lundahl, E., "Training Spark Testers," *Iron Age* (July 18, 1946).
9. Clauser, H., "Supersonic Inspection of Materials," *Materials and Methods* (August, 1946).
10. "Magnaflux and Magnetic Inspection," Magnaflux Corp., bulletins.
11. Moriarty, C., "X-ray Photometer for Non-destructive Testing," *General Electric Review* (February, 1947; *Materials and Methods*, May, 1947).
12. Hoyt, S. L., "Metals and Alloys Data Book," Reinhold Publishing Corp., 1945.

Appendix

Properties of Materials

Weights of Alloys and Metals

Alloys and Metals	Pounds per cu. ft.	Pounds per cu. in.
Aluminum	163	0.0943
Aluminum and Tin:		
Al 91%, Sn 9%	178	0.103
Aluminum, Copper, and Tin:		
Al 85%, Cu 7.5%, Sn 7.5%	188	0.1087
Al 6.25%, Cu 87.5%, Sn 6.25%	459	0.2656
Al 5%, Cu 5%, Sn 90%	425	0.2459
Aluminum and Magnesium:		
Al 70%, Mg 30%	125	0.0723
Aluminum and Zinc:		
Al 91%, Zn 9%	175	0.1012
Antimony	419	0.2424
Babbitt Alloy	454	0.2627
Bismuth	611	0.3535
Bismuth, Lead, and Tin:		
Bi 53%, Pb 40%, Sn 7%	659	0.3813
Wood's Metal:		
Bi 50%, Pb 25%, Cd 12.5%, Sn 12.5%	605	0.3501
Brass:		
Cu 90%, Zn 10%	536	0.3101
Cu 70%, Zn 30%	527	0.3049
Cu 60%, Zn 40%	521	0.3015
Cu 50%, Zn 50%	511	0.2957
Bronze:		
Cu 90%, Sn 10%	548	0.3171
Cu 85%, Sn 15%	555	0.3211
Cu 80%, Sn 20%	545	0.3153
Cu 75%, Sn 25%	551	0.3188
Cu 90%, Al 10%	480	0.2777
Cu 95%, Al 5%	522	0.3020
Cu 97%, Al 3%	542	0.3136
Bronze, Phosphorus, Average	537	0.3107
Bronze, Tobin, Average	503	0.291
Cadmium and Tin:		
Cd 32%, Sn 68%	480	0.2777
Chromium	436	0.2523
Cobalt	533	0.3084
Copper	557	0.3223
Copper and Nickel:		
Cu 60%, Ni 40%	554	0.3206
German Silver:		
Cu 60%, Zn 20%, Ni 20%	530	0.3067
Cu 52%, Zn 26%, Ni 22%	527	0.3049
Cu 59%, Zn 30%, Ni 11%	520	0.3009
Cu 63%, Zn 30%, Ni 7%	518	0.2997
Gold	1208	0.699
Gold and Copper:		
Au 98%, Cu 2%	1176	0.6805
Au 90%, Cu 10%	1071	0.6197
Au 86%, Cu 14%	1027	0.5943
Gun Metal, Average	544	0.3148
Iridium	1396	0.8078
Iron, Cast	450	0.2604
Iron, Wrought	480	0.2777

Alloys and Metals	Pounds per cu. ft.	Pounds per cu. in.
Lead	708	0.4097
Lead and Antimony:		
Pb 30%, Sb 70%	450	0.2604
Pb 37%, Sb 63%	460	0.2662
Pb 44%, Sb 56%	475	0.2748
Pb 63%, Sb 37%	514	0.2974
Pb 83%, Sb 17%	596	0.3449
Pb 90%, Sb 10%	658	0.3807
Lead and Bismuth:		
Bi 67%, Pb 33%	639	0.3697
Bi 50%, Pb 50%	656	0.3796
Bi 33%, Pb 67%	682	0.3946
Bi 25%, Pb 75%	697	0.4033
Bi 17%, Pb 83%	702	0.4062
Bi 12%, Pb 88%	703	0.4068
Lead and Tin:		
Pb 87.5%, Sn 12.5%	661	0.3825
Pb 84%, Sn 16%	644	0.3726
Pb 63.7%, Sn 36.3%	588	0.3402
Pb 46.7%, Sn 53.3%	545	0.3153
Pb 30.5%, Sn 69.5%	514	0.2974
Magnesium	109	0.063
Manganese	499	0.2887
Manganese, Copper, and Nickel:		
Mn 12%, Cu 84%, Ni 4%	530	0.3067
Mercury	849	0.4913
Nickel	550	0.3182
Osmium	1402	0.8113
Palladium	712	0.412
Platinum	1344	0.7777
Platinum and Iridium:		
Pt 90%, Iridium 10%	1348	0.780
Rhodium	755	0.4369
Ruthenium	765	0.4427
Silver	654	0.3784
Steel, Cast	490	0.2835
Tin	460	0.2662
Tin and Antimony:		
Sn 50%, Sb 50%	424	0.2453
Sn 75%, Sb 25%	442	0.2557
Tin and Bismuth:		
Bi 78%, Sn 22%	587	0.3396
Bi 63%, Sn 37%	570	0.3298
Bi 50%, Sn 50%	546	0.3159
Bi 37%, Sn 63%	530	0.3067
Bi 22%, Sn 78%	504	0.2916
Tin and Lead:		
Sn 97%, Pb 3%	456	0.2638
Sn 89%, Pb 11%	475	0.2748
Sn 80%, Pb 20%	487	0.2818
Sn 67%, Pb 33%	512	0.2962
Sn 50%, Pb 50%	550	0.3182
Titanium	224	0.1296
Tungsten	1078.7	0.6242
Zinc	437	0.2528

Weights of Various Materials

Material	Average per cubic foot in pounds
BRICK	
Common	100
CEMENTS	
Portland	94
COAL AND COKE	
Anthracite	60
Bituminous	49
Charcoal	18.5
Coke	26.3
CONCRETE	
Cement, fine	137
Rubble, coarse	119
EARTH	
Loam, dry, loose	76
Loam, packed	95
Loam, soft, loose mud	108
Loam, dense mud	125
GLASS	
Flint	192
Floor or skylight	158
Plate	172
Window, common	157
GRAVEL	
Dry, packed	118
Wet, packed	130
LIME	
Quick, loose lumps	53
Quick, fine	75
Stone, large rocks	168
Stone, irregular lumps	96
MASONRY	
Dry	138
Granite or limestone	165
MASONRY—Cont'd	
Mortar, rubble	154
Sandstone, dressed	144
METALS	
Aluminum	166
Brass, cast	524
Bronze	548
Copper, cast	537
Copper, rolled or wire	555
Iron, gray cast	445
Iron, white cast	475
Iron, wrought	490
Lead, cast	708
Lead, rolled	711
Nickel	537
Steel, cast	490
Steel, rolled	495
Steel, stainless	473–516
Tin, cast	455
Zinc, cast	443
OILS	
Crude	48
Engine	55
Gasoline	43
Petroleum	55
ROCKS	
Chalk	145
Granite	165
Gypsum	143
Limestone and marble	164
Pumice Stone	57
Quartz	165
Salt, coarse	
Salt	49
ROCKS—Cont'd	
Sandstone	150
Shales	162
Slate, American	175
Soapstone	170
SAND	
Dry, loose	100
Dry, packed	110
WATER	
As ice	58.7
At 39.2° F. (maximum density)	62.425
At 60° F.	62.37
At 212° F.	59.76
WOODS, DRY	
Apple	48
Beech	43
Birch	45
Black Walnut	35
Cedar, American	35
Chestnut	41
Ebony	76
Elm	35
Hemlock	25
Hickory	53
Ironwood	114
Mahogany	35–53
Maple	49
Oak, live	59
Oak, white	50
Pine, white	25
Pine, yellow northern	34
Pine, yellow southern	45
Spruce	25

Thermal Properties of Metals

Material	Mean Sp. Ht. 60 F to M.P Btu/Lb. per deg. F	Melting Point deg. F	Heat in Solid at M.P Btu/Lb.	Latent Heat of Fusion Btu/Lb.	Heat in Liquid at Melting Temp. Btu per Lb.	Average Pouring Temp. deg. F.	Heat in Liquid at Pouring Temp. deg
Aluminum	0.248	1215	286.0	169.0	455.0	1380	497.0
Antimony	0.054	1166	59.7	70.0	129.7	1320	138.0
Babbitt-Lead Base	0.039	462	15.8	26.2	42.0	625	48.0
Babbitt-Tin Base	0.071	464	28.6	34.1	67.7	916	91.0
Bismuth	0.033	418	15.1	18.5	33.6	620	37.2
Brass, Muntz Metal	0.105	1630	165.0	69.0	234.0	1850	261.0
Brass, Red	0.104	1952	197.0	86.5	283.5	2250	317.8
Brass, Yellow (85 Cu-15 Zn)	0.104	1877	189.0	84.4	273.4	2150	305.0
Bronze, Aluminum	0.126	1922	235.0	98.6	333.6	2200	368.0
Bronze, Bearing	0.095	1832	168.3	79.9	248.2	2050	272.0
Bronze, Bell Metal	0.100	1634	157.4	76.3	233.7	1900	265.4
Bronze, Gun Metal	0.107	1850	191.5	84.2	275.7	2100	302.0
Bronze, Tobin	0.107	1625	167.5	73.5	241.0	1850	268.9
Cadmium	0.058	610	37.4	19.5	56.9	750	10.0
Chromium	0.157	2929	479.0	—	479.0	—	—
Copper	0.104	1982	200.0	91.0	291.0	2200	24.0
Die Casting, Aluminum Base	0.236	1150	257.3	163.0	420.3	1400	481.0
Die Casting, Lead Base	0.038	600	20.5	17.5	38.0	820	146.0
Die Casting, Tin Base	0.070	450	27.6	30.2	57.8	650	70.0
Die Casting, Zinc Base	0.103	780	74.0	48.0	122.0	980	150.0
German Silver	0.109	1850	194.0	86.2	280.2	2100	311.
Gold	0.033	1945	62.2	28.5	90.7	2150	97.
Iron, 60 to 2786 F	0.165	2786	447.0	89.0	536.0	2912	555.
Iron, 60 to 2560 F	0.158	—	*395.0	3.5	†399.0	—	—
Iron, 60 to 1700 F	0.158	—	*258.0	12.5	†270.5	—	—
Iron, 60 to 1335 F	0.150	—	*187.5	11.5	†199.0	—	—
Lead	0.032	621	18.0	10.0	28.0	720	31.
Linotype	0.036	486	15.3	21.5	36.8	620	41.
Magnesium	0.272	1204	311.2	83.7	394.9	1380	441.
Manganese	0.171	2246	374.0	66.0	440.0	2400	469.
Molybdenum	0.060	4750	—	—	—	—	—
Monel Metal	0.129	2415	304.0	117.4	421.4	2750	468.
Nickel, 60 to 2644 F	0.134	2644	346.0	131.5	477.5	2850	505.
Platinum	0.032	3224	—	48.0	—	—	—
Rhodium	0.060	3570	—	—	—	—	—
Silver	0.063	1762	107.0	46.8	153.8	1950	167.
Solder, Bismuth	0.040	232	9.3	16.4	25.7	330	29.
Solder, Plumbers	0.051	414	18.0	23.0	41.0	500	45.
Steel	0.165	Not given because of the many kinds of steel					
Stereotype	0.036	496	15.5	26.2	41.7	620	46
Tin	0.069	450	27.0	25.0	52.0	650	64
Tungsten	0.035	6120	—	79.0	—	—	—
Vanadium	0.118	3110	—	—	—	—	—
Zinc	0.107	786	77.8	48.0	125.8	900	142
Zirconium	0.066	3090	—	—	—	—	—

* ***Heat in solid up to transformation point.*** † ***Heat in solid after allotropic change.***

(*Materials & Methods*, January

Coefficients of Linear Expansion

For 1 degree Centigrade.

For 1 degree Fahrenheit, multiply by 5/9.

Material	Centigrade	20 to 100	20 to 200	20 to 300	20 to 400	20 to 500	20 to 600	100 to 200	200 to 300	300 to 400	400 to 500	500 to 600
	Fahrenheit	70 to 210	70 to 390	70 to 570	70 to 750	70 to 930	70 to 1110	210 to 390	390 to 570	570 to 750	750 to 930	930 to 1110
Aluminum	Cast	23.8	24.7	25.7	26.7	27.7	28.7	25.5	27.5	29.5	31.5	33.5
Antimony		10.5*										
Arsenic		5.0*										
Bismuth		13.2*										
Brass, Soft (72 Cu, 28 Zn)	Rolled & Ann.	17.8	18.5	19.1	19.8	20.5						
Brass, Soft (66 Cu, 34 Zn)	Rolled & Ann.	19.5	20.0	20.5	21.1	21.6						
Brass, Naval (60 Cu, 1 Sn, 39 Zn)	Rolled	19.8	20.5	21.2	21.8	22.5						
Bronze, Aluminum	Cast	17.6	17.9	19.2								
Bronze, Lead	Cast	19.1	19.2	19.4	19.5	19.6						
Bronze, Manganese	Cast	20.0	20.4	20.8	21.6	22.7						
Bronze, Nickel	Cast	17.3	17.7	18.1	18.4	18.8						
Bronze, Phosphor	Cast	18.1	18.4	18.8	19.1	19.4						
Cadmium		31.6*										
Carbon (Graphite)		7.86*										
Cobalt		12.36*										
Copper	Rolled	16.6	17.1	17.6	18.1	18.6						
Duralumin		23.8	24.7	25.7	26.3	27.2						
Gold		13.8**										
Gun Metal	Cast	18.7	19.1	19.6	20.0	20.4						
Lead		27.09*										
Magnesium		25.8*										
Monel Metal	Rolled	13.9*	14.4*	14.9*	15.5*	16.0*						
" "	"	13.5*	14.1*	14.7*	15.3*	15.9*						
" "	Cast	16.5*	16.6*	16.8*	17.0*	17.2*						
Muntz Metal (60 Cu, 40 Zn)	Rolled	19.5	20.3	21.0	28.0							
Nickel	Rolled	13.1*	13.8*				15.5	13.5	14.8	17.2	16.6	17.1
Nichrome	Rolled	12.4*	13.0*	13.6*	14.1*	14.7*						
Palladium		11.76*										
Platinum		8.99*										
Silicon		7.63*										
Silver		19.21*										
Silver Solders		19.0*	19.2*	19.6*	20.4*	21.3*						
Tantalum		6.5*										
Tin		22.95*										
Tungsten		4.3*	4.4*	4.5*	4.5*	4.6*		4.5	4.6	4.7	4.8	
Zinc		29.76*										

EXPANSION OF WATER

MAXIMUM DENSITY = 1

C°	Volume	C°	Volume	C°	Volume	C°	Volume	C°	Volume	C°	Volume
0	1.000126	10	1.000257	30	1.004234	50	1.011877	70	1.022384	90	1.035829
4	1.000000	20	1.001732	40	1.007627	60	1.016954	80	1.029003	100	1.043116

*Starting at 0°C or 32° F.

**25—100° C or 75—210° F.

Data on coefficient of expansion abstracted from "Symposium on Effects of Temperature on the Properties of Metals," American Society for Testing Materials and American Society of Mechanical Engineers, June 1931—See Mochel, p. 509 on "Thermal Expansion of Metals."

All coefficients of expansion in table have been multiplied by 10^6. For example, the table gives 12.4, but the actual coefficient is 12.4×10^{-6} = .0000124.

Coefficients of Linear Expansion

For 1 degree Centigrade.

For 1 degree Fahrenheit, multiply by 5/9.

Material	Centigrade	0 to 100	0 to 200	0 to 300	0 to 400	0 to 500	0 to 600	100 to 200	200 to 300	300 to 400	400 to 500	500 to 600	600 to 700
	Fahrenheit	32 to 212	32 to 390	32 to 570	32 to 750	32 to 930	32 to 1110	212 to 390	390 to 570	570 to 750	750 to 930	930 to 1110	1110 to 1290
Electrolytic Iron		12.0		13.3			14.7	13.0	14.5	15.3	15.9	16.8	17.4
Armco Iron		12.2	12.8	13.4	13.9	14.5							
Cast Iron:													
1.10 Si, .300 P, 0.70 Mn, 2.75 GC, 3.06 TC		11.1	11.6	12.2	12.7	13.2							
2.00 Si, .255 P, 0.93 Mn, 2.48 GC, 3.12 TC		10.6	11.3	11.9	12.5	13.2							
1.44 Si, .291 P, 0.85 Mn, 2.88 GC, 3.66 TC		10.4	11.1	11.7	12.3	12.9							
Rolled Carbon Steels:													
0.17 C, 0.42 Mn........Rolled		11.8	12.4	13.0	13.6	14.2							
.08-.18 C, under .55 Mn. Rolled		12.8	13.3	13.9	14.4	14.9							
S.A.E. 1025..............Rolled		12.0	12.6	13.2	13.7	14.3							
S.A.E. 1035..............Rolled		12.6	13.1	13.6	14.0	14.5							
O. H. Screw Stock Cold—Drawn		12.2	12.8	13.5	14.2	14.8							
0.41 C, 0.64 Mn..Annealed		11.1		12.7			14.3	12.2	14.3	15.8	15.7	16.0	16.6
0.59 C, 0.92 Mn..Annealed		11.1		12.9			14.6	12.5	14.6	15.4	16.1	16.8	16.6
0.49 C, 1.21 Mn..Annealed		11.3		12.7			14.5	12.2	14.2	16.3	17.7	15.4	16.7
Forged Carbon Steels:													
0.40-0.45 C, 0.40-0.80 Mn, Nor. and Ann.		11.3	12.1	12.9	13.6	14.4							
S.A.E. 1025.............Q. & D.		12.2	12.8	13.4	14.0	14.7							
S.A.E. 1055............. do.		11.1	11.8	12.5	13.2	13.9							
Cast Carbon Steels:													
0.25-0.35 C, 0.40-1.00 Mn. Annealed		11.9	12.6	13.3	14.0	14.7							
Nickel Steels:													
0.33 C, 0.78 Mn, 3.59 Ni. Annealed		10.9		12.1			13.8	11.5	13.6	15.2	15.1	15.7	
0.33 C, 0.78 Mn, 3.59 Ni. Q. & D.		10.9	11.6	12.3	12.9	13.6							
5% Ni.........................Rolled		11.5	12.0	12.4	12.9	13.4							
35% Ni.		3.7		9.2			13.6	8.4	14.1	16.6	18.4	18.8	19.1
36½% Ni. (Invar)‡		2.9‡				10.9‡							14.6‡
Nickel-Chromium Steels:													
S.A.E. 3145.............Q. & D.		11.8	12.3	12.9	13.4	14.0							
S.A.E. 3440.............Q. & D.		11.5	12.1	12.7	13.3	13.9							
Chromium-Vanadium Steels:													
S.A.E. 6115.........Annealed		11.6		12.7			14.0	12.5	13.7	14.6	15.2	16.0	15.8
S.A.E. 6135.........Annealed		11.6		12.9			14.6	12.6	14.2	16.0	15.9	16.4	16.9
Chromium Molybdenum Steels:													
S.A.E. 4140.........Annealed		11.1	11.7	12.3	13.0	13.6							
Stainless Steels:													
0.30 C, 13.00 Cr...Annealed		10.0		11.0			12.0	10.6	12.0	12.6	13.5	13.9	13.7
0.13 C, 13.50 Cr...Annealed		10.2	10.5	10.9	11.3	11.7	12.1#						
0.15 C, 18.00 Cr, 8.00 Ni. Rolled		17.3											20.2@
0.07 C, 18.00 Cr, 8.00 Ni.		16.0											19.0¢

@ 20—1000° C, or 70—1830° F ‡ Invar 2.9—20° to 126° C; 10.9—20° to 506° C; 14.6—20° to 971° C.
¢ 600—1000° C, or 1110—1830° F.
0— 800° C, or 32—1470° F.

Data on coefficient of expansion abstracted from "Symposium on Effects of Temperature on the Properties of Metals," American Society for Testing Materials and American Society of Mechanical Engineers, June 1931—See Mochel, p. 509 on "Thermal Expansion of Metals."

All coefficients of expansion in table have been multiplied by 10^6. For example, the table gives 12.4, but the actual coefficient is 12.4×10^{-6}: = .0000124.

Physical Constants of the Alloy-forming Elements

Element	Symbol	Atomic weight	Melting point ° F.	Boiling point ° F.	Density grams per cc 20° C.	Atomic volume cc per gram-atom	Mean linear coefficient of thermal expansion per 12° C. $\times 10^6$ (20° C.)	Specific heat calories (15°) per gram per 1° C. at room temp.	Thermal conductivity at 0° C. calories per cc per sec. per 1° C.	Electric resistivity microhms per cc 20° C.	Crystallization shrinkage per cent	Young's modulus lbs. per sq. in. $\times 10^6$
Aluminum	Al	26.96	1,220	3,272	2.702	9.98	23.03	.214	.485	2.62	6.7	10
Antimony	Sb	121.77	1,167	2,516	6.684 s	18.22	11.4	.049	.044	39.	1.4	11
Arsenic	As	74.96	1,497 a	1,139	5.7M.H.	13.2	4.7	.0822 e	—	35. f	—	—
					4.7 Blk.	15.9	—	—	—	—	—	—
					2.0 Y.C.	38.0	—	—	—	—	—	—
Beryllium	Be	9.02	2,460	2,730	1.8	5.0	—	.427 e	(.79)	18.5	—	—
Bismuth	Bi	209.0	519.8	2,640	9.80	21.33	13.3	.0293	.020	115.	−3.3	4.6
Boron	B	10.82	4,172	4,622	2.3	4.70	2.0	.3091	—	1.8 x 10^{12}	—	—
Cadmium	Cd	112.41	609.6	1,413	8.6	13.1	29.8	.060	.223	7.5	4.7	10.0
Calcium	Ca	40.07	1,490	2,140	1.55	25.9	25. b	.155	(.32)	4.6	—	—
Carbon	C	12.000	—	7,600	—	—	—	—	—	—	—	—
Diamond		—	—	—	3.51	3.42	0.9	.121	—	5 x 10^{20} n	—	—
Graphite		—	6,300	—	2.255	5.32	8.0	.169	.0375	1400	—	—
Cerium	Ce	140.25	1,184	2,550	6.90	20.33	—	.0423 e	(.019)	78.	—	—
Chromium	Cr	52.01	2,939	4,000	7.1	7.3	8.2	.106	(.560)	2.6 f	—	—
Cobalt	Co	58.97	2,696	5,200	8.9	6.6	12.3	.1005	(.150)	9.7	—	—
Columbium	Cb	92.91	3,542	5,972	8.57	10.8	7.2	—	—	2.0	—	—
Copper	Cu	63.57	1,981	4,170	8.92	7.13	16.6	.0921	.927	1.69	4.1	17.8
Gold	Au	197.2	1,945	4,700	19.3	10.22	14.2	.0311 k	.707	2.4	5.2	11.1
Indium	In	114.8	311	2,640	7.3	15.7	33.	.0568 e	(.162)	9.	—	—
Iridium	Ir	193.1	4,262	8,670	22.4	8.62	6.5	.0323 e	.141	6.	—	71
Iron	Fe	55.84	2,795	5,430	7.86	7.10	11.7	.107	.148	10.	—	30
Alpha												
Gamma												

Lead	Pb	207.20	621.5	2,950	11.34	18.27	29.1	.0306	.084	21.9	3.4	1
Lithium	Li	6.939	367	2,190	0.53	13.1	56.	.79 f	.167	9.3	1.5	——
Magnesium	Mg	24.32	1,204	2,030	1.74	14.0	25.6	.25	.370	4.46	4.2	6.25
Manganese	Mn	54.93	2,300	3,450	7.2	7.6	23.	.107 f	(.291)	5.	——	——
Mercury	Hg	200.61	– 37.97	674.4	13.5465	14.810	182.	.0334 g	.020	——	3.75	——
Molybdenum	Mo	96.0	4,750	6,700	10.2	9.4	4.	.065 h	.349	4.77	——	——
Nickel	Ni	58.69	2,646	5,250	8.90	6.59	12.8	.105	.140	6.9	——	30
Osmium	Os	190.8	4,900	9,570	22.48	8.488	6.1	.031 h	(.162)	9.	——	——
Palladium	Pd	106.7	2,831	3,990	12.0	8.9	11.8	.0587 k	.161	10.8	——	14
Phosphorus	P	31.024	111.4Y.	536	1.82YH	17.1	125. d	.18 m	——	10^{17} r	——	——
			——	——	2.20RC	14.1	——	.19 t	——	——	——	——
Platinum	Pt	195.23	3,190	7,770	21.45	9.102	8.9	.0324	.166	10.5	——	23.5
Rhodium	Rh	102.91	3,550	4,500	12.5	8.2	8.4	.058 e	.214	5.1	——	42
Ruthenium	Ru	101.7	4,440	4,890	12.2	8.3	9.1	.061 e	(.145)	10.	——	——
Silicon	Si	28.06	2,590	4,710	2.4	11.7	2.8–7.3	.176	——	85 x 10^3	——	——
Silver	Ag	107.880	1,761	3,540	10.5	10.3	18.9	.0558	1.00	1.62	5.0	10.3
Sulphur	S	32.065	235.0	——	2.07R	15.5	64 p	.171	.0005	2 x 10^{23}	——	——
			246.2	832.3	1.96M	16.4	——	.179	——	——	——	——
Tantalum	Ta	181.5	5,160	7,410	16.6	10.93	7.	.036	.130	15.	——	27
Thorium	Th	232.15	3,353	5,400	11.2	20.7	——	.0276 e	(.081)	18.	——	——
Tin	Sn	118.70	449.3	4,100	7.31WT	16.24	20.	.0542	.157	11.4	2.7	5.9
				——	5.75GC	20.64	——	——	——	——	——	——
Titanium	Ti	47.9	3,270	5,400	4.5	10.7	——	.144 e	(.485)	3.	——	——
Tungsten	W	184.0	6,100	10,650	19.3	9.53	4.	.034 h	.382	5.48	——	60
Uranium	U	238.17	3,360	——	18.7	12.7	——	.028 e	(.0243)	60.	——	——
Vanadium	V	50.96	3,110	5,400	5.96	8.55	——	.115 e	——	——	——	——
Zinc	Zn	65.38	787.0	1,665	7.14	9.16	33.	.0925	.270	6.	6.5	12.4
Zirconium	Zr	91.	3,090	5,250	6.4	14.2	——	.0662 e	(.0086)	170. f	——	——

a, 36 atmospheres pressure. b, 0° to 21° C. c, −163 to −18° C. d, 0° to 40° C. e, 0° to 100° C. f, 0° C. g, −40° C. h, 20 to 100° C. k, 18° C. m, 9° C. n, 15° C. p, 40° C. r 11° C. s, 25° C. t, −21 to +7° C.

( ) Thermal Conductivity = 1.455 ÷ Electric Resistivity (for metals only). Results are approximate to 2 or 3%.

Rigidity or stiffness is usually considered as onb of the fundamental attributes of metals. For certain application, such as springs, we think of flexibility. The engineer realizes that both of these ideas are represented by the same property, modulus of elasticity.

The modulus of elasticity of a material is the ratio of unit stress due to an applied load,* to the unit strain or deformation, within the elastic limit. It is expressed in pounds per sq. in. It is not dependent upon the tensile strength or yield point of the material, nor with the heat treatment or processing of the material. Beryllium copper is an exception to this rule, in that changes in heat treatment actually produce a change in modulus of elasticity. Temperature of operation also affects the modulus, rising temperature causing a decrease.

While the values given in Table II illustrate the effects of bending, the same proportionate relationships hold approximately true for these materials in torsion.

Table I

Modulus of Elasticity for Some Common Materials
(in millions of pounds per sq. in.)

	E	G
Aluminum alloys	10.3	———
Beryllium copper	16.0 to 18.5	6.0 to 7.0
Brass (70-30)	15.0	5.5
Cast iron	14.0 to 18.0	———
Chrome vanadium steel	30.0	11.5
Flat spring steel	30.0	11.5
Hard-drawn steel spring wire	29.0	11.5
High carbon steel wire	30.0	11.5
Hot-rolled steel bars	28.5	10.5
Inconel	31.0	11.0
K Monel	26.0	9.5
Magnesium alloys	6.5	———
Malleable iron	25.0	———
Monel	26.0	9.5
Music wire	30.0	11.5 to 12.0
Nickel silver	16.0	5.5
Oil-tempered steel wire	29.0	11.5
Phosphor bronze	15.0	6.25
Plastics	0.5 to 3.0	———
Stainless steel	28.0	10.0
Z nickel	30.0	11.0

In springs, the material must frequently undergo twisting. The modulus of elasticity in bending, which has been described, is usually represented by the symbol E, while the modulus of elasticity in shear, expressing stiffness in twisting, is expressed as G. These moduli are related by a definite value called Poisson's ration, having the value $\frac{E-2G}{2G}$

As a guide to the deflections produced by a given weight in various materials, the following table has been constructed to show the deflection in inches that will be produced in a rod 1 in. in diam., 10 in. long, held at one end and supporting a 10-lb. weight at the other:

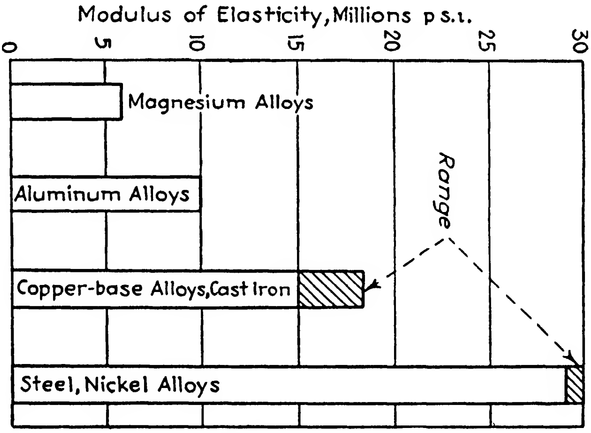
Table II

Material	Deflection	Load to Produce 0.001-in. Deflection
Aluminum alloys	0.0066 in.	1.5 lb.
Cast iron	0.0043 in.	2.4 lb.
Copper alloys	0.0043 in.	2.4 lb.
Magnesium alloys	0.0105 in.	0.95 lb.
Malleable iron	0.0027 in.	3.7 lb.
Steel	0.0023 in.	4.4 lb.

The following conditions or states of a given material are sometimes erroneously thought of as affecting its modulus of elasticity: (1) Hardness, (2) heat treatment or temper, (3) variations in alloy composition, and (4) method of production.

Except for very slight changes sometimes produced by variations in composition, and for the exception already noted in the case of beryllium copper, modulus of elasticity is independent of any changes in these properties. It is therefore impossible to attempt to reduce deflection under load for a given material by heat treating it. The only effect of hardening is to enable the material to carry a higher load without taking a permanent deformation. It does not affect its flexibility under loads below the elastic limit.

Modulus of elasticity for the common structural metals is shown in the accompanying bar graph. These values also represent the relative rigidity of the materials.



The modulus of elasticity finds a practical use in calculating sizes when substituting one material for another in a spring. The formula expressing these size relationships is:

$$t_1 = t_2 \sqrt[3]{\frac{E_2}{E_1}}$$

where t_1 and E_1 are the thickness and modulus of elasticity, respectively, of the new material, and t_2 and E_2 are the values for the material being replaced. Values of G are not given, as changing materials in a helical spring usually requires a more complete redesign of the part.

(Courtesy *Materials & Methods*, January 1945)

Prepared by Kenneth Rose. Based in part upon a Materials Laboratory letter of Sperry Gyroscope Co., Inc.

AISI STANDARD CARBON STEELS

BASIC OPEN HEARTH, ACID OPEN HEARTH AND ACID BESSEMER

Applicable only to BARS, RODS, BILLETS, BLOOMS AND SLABS

Subject to Permissible Variations for Check Analyses

B denotes acid bessemer carbon steel C denotes basic open hearth carbon steel
D denotes acid open hearth carbon steel

AISI Number	Chemical composition limits, per cent				SAE Number
	C	Mn	P, max.	S, max.	
C 1005	0.06 max.	0.35 max.	0.040	0.050	—
C 1006	0.08 max.	0.25–0.40	0.040	0.050	1006
C 1008	0.10 max.	0.25–0.50	0.040	0.050	1008
C 1010	0.08–0.13	0.30–0.60	0.040	0.050	1010
C 1012	0.10–0.15	0.30–0.60	0.040	0.050	—
C 1013	0.11–0.16	0.50–0.80	0.040	0.050	—
C 1015	0.13–0.18	0.30–0.60	0.040	0.050	1015
C 1016	0.13–0.18	0.60–0.90	0.040	0.050	1016
C 1017	0.15–0.20	0.30–0.60	0.040	0.050	1017
C 1018	0.15–0.20	0.60–0.90	0.040	0.050	1018
C 1019	0.15–0.20	0.70–1.00	0.040	0.050	1019
C 1020	0.18–0.23	0.30–0.60	0.040	0.050	1020
C 1021	0.18–0.23	0.60–0.90	0.040	0.050	—
C 1022	0.18–0.23	0.70–1.00	0.040	0.050	1022
C 1023	0.20–0.25	0.30–0.60	0.040	0.050	—
C 1024	0.19–0.25	1.35–1.65	0.040	0.050	1024
C 1025	0.22–0.28	0.30–0.60	0.040	0.050	1025
C 1026	0.22–0.28	0.60–0.90	0.040	0.050	—
C 1027	0.22–0.29	1.20–1.50	0.040	0.050	1027
C 1029	0.25–0.31	0.60–0.90	0.040	0.050	—
C 1030	0.28–0.34	0.60–0.90	0.040	0.050	1030
C 1033	0.30–0.36	0.70–1.00	0.040	0.050	1033
C 1034	0.32–0.38	0.50–0.80	0.040	0.050	1034
C 1035	0.32–0.38	0.60–0.90	0.040	0.050	1035
C 1036	0.30–0.37	1.20–1.50	0.040	0.050	1036
C 1038	0.35–0.42	0.60–0.90	0.040	0.050	1038
C 1039	0.37–0.44	0.70–1.00	0.040	0.050	—
C 1040	0.37–0.44	0.60–0.90	0.040	0.050	1040
C 1041	0.36–0.44	1.35–1.65	0.040	0.050	1041
C 1042	0.40–0.47	0.60–0.90	0.040	0.050	1042
C 1043	0.40–0.47	0.70–1.00	0.040	0.050	1043
C 1045	0.43–0.50	0.60–0.90	0.040	0.050	1045
C 1046	0.43–0.50	0.70–1.00	0.040	0.050	1046
C 1050	0.48–0.55	0.60–0.90	0.040	0.050	1050
C 1051	0.45–0.56	0.85–1.15	0.040	0.050	—

AISI STANDARD CARBON STEELS

BASIC OPEN HEARTH, ACID OPEN HEARTH AND ACID BESSEMER

Applicable only to BARS, RODS, BILLETS, BLOOMS AND SLABS

Subject to Permissible Variations for Check Analyses

B denotes acid bessemer carbon steel   C denotes basic open hearth carbon steel.
D denotes acid open hearth carbon steel

AISI Number	Chemical composition limits, per cent				SAE Number
	C	Mn	P, max.	S, max.	
C 1052	0.47–0.55	1.20–1.50	0.040	0.050	1052
C 1054	0.50–0.60	0.50–0.80	0.040	0.050	—
C 1055	0.50–0.60	0.60–0.90	0.040	0.050	1055
C 1057	0.50–0.61	0.85–1.15	0.040	0.050	—
C 1059	0.55–0.65	0.50–0.80	0.040	0.050	—
C 1060	0.55–0.65	0.60–0.90	0.040	0.050	1060
C 1061	0.54–0.65	0.75–1.05	0.040	0.050	—
C 1062	0.54–0.65	0.85–1.15	0.040	0.050	1062
C 1064	0.60–0.70	0.50–0.80	0.040	0.050	1064
C 1065	0.60–0.70	0.60–0.90	0.040	0.050	1065
C 1066	0.60–0.71	0.85–1.15	0.040	0.050	1066
C 1069	0.65–0.75	0.40–0.70	0.040	0.050	—
C 1070	0.65–0.75	0.60–0.90	0.040	0.050	1070
C 1071	0.65–0.76	0.75–1.05	0.040	0.050	—
C 1074	0.70–0.80	0.50–0.80	0.040	0.050	1074
C 1075	0.70–0.80	0.40–0.70	0.040	0.050	—
C 1078	0.72–0.85	0.30–0.60	0.040	0.050	1078
C 1080	0.75–0.88	0.60–0.90	0.040	0.050	1080
C 1084	0.80–0.93	0.60–0.90	0.040	0.050	—
C 1085	0.80–0.93	0.70–1.00	0.040	0.050	1085
C 1090	0.85–1.00	0.60–0.90	0.040	0.050	1090
C 1095	0.90–1.05	0.30–0.50	0.040	0.050	1095
B 1006	0.08 max.	0.45 max.	0.07–0.12	0.060	—
B 1010	0.13 max.	0.30–0.60	0.07–0.12	0.060	—
D 1049	0.43–0.50	0.50–0.80	0.050	0.050	—
D 1054	0.50–0.60	0.50–0.80	0.050	0.050	—
D 1059	0.55–0.65	0.50–0.80	0.050	0.050	—
D 1064	0.60–0.70	0.50–0.80	0.050	0.050	—
D 1069	0.65–0.75	0.40–0.70	0.050	0.050	—
D 1075	0.70–0.80	0.40–0.70	0.050	0.050	—

AISI STANDARD SULPHURIZED CARBON STEELS

BASIC OPEN HEARTH AND ACID BESSEMER SULPHURIZED

Applicable only to BARS, RODS, BILLETS, BLOOMS AND SLABS

Subject to Permissible Variations for Check Analyses

(Sulphurized steel is not subject to check analysis for sulphur)

AISI Number	Chemical composition limits, per cent				SAE Number
	C	Mn	P, max.	S, max.	
C 1106	0.08 max.	0.30–0.60	0.045	0.08–0.13	—
C 1108	0.08–0.13	0.50–0.80	0.045	0.07–0.12	—
C 1109	0.08–0.13	0.60–0.90	0.045	0.08–0.13	1109
C 1110	0.08–0.13	0.30–0.60	0.045	0.08–0.13	—
C 1111	0.08–0.13	0.60–0.90	0.045	0.16–0.23	—
C 1113	0.10–0.16	1.00–1.30	0.045	0.24–0.33	—
C 1114	0.10–0.16	1.00–1.30	0.045	0.08–0.13	1114
C 1115	0.13–0.18	0.60–0.90	0.045	0.08–0.13	1115
C 1116	0.14–0.20	1.10–1.40	0.045	0.16–0.23	1116
C 1117	0.14–0.20	1.00–1.30	0.045	0.08–0.13	1117
C 1118	0.14–0.20	1.30–1.60	0.045	0.08–0.13	1118
C 1119	0.14–0.20	1.00–1.30	0.045	0.24–0.33	1119
C 1120	0.18–0.23	0.70–1.00	0.045	0.08–0.13	1120
C 1125	0.22–0.28	0.60–0.90	0.045	0.08–0.13	—
C 1126	0.23–0.29	0.70–1.00	0.045	0.08–0.13	1126
C 1137	0.32–0.39	1.35–1.65	0.045	0.08–0.13	1137
C 1138	0.34–0.40	0.70–1.00	0.045	0.08–0.13	1138
C 1140	0.37–0.44	0.70–1.00	0.045	0.08–0.13	1140
C 1141	0.37–0.45	1.35–1.65	0.045	0.08–0.13	1141
C 1144	0.40–0.48	1.35–1.65	0.045	0.24–0.33	1144
C 1145	0.42–0.49	0.70–1.00	0.045	0.04–0.07	1145
C 1146	0.42–0.49	0.70–1.00	0.045	0.08–0.13	1146
C 1151	0.48–0.55	0.70–1.00	0.045	0.08–0.13	1151
B 1111	0.13 max.	0.60–0.90	0.07–0.12	0.08–0.15	1111
B 1112	0.13 max.	0.70–1.00	0.07–0.12	0.16–0.23	1112
B 1113	0.13 max.	0.70–1.00	0.07–0.12	0.24–0.33	1113

(a) Silicon content may not be specified on bars ordered as Merchant Bar Quality.

(b) Silicon ranges as noted below may be specified for open hearth grades of Special Bar Quality.

Low sulphur	Sulphurized	Silicon
Up to 1015 excl.	Up to 1113 excl.	0.10 max.
1015 to 1025 incl.	1113 to 1151 incl.	0.10 max., 0.10–0.20 or 0.15–0.30
Over 1025	——	0.10–0.20 or 0.15–0.30

If other limitations are required, the grade becomes non-standard.

(c) Bessemer compositions of either Merchant or Special Bar Quality are not supplied with specified silicon content.

(d) Copper may be specified as an added element to a low sulphur standard steel without causing the grade to become non-standard.

AISI STANDARD ALLOY STEELS

OPEN HEARTH AND ELECTRIC FURNACE

Applicable only to BARS, BILLETS, BLOOMS AND SLABS

Subject to Permissible Variations for Check Analyses

AISI and SAE Numbers	Chemical composition limits, per cent							
	C	Mn	P	S	Si	Ni	Cr	Mo
1320	0.18–0.23	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—
1321*	0.17–0.22	1.80–2.10	0.050	0.050	0.15–0.35	—	—	—
1330	0.28–0.33	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—
1335	0.33–0.38	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—
1340	0.38–0.43	1.60–1.90	0.040	0.040	0.20–0.35	—	—	—
2317	0.15–0.20	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	—
2330	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	3.25–3.75	—	—
2335*	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	3.25–3.75	—	—
2340	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	3.25–3.75	—	—
2345	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	3.25–3.75	—	—
E 2512	0.09–0.14	0.45–0.60	0.025	0.025	0.20–0.35	4.75–5.25	—	—
2515	0.12–0.17	0.40–0.60	0.040	0.040	0.20–0.35	4.75–5.25	—	—
E 2517	0.15–0.20	0.45–0.60	0.025	0.025	0.20–0.35	4.75–5.25	—	—
3115	0.13–0.18	0.40–0.60	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—
3120	0.17–0.22	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—
3130	0.28–0.33	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—
3135	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—
3140	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.55–0.75	—
3141	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	—
3145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	—
3150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	1.10–1.40	0.70–0.90	—
E 3310	0.08–0.13	0.45–0.60	0.025	0.025	0.20–0.35	3.25–3.75	1.40–1.75	—
E 3316	0.14–0.19	0.45–0.60	0.025	0.025	0.20–0.35	3.25–3.75	1.40–1.75	—
4017	0.15–0.20	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4023	0.20–0.25	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4024	0.20–0.25	0.70–0.90	0.040	0.035–0.050	0.20–0.35	—	—	0.20–0.30
4027	0.25–0.30	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4028	0.25–0.30	0.70–0.90	0.040	0.035–0.050	0.20–0.35	—	—	0.20–0.30
4032	0.30–0.35	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4037	0.35–0.40	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.35
4042	0.40–0.45	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4047	0.45–0.50	0.70–0.90	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4053	0.50–0.56	0.75–1.00	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4063	0.60–0.67	0.75–1.00	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4068	0.63–0.70	0.75–1.00	0.040	0.040	0.20–0.35	—	—	0.20–0.30
4130	0.28–0.33	0.40–0.60	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25
E 4132*	0.30–0.35	0.40–0.60	0.025	0.025	0.20–0.35	—	0.80–1.10	0.18–0.25
E 4135*	0.33–0.38	0.70–0.90	0.025	0.025	0.20–0.35	—	0.80–1.10	0.18–0.25
4137	0.35–0.40	0.70–0.90	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25
E 4137*	0.35–0.40	0.70–0.90	0.025	0.025	0.20–0.35	—	0.80–1.10	0.18–0.25
4140	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25
4142*	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25
4145	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25
4147*	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25
4150	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15–0.25

---

*These steels are not SAE standards.

AISI STANDARD ALLOY STEELS

OPEN HEARTH AND ELECTRIC FURNACE

Applicable only to BARS, BILLETS, BLOOMS AND SLABS

Subject to Permissible Variations for Check Analyses

AISI and SAE Numbers	Chemical composition limits, per cent							
	C	Mn	P	S	Si	Ni	Cr	Mo
4317	0.15–0.20	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	0.40–0.60	0.20–0.30
4320	0.17–0.22	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	0.40–0.60	0.20–0.30
E 4337*	0.35–0.40	0.60–0.80	0.025	0.025	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30
E 4340*	0.38–0.43	0.60–0.80	0.025	0.025	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30
4340	0.38–0.43	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	0.70–0.90	0.20–0.30
4608	0.06–0.11	0.40 max.	0.040	0.040	0.25 max.	1.40–1.75	—	0.15–0.25
4615	0.13–0.18	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30
E 4617	0.15–0.20	0.45–0.65	0.025	0.025	0.20–0.35	1.65–2.00	—	0.20–0.27
4620	0.17–0.22	0.45–0.65	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30
E 4620*	0.17–0.22	0.45–0.65	0.025	0.025	0.20–0.35	1.65–2.00	—	0.20–0.27
X 4620	0.18–0.23	0.50–0.70	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30
4621	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30
4640	0.38–0.43	0.60–0.80	0.040	0.040	0.20–0.35	1.65–2.00	—	0.20–0.30
E 4640*	0.38–0.43	0.60–0.80	0.025	0.025	0.20–0.35	1.65–2.00	—	0.20–0.27
4812	0.10–0.15	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30
4815	0.13–0.18	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30
4817	0.15–0.20	0.40–0.60	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30
4820	0.18–0.23	0.50–0.70	0.040	0.040	0.20–0.35	3.25–3.75	—	0.20–0.30
5045	0.43–0.80	0.70–0.90	0.040	0.040	0.20–0.35	—	0.55–0.75	—
5046	0.43–0.50	0.75–1.00	0.040	0.040	0.20–0.35	—	0.20–0.35	—
5120	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	—	0.70–0.90	—
5130	0.28–0.33	0.70–0.90	0.040	0.040	0.20–0.35	—	0.80–1.10	—
5132	0.30–0.35	0.60–0.80	0.040	0.040	0.20–0.35	—	0.80–1.05	—
5135	0.33–0.38	0.60–0.80	0.040	0.040	0.20–0.35	—	0.80–1.05	—
5140	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	—	0.70–0.90	—
5145	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	—	0.70–0.90	—
5147	0.45–0.52	0.75–1.00	0.040	0.040	0.20–0.35	—	0.90–1.20	—
5150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	—	0.70–0.90	—
5152	0.48–0.55	0.70–0.90	0.040	0.040	0.20–0.35	—	0.90–1.20	—
E 50100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	—	0.40–0.60	—
E 51100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	—	0.90–1.15	—
E 52100	0.95–1.10	0.25–0.45	0.025	0.025	0.20–0.35	—	1.30–1.60	—
								V
6120*	0.17–0.22	0.70–0.90	0.040	0.040	0.20–0.35	—	0.70–0.90	0.10 min.
6145*	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15 min.
6150	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	—	0.80–1.10	0.15 min.
E 6150*	0.48–0.53	0.70–0.90	0.025	0.025	0.20–0.35	—	0.80–1.10	0.15 min.
6152	0.48–0.55	0.70–0.90	0.040	0.040	0.20–0.35	—	0.80–1.10	0.10 min.
								Mo
8615	0.13–0.18	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8617	0.15–0.20	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8620	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8622	0.20–0.25	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8625	0.23–0.28	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8627	0.25–0.30	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8630	0.28–0.33	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8632	0.30–0.35	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8635	0.33–0.38	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25

---

*These steels are not SAE standards

AISI STANDARD ALLOY STEELS

OPEN HEARTH AND ELECTRIC FURNACE

Applicable only to BARS, BILLETS, BLOOMS AND SLABS

Subject to Permissible Variations for Check Analyses

AISI and SAE Numbers	Chemical composition limits per cent							
	C	Mn	P	S	Si	Ni	Cr	Mo
8637	0.35–0.40	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8640	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8641	0.38–0.43	0.75–1.00	0.040	0.040.060	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8642	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8645	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8647	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8650	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8653	0.50–0.56	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.50–0.80	0.15–0.25
8655	0.50–0.60	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8660	0.55–0.65	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.15–0.25
8720	0.18–0.23	0.70–0.90	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8735	0.33–0.38	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8740	0.38–0.43	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8742*	0.40–0.45	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8745	0.43–0.48	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8747*	0.45–0.50	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
8750	0.48–0.53	0.75–1.00	0.040	0.040	0.20–0.35	0.40–0.70	0.40–0.60	0.20–0.30
9255	0.50–0.60	0.70–0.95	0.040	0.040	1.80–2.20	—	—	—
9260	0.55–0.65	0.70–1.00	0.040	0.040	1.80–2.20	—	—	—
9261	0.55–0.65	0.75–1.00	0.040	0.040	1.80–2.20	—	0.10–0.25	—
9262	0.55–0.65	0.75–1.00	0.040	0.040	1.80–2.20	—	0.25–0.40	—
E 9310	0.08–0.13	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15
E 9315	0.13–0.18	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15
E 9317	0.15–0.20	0.45–0.65	0.025	0.025	0.20–0.35	3.00–3.50	1.00–1.40	0.08–0.15
9437	0.35–0.40	0.90–1.20	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
9440	0.38–0.43	0.90–1.20	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
9442	0.40–0.45	1.00–1.30	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
9445	0.43–0.48	1.00–1.30	0.040	0.040	0.20–0.35	0.30–0.60	0.30–0.50	0.08–0.15
9747	0.45–0.50	0.50–0.80	0.040	0.040	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25
9763	0.60–0.67	0.50–0.80	0.040	0.040	0.20–0.35	0.40–0.70	0.10–0.25	0.15–0.25
9840	0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30
9845	0.43–0.48	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30
9850	0.48–0.53	0.70–0.90	0.040	0.040	0.20–0.35	0.85–1.15	0.70–0.90	0.20–0.30

*These steels are not SAE standards.

Note 1—Grades shown in the above list with prefix letter E are manufactured by the basic electric furnace process. All others are normally manufactured by the basic open hearth process, but may be manufactured by the basic electric furnace or acid open hearth processes with adjustments in phosphorus and sulphur.

Note 2—The phosphorus and sulphur limitations for each process are as follows:

Basic electric furnace........ 0.025 pct. max. Acid electric furnace......... 0.05 pct. max.
Basic open hearth furnace..... 0.04 pct. max. Acid open hearth furnace..... 0.05 pct. max.

Note 3—The lowest minimum silicon limit to be specified for acid open hearth or acid electric furnace alloy steel is 0.15 pct.

Note 4—Small quantities of certain elements may be found in alloy and electric furnace carbon steels which are not specified or required. These elements are to be considered as incidental and acceptable to the following maximum amounts:
copper, 0.35; nickel, 0.25; chromium, 0.20; molybdenum 0.06 pct.

Note 5—Where minimum and maximum sulphur contents are shown, it is indication of sulphurized steels.

Average Physical Properties of Various Steels

This table of figures has been compiled from a large volume of tests and represents an AVERAGE of results. It is offered as a general guide to the PROBABLE physical expectancy of the steels listed. The size of the section, rolling temperature, permissible variation, within analysis limits and the atmospheric temperature at time of rolling, all influence the final physical properties of any steel in normal state. The following results are based on 1" round bars.

S.A.E.	AISI		Machinability Rating	Tensile Strength	Yield Point	Elongation in 2 inches	Reduction in Area	Approx. Hardness			Heat Treatment
								Brinell	Rockwell	Scleroscope	
S.A.E. 1010	C 1010	Natural Hot Rolled	50%	57,000	32,000	36%	66%	116	B66		
		Cold Drawn		67,000	58,000	22%	60%	134	B74	16	
S.A.E. 1020	C 1020	Natural Hot Rolled		65,000	41,000	30%	61%	131	B72	16	
		Cold Drawn	66%	77,000	67,000	18%	55%	156	B82	18	
		Quenched—Drawn 500° F.		92,000	55,000	22%	55%	183	B90	22	Water—1425° F.
S.A.E. X1020	C 1022	Natural Hot Rolled		71,000	43,000	30%	60%	146	B79	17	
		Cold Drawn	73%	84,500	73,000	18%	54%	170	B86	22	
		Quenched—Drawn 500° F.		95,000	67,000	23%	59%	192	B92	24	Water—1450° F.
S.A.E. 1030	C 1030	Natural Hot Rolled		76,000	46,000	28%	56%	152	B81	17	
		Cold Drawn	70%	90,000	78,000	17%	51%	183	B90	22	
		Quenched—Drawn 1000° F.		95,000	72,000	25%	67%	197	B92	24	Water—1600° F.
S.A.E. 1040	C 1040	Natural Hot Rolled		85,000	52,000	24%	50%	174	B87	20	
		Cold Drawn	63%	101,000	83,000	15%	45%	207	B94	27	
		Quenched—Drawn 1000° F.		109,000	84,000	22%	54%	217	C19	29	Water—1525° F.
S.A.E. 1060	C 1055	Natural Hot Rolled		105,000	58,000	18%	37%	223	C20	30	
		Cold Drawn	53%	102,000	87,000	17%	48%	207	C17	27	Annealed before drawing
		Quenched—Drawn 1000° F.		122,000	90,000	18%	52%	255	C25	35	Oil—1550° F.
S.A.E. 1095	C 1095	Natural Hot Rolled		145,000	75,000	10%	15%	293	C30	40	
		Cold Drawn	42%	115,000	90,000	15%	42%	235	C22	32	Annealed before drawing
		Quenched—Drawn 1000° F.		178,000	122,000	12%	36%	363	C37	48	Oil—1450° F.
S.A.E. 1112	B 1111	Natural Hot Rolled		71,000	47,000	25%	51%	146	B79	17	
		Cold Drawn	100%	84,000	75,000	15%	46%	170	B86	19	
X1112	B 1113		130%	84,000	75,000	15%	46%	170	B86	19	
S.A.E. 1120	C 1120	Natural Hot Rolled		69,000	40,000	32%	55%	140	B76	16	
		Cold Drawn	75%	82,000	72,000	18%	49%	167	B85	19	
S.A.E. X1314	C 1112	Natural Hot Rolled		79,000	44,000	28%	52%	149	B80	17	
		Cold Drawn	86%	83,500	74,000	17%	48%	170	B86	19	
		Quenched—Drawn 500° F.		100,000	71,000	24%	60%	201	B93	26	Water—1450° F.
S.A.E. X1315	C 1118	Natural Hot Rolled		72,000	47,000	28%	53%	149	B80	17	
		Cold Drawn	88%	85,000	75,000	17%	47%	174	B87	20	
		Quenched—Drawn 500° F.		110,000	81,000	22%	52%	223	B97	30	Water—1450° F.
S.A.E. X1340	C 1137	Natural Hot Rolled		110,000	70,000	20%	48%	223	C20	30	
		Cold Drawn	72%	108,000	97,000	17%	45%	217	C19	29	Annealed before drawing
		Quenched—Drawn 1000° F.		145,000	126,000	16%	47%	302	C31	91	Water—1500° F.
S.A.E. T1340		Natural Hot Rolled		115,000	75,000	20%	52%	235	C22	32	
		Cold Drawn	56%	112,000	95,000	18%	57%	229	C21	31	Annealed before drawing
		Quenched—Drawn 1000° F.		141,000	120,000	18%	52%	285	C29	38	Oil—1500° F.
S.A.E. T1350		Natural Hot Rolled		120,000	79,000	18%	39%	255	C25	35	
		Cold Drawn	48%	115,000	96,000	17%	45%	235	C22	32	Annealed before drawing
		Quenched—Drawn 1000° F.		150,000	129,000	17%	48%	311	C31	41	Oil—1500° F.

S.A.E. 2315.. A 2317	Natural Hot Rolled	60%	85,000	58,000	29%	60%	174	B87	20	
	Cold Drawn		101,000	91,000	18%	53%	207	C17	27	
	Quenched—Drawn 500° F.		127,000	88,000	23%	62%	269	C27	36	Water—1450° F.
S.A.E. 2340.. A 2340.	Natural Hot Rolled	40%	110,000	75,000	20%	45%	229	C21	30	
	Cold Drawn		110,000	100,000	18%	46%	223	C20	30	Annealed before drawing
	Quenched—Drawn 1000° F.		130,000	110,000	21%	48%	269	C27	37	Oil—1475° F.
S.A.E. 2350.	Natural Hot Rolled	35%	130,000	81,000	17%	42%	269	C26	37	
	Cold Drawn		120,000	105,000	16%	42%	223	C20	30	Annealed before drawing
	Quenched—Drawn 1000° F.		142,000	130,000	18%	52%	302	C30	41	Oil—1450° F.
S.A.E. 2515.. A 2514..	Natural Hot Rolled	49%	92,000	60,000	28%	67%	179	B88	22	
	Cold Drawn		109,000	99,000	17%	61%	223	C20	30	
	Quenched—Drawn 500° F.		165,000	148,000	18%	53%	341	C35	43	Oil—1425° F.
S.A.E. AISI 3115.. A 3115.	Natural Hot Rolled	56%	75,000	53,000	32%	65%	156	B82	18	
	Cold Drawn		89,000	79,000	19%	59%	183	B90	22	
	Quenched—Drawn 500° F.		105,000	65,000	28%	63%	201	C16	26	Oil—1425° F.
S.A.E. 3135.. A 3135	Natural Hot Rolled	56%	105,000	75,000	22%	53%	217	C19	29	
	Cold Drawn		115,000	105,000	16%	50%	235	C22	32	Annealed before drawing
	Quenched—Drawn 1000° F.		142,000	120,000	20%	55%	285	C29	39	Water—1500° F.
S.A.E. 3145.. A 3145.	Natural Hot Rolled	56%	115,000	82,000	18%	47%	235	C22	32	
	Cold Drawn		119,000	108,000	15%	43%	241	C23	33	Annealed before drawing
	Quenched—Drawn 1000° F.		146,000	130,000	18%	56%	293	C30	40	Oil—1500° F.
S.A.E. 3240. A 3240..	Natural Hot Rolled	48%	145,000	112,000	13%	27%	285	C29	40	
	Cold Drawn		115,000	106,000	17%	54%	235	C22	32	Annealed before drawing
	Quenched—Drawn 1000° F.		155,000	135,000	18%	55%	311	C32	42	Oil—1500° F.
4120. A 4120..	Natural Hot Rolled	66%	80,000	50,000	28%	62%	163	B84	18	
	Cold Drawn		88,000	75,000	21%	59%	179	B88	21	
	Quenched—Drawn 500° F.		102,000	66,000	24%	62%	207	B94	27	Oil—1575° F.
S.A.E. 4140.. A 4140..	Natural Hot Rolled	60%	130,000	92,000	18%	45%	269	C27	37	
	Cold Drawn		108,000	90,000	19%	53%	223	C20	30	Annealed before drawing
	Quenched—Drawn 1000° F.		180,000	160,000	12%	45%	363	C37	48	Oil—1575° F.
S.A.E. 4340.. A 4340..	Natural Hot Rolled	55%	190,000	150,000	8%	22%	401	C41	52	
	Cold Drawn		110,000	90,000	18%	42%	223	C20	30	Annealed before drawing
	Quenched—Drawn 1000° F.		183,000	165,000	16%	48%	375	C38	48	Oil—1550° F.
S.A.E. 4615. A 4615..	Natural Hot Rolled	66%	82,000	52,000	30%	62%	167	B85	20	
	Cold Drawn		98,000	87,000	18%	56%	197	B93	25	
	Quenched—Drawn 500° F.		116,000	79,000	24%	63%	229	C21	30	Oil—1475° F.
S.A.E. 4640. A 4640..	Natural Hot Rolled	57%	119,000	89,000	13%	41%	241	C23	32	
	Cold Drawn		137,000	113,000	18%	38%	269	C27	37	Annealed before drawing
	Quenched—Drawn 1000° F.		153,000	140,000	22%	57%	293	C30	39	Oil—1500° F.
S.A.E. 5140. A 5140..	Natural Hot Rolled	56%	115,000	75,000	20%	55%	223	C20	29	
	Cold Drawn		99,000	84,000	19%	59%	201	C16	26	Annealed before drawing
	Quenched—Drawn 1000° F.		152,000	130,000	18%	55%	302	C31	41	Oil—1550° F.
S.A.E. 6115.	Natural Hot Rolled	65%	82,000	60,000	30%	65%	174	B86	20	
	Cold Drawn		98,000	87,000	18%	59%	197	B93	25	
	Quenched—Drawn 500° F.		100,000	60,000	30%	60%	201	C15	26	Water—1475° F.
S.A.E. 6140.	Natural Hot Rolled	56%	132,000	111,000	18%	45%	277	C28	37	
	Cold Drawn		108,000	99,000	18%	50%	223	C20	30	Annealed before drawing
	Quenched—Drawn 1000° F.		148,000	133,000	18%	55%	311	C32	41	Oil—1600° F.
S.A.E. 9255.. A 9255.	Natural Hot Rolled	43%	133,000	90,000	18%	40%	269	C27	37	
	Cold Drawn		126,000	118,000	15%	42%	255	C25	35	Annealed before drawing
	Quenched—Drawn 1000° F.		182,000	160,000	15%	33%	363	C36	47	Oil—1650° F.

Standard Stainless Steels, Wrought and Cast

Wrought Stainless Steels *(a)*
(American Iron and Steel Institute Designations; April 1947)

Type No.	Carbon	Chromium	Nickel	Other Elements *(b)*	S.A.E. No. *(c)*
301	0.08-0.20	16.0-18.0	6.0- 8.0		30301
302	0.08-0.20	17.0-19.0	8.0-10.0		30302
302-B	0.08-0.20	17.0-19.0	8.0-10.0	Si 2.00-3.00	
303	0.15 max.	17.0-19.0	8.0-10.0	P or S or Se 0.07 min. Mo or Zr 0.60 max.	30303-F
304	0.08 max.	18.0-20.0	8.0-11.0		30304
305	0.12 max.	17.0-19.0	10.0-13.0		30305
308	0.08 max.	19.0-21.0	10.0-12.0		
309	0.20 max.	22.0-24.0	12.0-15.0		30309
310	0.25 max.	24.0-26.0	19.0-22.0	Si 1.50 max.	30310
314	0.25 max.	23.0-26.0	19.0-22.0	Si 1.50-3.00	
316	0.10 max.	16.0-18.0	10.0-14.0	Mo 2.00-3.00	30316
317	0.10 max.	18.0-20.0	11.0-14.0	Mo 3.00-4.00	30317
321	0.08 max.	17.0-19.0	8.0-11.0	Ti is 5 × C (min.)	30321
	0.25 max.	7.0-10.0	19.0-23.0	Cu 1.00-1.50	30325
347	0.08 max.	17.0-19.0	9.0-12.0	Cb is 10 × C (min.)	30347
403	0.15 max.	11.5-13.0		Turbine quality Si 0.50 max.	
405	0.08 max.	11.5-13.5		Al 0.10-0.30	
406	0.15 max.	12.0-14.0		Al 3.50-4.50	
410	0.15 max.	11.5-13.5			51410
414	0.15 max.	11.5-13.5	1.25-2.50		51414
416	0.15 max.	12.0-14.0		P or S or Se 0.07 min. Mn 1.25 max. Mo or Zr 0.60 max.	51416-F
420	Over 0.15	12.0-14.0			51420
	0.30-0.40	12.0-14.0		*(d)*	51420-F
430	0.12 max.	14.0-18.0			51430
430-F	0.12 max.	14.0-18.0		P or S or Se 0.07 min. Mn 1.25 Mo or Zr 0.60 max.	51430-F
431	0.20 max.	15.0-17.0	1.25-2.50		51431
440-A	0.60-0.75	16.0-18.0		Mo 0.75 max.	51440-A
440-B	0.75-0.95	16.0-18.0		Mo 0.75 max.	51440-B
440-C	0.95-1.20	16.0-18.0		Mo 0.75 max.	51440-C
	0.95-1.20	16.0-18.0		*(e)*	51440-F
	0.20 max.	18.0-23.0			51442
446	0.35 max.	23.0-27.0		N_2 0.25 max. Mn 1.50 max.	51446
501	Over 0.10	4.0- 6.0			51501
502	0.10 max.	4.0- 6.0			

Cast Stainless Steels
(Alloy Casting Institute Designations; October 1947)

Type No. *(f)*	Carbon	Silicon (Max.)	Chromium	Nickel	Other Elements *(g)*
CA-15	0.15 max.	1.50	11.5-14.0	1.0 max.	Mo 0.5 max.
CA-40	0.20-0.40	1.50	11.5-14.0	1.0 max.	Mo 0.5 max.
CB-30	0.30 max.	1.00	18.0-22.0	2.0 max.	
CC-50	0.50 max.	1.00	26.0-30.0	4.0 max.	
CE-30	0.30 max.	2.00	26.0-30.0	8.0-11.0	
CF-8	0.08 max.	2.00	18.0-21.0	8.0-11.0	
CF-20	0.20 max.	2.00	18.0-21.0	8.0-11.0	
CF-8C	0.08 max.	2.00	18.0-21.0	9.0-12.0	Cb 8 × C *(h)*
CF-8M	0.08 max.	1.50	18.0-21.0	9.0-12.0	Mo 2.0-3.0
CF-12M	0.12 max.	1.50	18.0-21.0	9.0-12.0	Mo 2.0-3.0
CF-16F*	0.16 max.	2.00	18.0-21.0	9.0-12.0	Mo 1.5 max. P 0.17 max. Se 0.20-0.35
CF-16F*	0.16 max.	2.00	18.0-21.0	9.0-12.0	Mo 0.40-0.80 S 0.20-0.40
CG-12	0.12 max.	2.00	20.0-23.0	10.0-13.0	
CH-10	0.10 max.	2.00	22.0-26.0	12.0-15.0	
CH-20	0.20 max.	2.00	22.0-26.0	12.0-15.0	
CK-20	0.20 max.	2.00	23.0-27.0	19.0-22.0	
HC	0.50 max.	2.00	26.0-30.0	4.0 max.	Mo 0.5 max. *(i)*
HD	0.50 max.	2.00	26.0-30.0	4.0- 7.0	Mo 0.5 max. *(i)*
HE	0.20-0.50	2.00	26.0-30.0	8.0-11.0	Mo 0.5 max. *(i)*
HF	0.20-0.40	2.00	18.0-23.0	8.0-12.0	Mo 0.5 max. *(i)*
HH	0.20-0.50	2.00	24.0-28.0	11.0-14.0	Mo 0.5 max. *(i)* N 0.2 max.
HI	0.20-0.50	2.00	26.0-30.0	14.0-18.0	Mo 0.5 max. *(i)*
HK	0.20-0.60	3.00	24.0-28.0	18.0-22.0	Mo 0.5 max. *(i)*
HL	0.20-0.60	3.00	28.0-32.0	18.0-22.0	Mo 0.5 max. *(i)*
HT	0.35-0.75	2.50	13.0-17.0	33.0-37.0	Mo 0.5 max. *(i)*
HU	0.35-0.75	2.50	17.0-21.0	37.0-41.0	Mo 0.5 max. *(i)*
HW	0.35-0.75	2.50	10.0-14.0	58.0-62.0	Mo 0.5 max. *(i)*
HX	0.35-0.75	2.50	15.0-19.0	64.0-68.0	Mo 0.5 max. *(i)*

*Alternate types.

Notes

(a) All composition ranges are based on ladle analysis. For standard permissible variations from specified chemical ranges or limits for check analysis, see pages 10 to 13, Section 24, A.I.S.I. Steel Products Manual.

(b) **Manganese:** 2.00 max. in all 300 types except S.A.E. 30325 which has 0.60 to 0.90; 1.00 max. in all 400 and 500 types except 416 (1.25 max.), 430-F (1.25 max.) and 446 (1.50 max.). **Silicon:** 1.00 max. in all types except 302-B (2.00 to 3.00), 310 (1.50 max.), 314 (1.5 to 3.0), S.A.E. 30325 (1.00 to 2.00) and 403 (0.50 max.). **Phosphorus** is 0.40 max. and **sulphur** is 0.30 max. in all types except 303, 416, 430-F, in each of which they are 0.07% min. if added for improving machinability.

(c) S.A.E. composition limits may be slightly different from the A.I.S.I. analyses quoted.

(d) Same as in 51416-F and 51430-F.

(e) Same as in 51416-F except that Mn or Zr is 0.75 max.

(f) Designations with the initial letter C indicate alloys generally used to resist corrosive attack at temperatures less than 1200° F. Designations with the initial letter H indicate alloys generally used under conditions where the metal temperature is in excess of 1200° F.

(g) **Manganese:** 1.00 max. in CA-15, CA-40, CB-30 and CC-50; 1.50 max. in all other C alloys; 1.00 max. in HC; 1.50 max. in HD; 2.00 max. in all other H alloys. **Phosphorus and sulphur:** each 0.04 max. in all alloys except CF-16F regular, wherein P is 0.17 max., and in CF-16F alternate, wherein S is 0.20 to 0.40.

(h) Columbium 1.00% max.

(i) Molybdenum not intentionally added.

(Courtesy *Metal Progress*)

Properties of Important Wrought Chromium-Iron Alloys

Nominal Alloy	2% Cr	5% Cr		9% Cr	12% Cr		Cutlery		17% Cr		27% Cr	
A.I.S.I. Type No.	—	502		—	410;416		420		430		446	
Chemical composition												
Chromium	1.75 to 2.25	4 to 6		8 to 10	10 to 14		12 to 14		16 to 18		23 to 27	
Molybdenum	0.6	0.5		1.0 or 1.5	(0.6 max.)		—		(0.5 max. Ni)		(1.0 max. Ni)	
Mn (max.)	0.65	0.50		0.5	0.6		0.55		0.5		1.5	
Carbon	0.15 max.	0.10 to 0.20		0.15 max.	0.15 max.		0.30 to 0.40		0.12 max.		0.35 max.	
Specific gravity												
Lb. per cu. in.	—	0.28		0.282	0.28		0.278		0.277		0.273	
(Mild steel-1.00)	—	0.99		1.00	0.98		0.98		0.98		0.96	
Resistance at 70°F.												
Microhms per cm³	—	35		—	57		60		60		67	
(Mild steel-1.00)	—	3.2		—	5.2		5.5		5.5		6.1	
Melting range, °F.												
Top	—	2800		—	2790		2750		2750		2750	
Bottom	—	2700		—	2700		2580		2700		2700	
Structure (normal)	Pearlitic	Martensitic		Martensitic	Martensitic or Ferritic		Martensitic		Ferritic		Ferritic	
Magnetism												
Ferromagnetic	Yes	Yes		Yes	Yes		Yes		Yes		Yes	
Permeability As annealed	—	—		—	—		—		—		—	
Permeability Cold worked 10%	—	—		—	—		—		—		—	
Specific heat												
Cgs units, 0 to 100°C.	0.11	0.11		0.11	0.11		0.117		0.11		0.12	
(Mild steel-1.00)	1.0	1.0		1.0	1.0		1.1		1.0		1.1	
Thermal conductivity												
* Cgs. units at 100°C.	—	0.0874		—	0.0595		0.054		0.0595		0.0500	
(Mild steel-1.00)	—	0.73		—	0.50		0.45		0.50		0.42	
Cgs units at 500°C.	—	0.0804		—	0.0686		—		0.0624		0.0581	
Thermal expansion per °F x 1,000,000												
From 32 to 212°F.	—	6.2		6.2	6.1		5.7		5.6		5.9	
(Mild steel-1.00)	—	0.94		0.94	0.93		0.87		0.86		0.90	
From 32 to 932°F.	7.3	7.2		6.9	6.7		6.6		6.7		6.3	
Mechanical Properties at Room Temperature	Annealed	Annealed	Quenched (1600°); Tempered (1000°)	Annealed	Annealed	Quenched & Tempered (800-1300°)	Annealed	†† Heat Treated	Annealed	Cold Worked (Wire)	Annealed	Cold Worked (Wire)
Tensile strength, 1000 psi	60 to 70	65 to 85	175	70 to 87	65 to 85	90 to 180	90	250 to 260	70 to 80	90 to 110	75 to 95	85 to 175
Yield strength, 1000 psi.	30 to 45	30 to 60	145	35 to 45	35 to 45	70 to 160	65	200 to 220	40 to 50	80	50 to 60	55 to 155
Elastic modulus, 10⁶ psi.	29	29	—	29	29	29	29	—	29	—	29	—
Elongation, % in 2 in.	40 to 30	45 to 35	17	40 to 25	35 to 25	25 to 15	27	5	30 to 25	25 to 8	30 to 20	25 to 2
Reduction of Area, %	65 to 45	75 to 60	60	70 to 50	65	65 to 45	59	7	75 to 50	70	60 to 50	55 to 25
Impact, ft-lb, Charpy	35 to 65	45 to 75	—	45	—	—	—	—	—	—	—	—
Izod	—	75 to 85	32	90	100 to 60	20 to 30	65	—	—	—	2	—
Fatigue endurance limit, 1000 psi	—	—	—	—	43	55	50	—	34	50	50	—
Hardness, Brinell	130 to 160	135 to 180	300	145 to 180	135 to 165	180 to 380	190	480	175	197	160 to 190	150 to 250
Rockwell	—	B-75 to 85	C-24	—	B-80	—	B-90	C-54	B-80	B-97	B-85	C-0 to 25
Erichsen value, mm.	—	—	—	—	7 to 8	—	—	—	7 to 9	—	—	—
Olsen value, in.	—	0.375 to 0.450	—	—	—	—	—	—	—	—	—	—
Stress in psi causing 1% "creep" in 10,000 hr at 1000°F.	11,000	9,000		11,000	12,000		4,500		8,500		6,200	
1100	5,500	4,500		6,950	4,700		1,700		5,000		3,000	
1200	3,000	2,100		2,400	2,200		1,300		2,100		1,600	
1350	—	—		—	1,400				1,000		400	
Scaling temp., °F	1100	1,150		1200	1,250		1,250		1,550		2,000	
Initial forging temp., °F.	2200	2,100 to 2200		2000 to 2150	2,000 to 2,100		2,000 to 2,100		1,900 to 2,050		1,900 to 2,000	
Finishing temp., °F.	1500	1500 to 1600		1600	1,500		1,700 to 1,750		1,500		1,300 to 1,450	
Annealing treatment	†	†††		***	**		Cool from 1,450 to 1550		Air cool from 1,400 to 1,450		Rapid cool from 1,450 to 1,550	

* Thermal conductivity is measured as calories per sq. cm per sec per °C. per cm.
†† Oil quenched from 1850°F. and tempered
** Furnace cool from 1550 to 1100°F., or air cool from long heat at 1250 to 1350°F.
*** Cool from 1525 to 1375°F. or slow cool from 1600 to 1675°F.
††† " " " " " " " " " 1525 to 1600°F.
† Furnace cool from 1620°F.

(Courtesy *Metal Progress*)

Properties of Important Wrought Chromium-Nickel-Iron Alloys

Revised 1943, from data furnished by U.S. Steel Corp., Electro Metallurgical Co., and Commitee A-10, A.S.T.M.

Nominal Alloy A.I.S.I. Type No.	18-8 302†	18-8 Ti 321	18-8 Cb 347	18-12 Mo 316	20-12 308	24-12 309	25-20 310	18-26 311
Chemical composition								
Chromium	17 to 19	17 to 19	17 to 19	16 to 18	19-22	22 to 24	24 to 26	18 to 20
Nickel	8 to 10††	8 to 11	9 to 12	10 to 14	10-12	12 to 15	19 to 22	24 to 26
Mn (max.)	1.25	2.00	2.00	2.50	2.00	2.00	2.00 max.	2.00 max.
Carbon	0.08 to 0.20	0.10 max.	0.10 max.	0.10 max.	0.10 (max.)	0.20 max.	0.25 max.	0.25 max.
Others	—	Ti 4 x C	Cb 10 x C	2 to 3 Mo	—	—	—	—
Specific gravity								
Lb. per cu. in.	0.288	0.286	0.29	0.291	0.287	0.29	0.285	0.280
(Mild steel-1.00)	1.02	1.01	1.02	1.03	1.01	1.01	1.01	0.99
Electrical resistance at 70°F.								
Microhm per cm.^{3}	72*	72	73	74	—	78	80±	102
(Mild steel-1.00)	6.6	6.6	6.7	6.8	—	7.1	7.3	9.3
Melting range, °F.								
Top	2590	2600		2550	2590	2650	2650	—
Bottom	2550	2550		2500	2550	2550	2550	—
Structure	Austenitic	Austenitic		Austenitic	Austenitic	Austenitic	Austenitic	
Magnetism								
Ferromagnetic	—	—	—	—	—	—	Trace	—
Permeability As annealed	1.003	1.003	1.02	1.003	—	1.003	1.003	—
Cold Worked	1.10 to 7.0	—	—	1.10 to 10.0	—	—	—	—
Specific heat								
C.g.s. units, 0 to 100°C.	0.12	0.12		0.12	—	0.12	0.14	—
(Mild steel-1.00)	1.1	1.1		1.1	—	1.1	1.3	—
Thermal conductivity								
** C.g.s. units at 100°C.	0.0388	0.0385		0.0372	0.039	0.03 to 0.04	0.0330	—
(Mild steel-1.00)	0.33	0.32		0.316	0.33	0.25 to 0.35	0.280	—
C.g.s. units at 500°C.	0.0512	0.0528		0.0499	—	—	0.0413	—
Thermal expansion per °F. x 1,000,000								
From 32 to 212°F.	9.5	9.3		8.9	9.6	8.3	8.0	8.8
(Mild steel-1.00)	1.44	1.40		1.35	1.45	1.26	1.21	1.33
From 32 to 932°F.	10.2	10.2		9.7	—	9.6	9.2	9.3

Mechanical Properties at Room Temperature	Annealed	Cold Worked (Type 301X)†	Annealed	Annealed	Cold Worked	Annealed	Annealed	Cold Worked	Annealed	Annealed
Tensile strength, 1000 psi.	80 to 100	150 to 300	75 to 95	80 to 95	140 to 200	70 to 90	90 to 100	110 to 270	80 to 110	90 to 110
Yield strength, 1000 psi.	30 to 45	130 to 275	30 to 45	35	120 to 180	30 to 60	40	65 to 230	35 to 55	45 to 50
Elastic modulus, 10^6 psi.	28	26 to 28	29	28	—	28	29	—	·30	30±
Elongation, % in 2 in.	65 to 45	20 to 2	60 to 45	65 to 50	18 to 6	75 to 50	55 to 35	15 to 3	60 to 45	35 to 30
Reduction of area, %	70 to 50	55 to 10	65 to 50	70 to 55	65	70 to 45	60 to 50	55 to 20	60 to 50	45 to 35
Impact, ft-lb.; Charpy	90 to 60	—	80	80	—	—	90 to 60	—	80 to 70	—
Izod	110 to 75	50 to 20	100	100	—	—	—	—	100 to 60	50 to 90
Fatigue endurance limit, 1000 psi.	30 to 40	85	45	39	—	—	42	—	—	—
Hardness, Brinell	150 to 160	365 to 410	135 to 149	135 to 165	—	135 to 185	150 to 185	170 to 375	160	160 to 185
Rockwell	B-75 to 80	C-36 to 50	B-75	B-75 to 90	C-30 to 38	—	B-80 to 90	C-5 to 40	B-80	—
Erichsen value, mm.	10 to 14	—	12	12	—	—	7 to 8	—	—	—
Stress in psi. causing 1% "creep" in 10,000 hr. at			321 347							
1000 °F.	17,000		18,000 19,000	23,000			17,000		17,000	17,000
1200	7,000		7,800 9,500	10,000			8,500		9,000	—
1350	2,500		3,600 4,000	5,500			3,500		3,300	—
1500	850		850 —	2,000			1,000		1,100	—
1600	—		— —	—			—		—	1,900
Scaling temp., °F.	1650		1650	1650		1650	2000		2000	1650
Initial forging temp., °F.	2000 to 2200		2100 to 2200	2100 to 2200		—	2000 to 2150		2000 to 2150	2050
Finishing temp., °F.	Not under 1700		Same as 18-8	As for 18-8		—	Not under 1800		1800 to 1850	1700
Annealing treatment	Heat at 1950 to 2050°F. and Quench		Same as 18-8	1950 to 2050 °F. and Quench		—	Heat at 2000 to 2100°F. and Quench		Same as for 24-12	2000°(Quick Heat & Quench)

* Electrical resistance of cold worked 18-8 ranges from 70 to 82 microhms per cm. cube

** Thermal conductivity is measured as calories per sq. cm. per sec. per °C. per cm.

† Type 301X is the cold-worked sheet for light weight structure

†† For spinning purposes Ni is sometimes specified 10 to 12%

(Courtesy *Metal Progress*)

Gray Iron Castings—Engineering Properties

These tables give the engineering and physical properties of some typical cast irons—both plain and alloy—falling within the familiar A.S.T.M. strength classifications.

PLAIN GRAY IRONS

Property		A.S.T.M. Class					
		20	25	30	35	40	
Tensile strength, p.s.i.		20,000	25,000	30,000	35,000	40,000	45,000
Compressive strength, p.s.i.		80,000	90,000	100,000	110,000	125,000	135,000
Hardness (Brinell)		110	140	170	200	230	265
Permanent set		5,000	7,000	9,000	11,000	13,000	15,000
Endurance limit		8-10,000	10-12,000	12-15,000	14-16,000	16-20,000	18-22,000
Mod. of elasticity, p.s.i.		11,000,000	12,000,000	13,000,000	14,000,000	15,000,000	16,000,000
Torsion modulus, p.s.i.		4,000,000	4,500,000	5,000,000	5,500,000	6,000,000	6,500,000
Toughness (Izod impact)		——	less than 1	——	——	——	——
Creep	840° F.	——	——	8,000	8,000	no data	no data
0.1%/1000 hrs.	1000° F.	——	——	0	0	——	
Machinability		excellent	excellent	excellent	excellent	good	fair
Wear resistance		good	good	good to exc.	excellent	excellent	good to exc.
Corrosion resistance		fair	fair	fair	fair	fair	fair
Vibration damping capacity		excellent	excellent	excellent	excellent	good to exc.	good.
Specific gravity		7.0	7.0	7.1	7.2	7.3	7.4
Melting point °F.			2150-2300				
Thermal exp. $X10^{-6}$		6.7	6.7	6.7	6.7	6.7	6.7
Thermal conductivity (cgs units)		0.11	0.11	0.11	0.11	0.11	0.11
Electrical res. (microhms)		80-100	80-100	80-100	80-100	80-100	80-100
Magnetic permeability (gausses with H at 100)		9000	9000	9000	9000	9000	9000

ALLOY GRAY IRONS

Property	A.S.T.M. Class					
	30	35	40		50	60
Tensile strength, p.s.i.	30,000	35,000	40,000	45,000	50,000	60,000
Compressive strength, p.s.i.	100,000	110,000	125,000	135,000	150,000	175,000
Hardness (Brinell)	170	190	210	230	250	275
Permanent set	9,000	11,000	13,000	15,000	17,000	19,000
Endurance limit	15,000	17,000	20,000	22,000	25,000	30,000
Mod. of elasticity, p.s.i.	14,000,000	15,000,000	16,000,000	17,000,000	18,000,000	20,000,000
Torsion modulus, p.s.i.	5,500,000	6,000,000	6,500,000	7,000,000	8,000,000	9,000,000
Toughness (Izod impact)	——	——	less than 1	——	up to 2	up to 2
Creep 0.1%/1000 hrs. 840° F.	——	9500	no data	no data	no data	no data
1000° F.	——	0	no data	no data	no data	no data
Machinability	excellent	excellent	excellent	excellent	good to exc.	good to exc.
Wear resistance	excellent	excellent	excellent	excellent	good to exc.	good to exc.
Corrosion resistance	fair to good	fair to good	fair to good	fair to good	fair to good	fair to good
Vibration damping capacity	excellent	excellent	excellent	excellent	good to exc.	good to exc.
Specific gravity	7.1	7.1	7.2	7.2	7.3	7.3
Melting point, °F.			2150-2300			
Thermal exp. X10^{-6}	6.7	6.7	6.7	6.7	6.7	6.7
Thermal conductivity (cgs units)	.11	.12	.12	.12	.12	.12
Electrical res. (microhms)	80-100	80-100	80-100	80-100	80-100	80-100
Magnetic permeability (gausses with H at 100)	9000	9000	9000	10000	10000	10000

Prepared by F. G. Sefing. (Courtesy *Materials & Methods*)

Wrought Aluminum

Compositions, Properties, and Designations

Compiled by H. S. Jerabek, University of Minnesota, principal manufacturers, the American Society of Engineers.

Designations					Composition Aluminum = Balance					Form Tested	Tensile Strength (c)	
S.A.E. No.	A.S.T.M. Spec. No.	A.S.T.M. Alloy No.	Alcoa No.(a)	Reynolds (b)	Cu	Si	Mn	Mg	Others		Ave.	Min.
									WORK HARDENING ALLOYS~NOT			
25	B25	A2	2S-0	2S					99 Al	1/16" Sheet	13	(15.5ma
	B25	A2	2S-½H							" "	17	18
	B25	A2	2S-H							" "	24	22
29	B79	M1	3S-0	3S			1.2			" "	16	(19max.
	B79	M1	3S-½H							" "	21	19.5
	B79	M1	3S-H							" "	29	27
201	B109	MR1	52S-0	52S				2.5	0.25 Cr	" "	29	(31max.
	B109	MR1	52S-½H							" "	37	34
	B109	MR1	52S-H							" "	41	39
									PRECIPITATION HARDENING ALLOY			
26	B78	CM21	17S-0	17S	4		0.5	0.5		1/16" Sheet	26	(35max.
	B78	CM21	17S-T							" "	62	58
	B89	CM21	17S-T							½" Rod Extruded		55
			17S-T							Forgings	60	55
24			24S-0	24S	4.6		0.6	1.5		1/16" Sheet	27	(36max
			24S-T							" "	68	64
			24S-RT							" "	73	69
240			Alclad 24S-T	Pure Clad 24S						" "	64	59
			Alclad 24S-T86							" "	70	66
			24S-T							½" Ext. Shapes		60
260			14S-0		4.4	0.8	0.8	0.4		½" Ext. Shapes	27	(35max.
			14S-W							" " "	56	50
			14S-T							" " "	70	65
			14S-T	14S						Forgings		65
			Alclad 14S-T							1/16" Sheet	65	64
				R301-T	4.5	1.0	0.8	0.4		" "	68	63
			75S-0		1.6	5.6 Zn	0.2	2.5	0.3 Cr	1/16" Sheet	33	(40max
			75S-T							" "	82	77
			Alclad 75S-T							" "	76	72
			75S-T							½" Ext. Shapes		80
				R303-T275	1.3	6.5 Zn		2.5	0.3 Cr	" " "	85	80
281			61S-W	R361	0.25	0.6		1.0	0.25 Cr	½" Ext. Shapes	35	30
			61S-T							" " "	45	42
282			53S-W	R353		0.7		1.3	0.25 Cr	½" Rod Extruded	33	25
			53S-T							" " "	39	32
			53S-T							Forgings		36
201			A51S-T	A51S		1.0		0.6	0.25 Cr	Forgings		44
27			25S-T	25S	4.5	0.8	0.8			"		55
270			18S-T	18S	4			0.5	2 Ni	"		55
290			32S-T	32S	0.9	12.5		1.0	0.9 Ni	"		52
			11S-T3		5.5			(0.5 Bi)	0.5 Pb	½" Rod	53	45
				R317-T	4	(0.5 Bi)	0.7	0.5	0.5 Pb	" "		55

(a) Aluminum Co. of America alloy numbers and heat treatment designations: O=annealed, W=as quenched, T=
H=cold rolled to hard temper, ½H=half hard temper, R=cold rolled after heat treatment, S=wrought al

(b) Reynolds Metals Company designations.

(c) In thousands of pounds per square inch. Yield strength taken at 0.2% permanent set.

(d) 500 million cycles in reverse bending.

Alloys

of American Commercial Alloys

July 1946, from handbooks and specifications of the
Testing Materials, and the Society of Automotive

Yield Strength (c) Ave.	Yield Strength (c) Min.	Elongation, % in 2 In. Ave.	Elongation, % in 2 In. Min.	Brinell Hardness	Shear Strength (c)	Endurance Limit (c)(d)	Cold Bend Test (e)	Corrosion Resistance in NaCl (f)	Uses and Characteristics
HEAT TREATABLE (g)									
) 5		35	30	23	9.5	5	A	A	Commercial Al: good forming properties.
14		9	5	32	11	7	B	A	Good corrosion resistance, low yield strength.
21		5	4	44	13	8.5	F	A	Cooking utensils; sheet and tubing.
6		30	25	28	11	7	A	A	Similar to 2S
18		8	5	40	14	9	C	A	Slightly stronger and less ductile.
25		4	4	55	16	10	G	A	Cooking utensils; sheet metal work.
14		25	20	45	18	17	A	A	Strongest work hardening alloy.
29		10	6	67	21	18	D	A	High yield strength and fatigue limit.
36		7	4	85	24	19	G	A	Highly stressed sheet metal products.
S~HEAT TREATABLE (h)									
) 10		20	12	45	18	11	B	E	Duralumin. Original strong alloy.
40	34	20	18	105	38	18	H	D	Hardened by quenching and aging.
	32		12					D	Being replaced somewhat by stronger alloys:
30	30	16	16	100	38	18		D	24S, 75S and R303.
) 11		19	12	42	18	12	B	E	Stronger than 17S
46	42	19	17	120	41	18	J	D	Used widely in aircraft construction.
57	52	13	12	130	42		K	D	More difficult to form than 17S.
43	39	18	15		40		J	A	Alclad has improved corrosion resistance.
66	62	6	3					A	T86, cold worked before aging.
	44		12					D	Standard alloy for thin extrusions.
) 14		18	12	45	18	11			Strong alloy for extruded shapes.
40	32	25	12	100	34	18			Will not age harden at room temperature.
60	55	13	7	135	42	18		D	
	55		10	125	42	18		D	Strongest forging alloy
58	57	9	8		41			A	Higher yield strength than Alclad 24S
60	56	10	7		43	12			Clad with heat treatable alloy.(i)
) 15		17	10					E	New alloy of highest strength.
72	66	11	8	150	47	22.5		D	Lower ductility than 24S.
67	62	11	8		46			A	Strongest Alclad product
	70		6						Strongest alloy for extrusions.
77	72	9	7		48	22.5			High strength alloy for sheet, rod, forgings.
21	18	22	16	65	24	13.5	E	C	Good forming properties; high yield str.
40	35	12	10	95	30	13.5	F	C	Will not age harden at room temperature.
20	14	22	16	65	20	13	F	B	Good forming properties and corrosion
33	25	14	14	80	24	13	G	B	resistance.
	30		14	75	24	13			
	34		12	90	32	11		C	For intricate forgings.
	30		16	100	35	18		E	Good forgeability. Lower cost.
	40		10	100	39	17		E	Strong at elevated temp.: forged pistons.
	40		5	115	38	18		C	Forged aircraft pistons. "Low-X."
47	38	15	10	95	30	12.5		E	Free cutting, screw machine products.
	32		12	105					″ ″ ″ ″ ″

uenched and aged,
y.

(e) Relative forming properties in cold bending; A-best
(f) Relative resistance to salt water corrosion; A-best
(g) Can be hardened by cold work only.
(h) ″ ″ ″ ″ heat treatment.
(i) Cladding alloy: 1.0 Mg, 0.7 Si, 0.6 Mn.

(*Metal Progress Data Sheet,* November 1946)

Aluminum Casting

Compositions, Properties, and Designations

Compiled by H. S. Jerabek, University of Minnesota, principal manufacturers, the American Society for Engineers.

Designations				Composition Aluminum-Balance						Form Tested (b) (c)	Tensile Strength (d)		Yield(d) Strength
S.A.E. No.	A.S.T.M. Spec. No.	A.S.T.M. Alloy No.	Alcoa No.(a)	Cu	Si	Mg	Zn	Max. Fe	Others		Ave.	Min.	Ave.
											SAND CASTIN		
33	B26	CS22	113	7.0	2.0		1.7	1.4		As Cast	24	19	15
			212	8.0	1.2					As Cast	23	19	14
			112	7.0			1.7			As Cast	24	19	15
			645	2.7			10.5	2.0		As Cast	29	25	17
310	B26	ZG41				0.6	5.5	(0.5Cr)	0.2Ti	As Cast; Aged		30	25
35	B26	S1,S2	43		5.0			0.8		As Cast	19	17	9
			45		10.0					As Cast	21	18	10
37					12.0			0.8	Trace Na	As Cast "Modified"	26	24	11
326			108	4.0	3.0			1.2		As Cast	21	19	14
320	B26	G1	214			3.8		0.6		As Cast	25	22	12
38	B26	C1	195-T4	4.6	0.8			1.0		Soln. H.T.(b)	32	29	16
38	B26	C1	195-T62							Soln. H.T.; Aged(c)	40	36	30
325	B26	C2		3.8	2.0			1.2		Soln. H.T.(b)		27	16
322	B26	SC21	355-T6	1.3	5.0	0.5		0.6		Soln. H.T.; Aged(c)	35	32	25
322	B26	SC21	355-T61							Soln. H.T.; Aged(c)	39	36	35
323	B26	SG1	356-T6		7.0	0.3		0.6		Soln. H.T.; Aged(c)	33	30	24
324	B26		220-T4			10.0		0.3		Soln. H.T.(b)	46	42	25
39	B26	CN21	142-T571	4.0		1.5		1.0	2Ni	Soln. H.T.; Aged(c)	32	29	28
										PERMANENT MOLD			
33	B108	C3	113	7.0	2.0		1.7	1.4		As Cast	28	24	19
			C113	7.0	3.5					As Cast	30	25	24
			138	10.0	4.0	0.3				As Cast	28	26	24
	B108	SC1	A108	4.5	5.5			1.0		As Cast	28	24	16
35	B108	S1,S2	43		5.0			0.8		As Cast	24	21	9
37					12.0			0.8		As Cast			
			A214			3.8	1.8			As Cast	27	22	16
380	B108	CS4	B195-T6	4.5	2.5			1.2		As Cast	45	35	33
34	B108	CG1	122-T52	10.0		0.2		1.5		Soln. H.T.(b)	35	30	31
34	B108	CG1	122-T65							Soln. H.T.; Aged(c)	48	40	36
39	B108	CN21	142-T61	4.0		1.5		1.0	2Ni	Soln. H.T.; Aged(c)	47	40	42
321	B108	SN41	A132-T65	0.8	12.0	1.2		1.3	2.5Ni	Soln. H.T.; Aged(c)	47	40	
	B108	SC41		1.5	12.2	0.5		0.9	0.75Mn	Soln. H.T.(b)		33	
300			152-T74	7.0	5.5	0.3		1.5		Soln. H.T.; Aged(c)	35	30	26
322			355-T6	1.3	5.0	0.5		0.6		Soln. H.T.; Aged(c)	43	37	27
323	B108	SG1	356-T6		7.0	0.3		0.6		Soln. H.T.; Aged(c)	40	33	27
			750-T533	1.0				(1Ni)	6.5Sn	Soln. H.T.; Aged(c)	20	18	8.5
											DIE CASTINGS		
304	B85	S4	43		5.0			2.0		As Cast	30	29	14
305	B85	S5	13		12.0			2.0		As Cast	37	33	18
			360		9.5	0.5				As Cast	42		23
E306	B85a	SC6	380	3.5	8.5			1.3		As Cast	45	34	25
307	B85	SC2	85	4.0	5.0			2.3		As Cast	40	23	22
312				7.0	2.0		1.7	2.3		As Cast		33	
			218			8.0				As Cast	42		23

(a) Aluminum Co. of America alloy numbers. Heat treated alloys designated by letter T and heat treatment number after alloy number. T4 is solution treatment.
(b) Solution heat treatment: soaking at high temperature followed by quenching.
(c) Solution heat-treatment followed by artificial aging above room temperature.

Alloys

of American Commercial Alloys

July 1946, from handbooks and specifications of the Testing Materials, and the Society of Automotive

Elongation, % in 2 In.		Brinell Hardness	Shear Strength(d)	Endurance Limit(d)(e)	Relative Impact Toughness	Corrosion(g)	Alcoa No.(a)	Uses and Characteristics
Ave.	Min.							
GS								
1.5		70	20	9		D	113	General casting alloy; not heat treated.
2		65	20	8	0.6	D	212	-"- -"- -"- -"- -"- -"-
1.5		70	20	9	0.6	D	112	-"- -"- -"- -"- -"- -"-
4	2.5	70	22	7.5	2.0	D	645	Toughness drops on aging at room temp.
	3					C		High strength after aging at room temp.
6	3	40	14	6.5	1	B	43	Thin walled, pressure tight castings.
4.5	1.5	45	16	6		B	45	Excellent casting properties.
8	5	50	18	6	3	B		Alpax or Silumin. High strength "as cast."
2.5	1.5	55	20	8			108	Used mostly "as cast" but responds to H.T.
9	6	50	20	5.5	3.8	A	214	Good corr. resistance and toughness.
8.5	6	60	24	6	2.8	C	195-T4	Heat treatable. High strength, toughness.
2		95	31	7	1.3	C	195-T62	Fully hardened alloy has low ductility.
	3					C		High strength and ductility.
2.5	2	80	30	8.5	1.1	C	355-T6	Liquid cooled cylinder heads.
1		90	32		0.8	C	355-T61	Good strength at elevated temperatures.
4	3	70	27	8	1.0	A	356-T6	Intricate heat treated castings.
14	12	75	33	7	4.5	A	220-T4	Good corr. resistance; highest toughness.
0.5		85	27	8		C	142-T571	Good strength, stability at elevated temperatures.
CASTINGS								
2		70	23			D	113	Low cost alloy. Not heat treated.
1		80	22	9.5		D	C113	-"- -"- -"- -"- -"- -"-
0.5		100	22			D	138	High temperature strength, hardness.
2		70	25			D	A108	Good casting properties.
9	5	45	18			B	43	Al-Si alloys have excellent casting properties and corrosion resistance.
						B		
7	2.5	60	22			A	A214	Excellent resistance to corrosion.
5	2	90	32	10		C	B195-T6	High strength, heat treatable alloy.
1		100	25			D	122-T52	Standard piston alloy. High temp. strength and good wear resistance.
		140	30	9		D	122-T65	
0.5		110	31	9.5		C	142-T61	High temp. strength and stability.
0.5		125	27			C	A132-T65	Pistons. Reduced thermal expansion.
	3					C		Piston alloy.
0.5		100	29			D	152-T74	-"- -"-
4	1.5	90	30	9		C	355-T6	Good strength at elevated temperatures.
5	3	90				A	356-T6	Intricate castings. High temp. strength.
10	8	45	14	9			750-T533	Bearing alloy.
					Charpy(f)			
7	3.5				4.5	B	43	Tough, corrosion resistant, good casting properties.
1.8	1.5			15	2	B	13	Corrosion resistant; good casting properties.
1.8						B	360	High strength and corrosion resistance.
2	2				2.5	D	380	High strength and hardness.
3.5	2			17	2.5	D	85	-"- -"- -"- -"-
	1				3.2	D		Low cost, general purpose alloy.
7				18		A	218	High corrosion resistance, strength, toughness.

(d) In thousands of pounds per square inch. Yield strength taken at 0.2% permanent set.
(e) 500 million cycles in reverse bending.
(f) Modified Charpy impact toughness; 40-mm. span.
(g) Relative resistance to salt water corrosion. A = best.

(*Metal Progress Data Sheet*, November 1946)

	Alloy No.			Nominal Composition (Mg = Remainder)			Heat Treatment†	Specific Gravity (75 F)	Weight, Lb./Cu. In.	Melting Point, F	Ultimate Strength M Psi.	
	ASTM	DOW	AMC	Al	Zn	Mn					Typ.	Min.
Sheet	AZ31X	FS-1a	C52S-O	3.0	1.0	0.3	a	1.77	0.064	1160	37	32
		FS-1h	C52S-H	3.0	1.0	0.3	h	1.77	0.064	1160	43	38
	AZ51X	JS-1a	C54S-O	5.0	1.0	0.2	a	1.79	0.065	1150	40	—
		JS-1h	C54S-H	5.0	1.0	0.2	h	1.79	0.065	1150	47	—
	M1	Ma	3S-O	—	—	1.5	a	1.76	0.064	1200	33	28
		Mh	3S-H	—	—	1.5	h	1.76	0.064	1200	37	32
Bars	AZ31X	FS-1	C52S	3.0	1.0	0.3	—	1.77	0.064	1160	40	35
	AZ61X	J-1	C57S	6.5	1.0	0.2	—	1.80	0.065	1145	45	40
	AZ80X	O-1	C58S	8.5	0.5	0.2	—	1.80	0.065	1130	49	43
	M1	M	3S	—	—	1.5	—	1.76	0.064	1200	38	30
Shapes	AZ31X	FS-1	C52S	3.0	1.0	0.3	—	1.77	0.064	1160	38	33
	AZ61X	J-1	C57S	6.5	1.0	0.2	—	1.80	0.065	1145	44	40
	AZ80X	O-1	C58S	8.5	0.5	0.2	—	1.80	0.065	1130	46	41
	M1	M	3S	—	—	1.5	—	1.76	0.064	1200	34	29
Tubing	AZ31X	FS-1	C52S	3.0	1.0	0.3	—	1.77	0.064	1160	36	32
	AZ61X	J-1	C57S	6.5	1.0	0.2	—	1.80	0.065	1145	40	36
	M1	M	3S	—	—	1.5	—	1.76	0.064	1200	33	28
Castings	A10	G	240	10.0	—	0.1	AC	1.81	0.066	1100	22	18
				10.0	—	0.1	HT	1.81	0.066	1100	33	29
				10.0	—	0.1	HTA	1.81	0.066	1100	34	29
	AZ63	H	265	6.0	3.0	0.2	AC	1.83	0.066	1135	29	24
				6.0	3.0	0.2	ACS	1.83	0.066	1135	29	24
				6.0	3.0	0.2	HT	1.83	0.066	1135	40	34
				6.0	3.0	0.2	HTA	1.83	0.066	1135	40	34
				6.0	3.0	0.2	HTS	1.83	0.066	1135	40	34
	AZ92	C	260	9.0	2.0	0.1	AC	1.82	0.066	1110	24	20
				9.0	2.0	0.1	ACS	1.82	0.066	1110	24	20
				9.0	2.0	0.1	HT	1.82	0.066	1110	40	34
				9.0	2.0	0.1	HTA	1.82	0.066	1110	40	34
				9.0	2.0	0.1	HTS	1 82	0.066	1110	40	34
	M1	M	403	—	—	1.5	AC	1.76	0.064	1200	14	12
	AZ90	R	263	9.0	0.7	0.2	—	1.81	0.063	1120	33	—

Tension				Compression M Psi.		Shear M Psi.	Brinell	Rockwell E	Fatigue M Psi.	Impact Izod Ft./Lb.	Resistance to Salt Water, A = Best	Relative Cost A = Lowest	Color Code AS = Aluminum Stripe
Yield Strength M Psi.		% Elong. in 2 In.		Ult. Str.	Y'd. Str.								
Typ.	Min.	Typ.	Min.										
22	—	21	12	—	16	21	56	67	12	—	B	B	Red-AS
33	26	11	4	—	26	23	73	83	14	—	B	B	Red-AS
23	—	18	—	—	15	20	59	71	14	—	A	D	Brown-AS
34	—	10	—	—	30	21	72	82	16.5	—	A	D	Brown-AS
15	—	17	12	—	12	17	48	55	9	—	C	A	Yellow
29	22	8	4	—	20	17	56	67	10	—	C	A	Yellow
30	22	15	10	60	17	19	49	57	14	—	A	B	Red-AS
32	26	15	11	—	20	—	58	70	18	—	A	C	Gray-AS
33	25	11	9	—	22	—	55	77	19	—	A	D	White-AS
26	20	10	3	—	14	—	42	41	9	—	B	A	Yellow
26	20	14	8	—	15	—	50	59	—	—	A	B	Red-AS
28	22	16	9	—	19	—	64	76	—	—	A	C	Gray-AS
29	25	9	6	—	22	—	67	78	—	—	A	D	White-AS
20	17	9	3	—	11	—	46	50	—	—	B	A	Yellow
21	16	16	8	—	15	—	46	51	—	—	A	B	Red-AS
21	16	14	7	—	15	—	50	60	—	—	A	C	Gray-AS
21	—	9	3	—	10	—	42	41	—	—	B	A	Yellow
13	10	2	1	48	13	17	54	65	10	2	D	A	Purple
12	10	8	5	50	12	19	52	62	12	4	D	B	Purple
19	17	2	—	54	19	21	69	80	10	2	D	C	Purple
14	10	6	4	45	14	18	50	59	11	3	C	A	Green
14	10	5	2	—	—	—	—	—	11	—	C	B	Green
14	10	12	7	46	14	19	55	66	14	5	C	B	Green
19	16	5	3	50	19	20	73	83	13	2	C	C	Green
17	13	7	4	—	—	—	59	71	13	—	C	C	Green
14	10	2	1	55	16	18	65	77	11	1	C	A	Orange
14	11	2	—	—	—	—	—	—	11	—	C	B	Orange
16	10	10	6	60	16	20	63	75	14	4	C	B	Orange
23	18	2	1	70	23	21	84	90	13	1	C	C	Orange
20	16	3	1	—	—	—	75	83	13	—	C	C	Orange
4.5	—	5	3	27	4.5	11	33	3	—	9	B	B	Yellow
22	—	3	—	58	22	20	60	72	14	2	A	B	Blue

(Courtesy *Materials & Methods,* May 1947)

Modulus of Elasticity—6,500,000 psi.
Coefficient of Therman Expansion—0.000016 inch per inch per degree F(65 to 750 F.)
NOTES: † Heat treatment: AC = as cast, HT = solution heat-treated, HTA = heat-treated and aged, S(ACS and HTS) = stabilized, a = annealed, h = hard rolled.

Properties of Commercial Brasses

Name	Form for Which Hardness and Tensile Properties Are Given	Temper	Rockwell Hardness		Tensile Strength p.s.i.	Elongation in 2 In. Per Cent	Yield Strength at ½% Elongation Under Stress p.s.i.	Shear Strength p.s.i.
			F	B				
Muntz Metal	0.040″ Sheet	Hot Rolled	80		54,000	45	20,000	40,000
	0.040″ Sheet	Cold Rolled			80,000	5	60,000	47,000
High Brass	0.040″ Sheet	0.025 mm Anneal	73		52,000	56	20,000	35,000
	0.040″ Sheet	0.070 mm Anneal	60		46,000	64	15,000	33,000
	0.040″ Sheet	Hard		80	75,000	7	60,000	43,000
	0.040″ Sheet	Spring		88	90,000	3	65,000	48,000
	0.100″ Wire	Rivet			60,000	30	45,000	38,000
	0.100″ Wire	Spring			125,000		68,000	60,000
70/30 Brass	0.040″ Sheet	0.025 mm Anneal	73		52,000	56	20,000	35,000
	0.040″ Sheet	0.070 mm Anneal	60		46,000	64	15,000	33,000
	0.040″ Sheet	Hard		83	76,000	7	60,000	43,000
	0.040″ Sheet	Spring		90	93,000	3	65,000	48,000
Low Brass	0.040″ Sheet	0.015 mm Anneal	75		47,000	47	18,000	33,000
	0.040″ Sheet	0.050 mm Anneal	60		43,000	55	15,000	32,000
	0.040″ Sheet	Hard		83	73,000	7	60,000	42,000
	0.040″ Sheet	Spring		90	90,000	3	65,000	48,000
	0.100″ Wire	Spring			120,000		68,000	58,000
Rich Low Brass	0.100″ Wire	Soft			42,000		14,000	32,000
Red Brass	0.040″ Sheet	0.015 mm Anneal	71		45,000	43	20,000	33,000
	0.040″ Sheet	0.030 mm Anneal	64		42,000	47	14,000	32,000
	0.040″ Sheet	Hard		75	70,000	5	58,000	42,000
	0.040″ Sheet	Spring		85	83,000	3	63,000	45,000

Commercial Bronze	0.040″ Sheet	0.015 mm Anneal	65		41,000	42	30,000	31,000
	0.040″ Sheet	0.030 mm Anneal	58		38,000	45	12,000	30,000
	0.040″ Sheet	Hard		70	62,000	5	55,000	38,000
	0.040″ Sheet	Spring		78	73,000	3	63,000	42,000
Gilding Metal	0.040″ Sheet	0.015 mm Anneal	60		38,000	42	10,000	30,000
	0.040″ Sheet	0.030 mm Anneal	52		36,000	44	8,000	29,000
	0.040″ Sheet	Hard		62	55,000	6	48,000	37,000
	0.040″ Sheet	Spring		72	63,000	5	57,000	38,000
Architectural Bronze	1 in. Rod	Extruded		50	54,000	45	18,000	32,000
	Shapes	Extruded & Stretched		58	60,000	25	22,000	35,000
Forging Brass	1 in. Rod	Forged or Hot Pressed		45	50,000	45	18,000	32,000
Free Cutting Brass	¼ in. Rod	Half Hard		80	68,000	18	52,000	40,000
	½ in. Rod	Half Hard		79	63,000	20	48,000	37,000
	1 in. Rod	Half Hard		78	58,000	25	45,000	32,000
High-leaded Brass	0.040″ Sheet	Half Hard		70	61,000	20	50,000	40,000
	0.040″ Sheet	Hard		80	75,000	7	60,000	43,000
High-leaded Brass (Tube)	Tube	0.025 mm Anneal	75		52,000	50	20,000	.
	Tube	Hard		80	75,000	7	62,000	.
Medium-leaded Brass	0.040″ Sheet	0.025 mm Anneal	73		52,000	56	20,000	33,000
	0.040″ Sheet	Half Hard		70	61,000	21	50,000	40,000
Low-leaded Brass (Tube)	Tube	0.025 mm Anneal	75		52,000	50	20,000	
	Tube	Hard		80	75,000	7	60,000	. .
Leaded Commercial Bronze	¼ in. Rod	Half Hard		65	60,000	10	55,000	32,000
	½ in. Rod	Half Hard		61	55,000	14	55,000	31,000
	1 in. Rod	Half Hard		58	50,000	20	45,000	30,000

NOTE: The above figures are typical and are not to be used for minimum specification requirements. Variations must be expected in practice.

(Courtesy *Chase Brass & Copper Co.*)

Properties of Wrought Bronzes

TYPICAL WROUGHT BRONZES and OTHER COPPER ALLOYS	APPROXIMATE CHEMICAL COMPOSITION (Per Cent)												APPROXIMATE TENSILE STRENGTH (1,000 lb. per sq. in.)				APPROXIMATE YIELD POINT (‡) (1,000 lb. per sq. in.)			
	Copper	Tin	Phosphorous	Lead	Manganese	Silicon	Nickel	Zinc	Iron	Aluminum	Beryllium	Arsenic	Commercial Sheet Stock Approx. 0.040-in. Thick		Commercial Rod Stock Approx. 1-in. Dia.		Commercial Sheet Stock Approx. 0.040-in. Thick		Commercial Rod Stock Approx. 1-in. Dia.	
Commonly Used Trade Names	Cu	Sn	P	Pb	Mn	Si	Ni	Zn	Fe	Al	Be	As	Hard (*)	Soft	Hard (*)	Soft	Hard (*)	Soft	Hard (*)	Soft
Tin or Phosphor Bronzes																				
Phosphor Bronze	98.75	1.25	Tr.	...	...	...	...	...	...	...	...	...	65	40	...	...	...	...	...	...
4% Phosphor Bronze (Grade A)	95.75	4.0	0.25	...	...	...	...	...	...	...	...	...	82	50	...	...	...	18	...	...
5% Phosphor Bronze (Grade A)	94.9	5.0	0.10	...	...	...	...	...	...	...	...	...	82	50	70	...	60	20	55	...
8% Phosphor Bronze (Grade C)	91.9	8.0	0.10	...	...	...	...	...	...	...	...	...	92	60	...	...	65	25	...	...
10% Phosphor Bronze (Grade D)	89.4	10.5	0.10	...	...	...	...	...	...	...	...	...	102	65	...	...	70	28	...	...
Leaded Phosphor Bronze (Grade B)	93.9	5.0	0.10	1.0	...	...	...	...	...	...	...	...	82	50	70	...	60	20	55	...
Free-Cutting Phosphor (Bushing) Bronze	87.55	4.0	0.45	4.0	...	...	...	4.0	...	...	...	...	...	...	60	...	...	...	45	...
" Carobronze " Bearing Alloy	91.2	8.5	0.30	...	...	...	...	...	...	...	...	...	90	63	100	65	...	...	...	...
Nickel Silvers																				
10% Nickel Silver	65.0	...	...	...	...	...	10.0	25.0	...	...	...	...	86	55	...	...	70	20	...	...
15% Nickel Silver (64% Copper)	64.0	...	...	...	...	...	15.0	21.0	...	...	...	...	85	55	...	...	...	...	...	...
15% Nickel Silver (57% Copper)	57.0	...	...	...	...	...	15.0	28.0	...	...	...	...	90	55	...	...	...	...	...	...
18% Nickel Silver (65% Copper)	65.0	...	...	...	...	...	18.0	17.0	...	...	...	...	86	58	...	...	65	...	...	...
18% Nickel Silver (55% Copper)	55.0	...	...	...	...	...	18.0	27.0	...	...	...	...	100	60	...	...	...	...	...	...
20% Nickel Silver	75.0	...	...	...	...	...	20.0	5.0	...	...	...	...	75	50	70	50	55	20	50	18
12% Leaded Nickel Silver	65.0	...	...	1.0	...	...	12.0	22.0	...	...	...	...	85	58	...	...	...	...	...	...
12.5% Leaded Nickel Silver	61.0	...	...	1.5	...	...	12.5	25.0	...	...	...	...	90	...	...	...	...	...	...	...
18% Leaded Nickel Silver	63.25	...	...	1.0	...	...	18.0	17.75	...	...	...	...	...	...	75	...	...	...	...	...
10% Extruded Nickel Silver	46.5	...	...	2.75	...	...	10.0	40.75	...	...	...	...	...	...	...	...	...	...	...	...
13% Extruded Nickel Silver	42.25	...	...	0.5	2.0	...	13.0	42.25	...	...	...	...	...	...	...	...	...	...	...	...
13% Extruded Nickel Silver	43.25	...	...	...	...	...	13.0	43.75	...	...	...	...	...	...	...	...	...	...	...	...

Cupro — Nickels																				
15% Cupro — Nickel	85.0	...	...	...	...	...	15.0	...	...	...	...	...	67	45	....	...	50	...	....	...
20% Cupro — Nickel	80.0	...	...	...	...	...	20.0	...	...	...	...	...	70	48	....	...	....	...	....	...
30% Cupro — Nickel	70.0	...	...	...	...	...	30.0	...	...	...	...	...	72	50	70	50	60	20	55	20
Copper — Nickel — Tin (Adnic)	70.0	1.00	...	...	...	...	29.0	...	...	...	...	...	130	55	95	55	....	25	....	25
Aluminum Bronzes																				
5% Aluminum Bronze	95.0	...	...	...	...	...	...	...	...	5.0	...	...	90	52	75	52	....	...	....	...
8% Aluminum Bronze	92.0	...	...	...	...	...	...	...	...	8.0	...	...	100	60	90	60	65	...	60	...
Nickel — Aluminum Bronze	89.5	...	...	...	...	...	0.5	...	0.5	9.5	...	...	....	...	88	...	....	...	43	...
5% Nickel — Aluminum Bronze	81.9	...	...	...	1.0	...	5.0	...	2.5	9.6	...	...	....	...	105	...	....	...	60	...
Nickel — Aluminum Bronze (Type A)	92.0	...	...	...	...	...	4.0	...	...	4.0	...	...	90	50	....	...	....	...	....	...
Nickel — Aluminum Bronze (Type B)	91.0	...	...	...	...	...	7.5	...	...	1.5	...	...	....	...	115	50	....	...	....	...
Copper — Silicon Alloys																				
Everdur No. 1010	95.8	...	...	...	1.1	3.1	...	...	...	...	...	...	95	55	95	55	65	20	65	20
Everdur No. 1012	95.6	...	...	0.40	1.0	3.0	...	...	...	...	...	...	....	...	95	...	....	...	65	...
Everdur No. 1015	98.25	...	...	...	0.25	1.5	...	...	...	...	...	...	65	40	70	40	50	10	55	10
Duronze I	97.5	1.50	...	...	...	1.0	...	...	...	...	...	...	65	40	70	40	....	...	....	...
Duronze II	97 0	...	...	...	...	3.0	...	...	...	...	...	...	92	55	85	55	60	15	50	15
Duronze III (Silicon — Aluminum Bronze)	91.0	...	...	...	...	2.0	...	...	...	7.0	...	...	....	...	95	80	....	...	....	...
Olympic Bronze — Type A	96.0	...	...	...	...	3.0	...	1.0	...	...	...	...	93	56	93	...	....	...	....	...
Olympic Bronze — Type D	95.5	...	...	0.50	...	3.0	...	1.0	...	...	...	...	....	...	93	...	....	...	....	...
Olympic Bronze — Type G (Silicon Brass)	77.0	...	...	...	...	1.0	...	22.0	...	...	...	...	96	63	....	...	....	...	....	...
Herculoy No. 418	96.25	0.50	...	...	...	3.25	...	...	...	...	...	...	110	60	125	60	100	24	120	24
Herculoy No. 419	97.75	0.25	...	...	...	2.0	...	...	...	...	...	...	100	45	110	45	95	22	97	22
Herculoy No. 420	96.0	...	...	...	1.0	3.0	...	...	...	...	...	...	110	60	125	60	100	24	120	24
Herculoy No. 421	98.0	...	...	...	0.25	1.75	...	...	...	...	...	...	100	45	110	45	95	22	97	22
P-M-G No. 3	98.2	...	...	...	...	1.20	...	...	0.60	...	...	...	75	40	75	40	40	15	40	15
P-M-G No. 10	95.6	...	...	...	...	3.20	...	...	1.20	...	...	...	95	60	110	60	60	24	65	30
P-M-G No. 95	96.6	...	...	0.40	...	2.50	...	...	0.50	...	...	...	....	...	90	55	....	...	55	25
P-M-G No. 96	97.0	...	...	...	...	2.50	...	...	0.50	...	...	...	90	55	90	55	-55	20	55	20
Other Alloys																				
Arsenical Bronze	56.5	...	...	0.70	...	...	2.0	39.0	1.20	...	...	0.60	....	...	87	65	....	...	....	...
Beryllium Copper	97.4	...	...	...	...	...	0.35	...	Tr.	...	2.25	...	118	70	....	...	90	30	....	...
Beryllium Copper (Precipitation Hardened)	97.4	...	...	...	...	...	0.35	...	Tr.	...	2.25	...	190	175	....	...	97	95	....	...
Manganese Bronze	59.0	0.70	...	...	0.50	...	...	39.0	0.80	...	...	...	90	60	85	60	....	25	60	25

Note: All of the values shown are subject to manufacturing limitations. These data should not be used in the preparation of specifications. — Note (*): For some alloys the values given are for a temper slightly different from that commonly known as hard (Rolled about 4 B. & S. gage numbers hard for sheet stock) — Note (‡): Yield strength taken as the load producing an extension under stress of 0.50 per cent.

(*American Machinist*, August 23, 1939)

Specifications for Beryllium-Copper Alloy Rods, Bars, Sheet, Strip, and Wire

A.S.T.M. Designation: B 120 - 41 T

ISSUED, 1939; REVISED, 1940, 1941.

MECHANICAL TEST REQUIREMENTS OF COLD-ROLLED SHEET AND STRIP

Condition	Tensile Strength, psi.	Yield Strength,* min., psi.	Elongation in 2 in., min., per cent	Rockwell Hardness (Note)	
				B Scale	Superficial 30-T Scale
CONDITIONS COMMERCIALLY AVAILABLE					
A	80 000 max.	——	35.0	80 max.	68 max.
¼ H	73 000 min.	——	10.0	72 min.	62 min.
½ H	80 000 min.	——	5.0	82 min.	69 min.
H	95 000 min.	——	2.0	93 min.	77 min.

MECHANICAL PROPERTIES WHEN PRECIPITATION HARDENED

Condition	Tensile Strength, psi.	Yield Strength,* min., psi.	Elongation in 2 in., min., per cent	Rockwell Hardness, min. (Note)			
				C Scale	A Scale	Superficial 30-N Scale	Superficial 15-N Scale
AT	150 000 min.	90 000	5.0	33	67	53	77
¼ HT	160 000 min.	92 000	3.5	35	68	55	78
½ HT	170 000 min.	93 000	2.0	37	69	57	79
HT	180 000 min.	95 000	1.0	39	70	59	80

*The yield strength shall be determined as the stress producing an elongation under load of 0.5 per cent, that is, 0.01 in. in a gage length of 2 in.

NOTE—The minimum thickness of material that may be tested in the case of the above Rockwell hardness scales is as follows:

	Thickness, in.
B Scale	0.040 and over
Superficial 30-T Scale	0.010 and over
C Scale	0.050 and over
A Scale	0.020 to 0.050
Superficial 30-N Scale	and over
Superficial 15-N Scale	0.010 to 0.020

MECHANICAL TEST REQUIREMENTS OF RODS AND BARS

Condition	Diameter or Thickness, in.	Tensile Strength, psi.	Yield Strength, min., psi.	Elongation in 2 in., min., per cent	Rockell Hardness	
					B Scale	Superficial 30-T Scale
CONDITIONS COMMERCIALLY AVAILABLE						
A	All sizes	80 000 max.	—	35.0	80 max.	68 max.
H	¼ to ¾	95 000 min.	—	10.0	90 min.	74 min.
	Over ¾	80 000 min.	—	10.0	80 min.	68 min.
MECHANICAL PROPERTIES WHEN PRECIPITATION HARDENED						
					C Scale	Superficial 30-N Scale
AT	All sizes	150 000 min.	85 000	3.0	33 min.	53 min.
HT	All sizes	175 000 min.	88 000	2.0	38 min.	57 min.

*The yield strength shall be determined as the stress producing an elongation under load of 0.5 per cent, that is, 0.01 in. in a gage length of 2 in.

MECHANICAL TEST REQUIREMENTS OF WIRE

Condition	Tensile Strength, psi.	Elongation in 2 in., min., per cent
CONDITIONS COMMERCIALLY AVAILABLE		
A	80 000 max.	35.0
¼ H	90 000 min.	5.0
½ H	100 000 min.	2.0
MECHANICAL PROPERTIES WHEN PRECIPITATION HARDENED		
AT	150 000 min.	1.5
¼ HT	165 000 min.	1.0
½ HT	180 000 min.	0.5

(Courtesy *American Society for Testing Materials*)

Physical Properties of Copper

Name	Density Lbs. per Cu Inch	Melting Point Deg. F	Coefficient of Thermal Expansion Average 25° C to 300°C X 10^{-6}	Electrical Conductivity % I A C S (Annealed)	Thermal Conductivity Cal./sq. cm./cm., Sec./deg. C at 20 deg. C
Electrolytic Tough Pitch Copper	0.323	1980	17 7	101	0.94
Oxygen-Free Copper	0.323	1980	17 7	101	0.94
High Conductivity Phosphorized Copper	0.323	1980	17 7	101	0.94
Low Conductivity Phosphorized Copper	0.323	1980	17 7	80-90	0.77-0.85
Arsenical Copper	0.323	1980	17.7	45-80	0.46-0 73

NOTE: The above figures are typical and are not to be used for minimum specification requirements Variations must be expected in practice

Hardness and Tensile Properties of all the Types of Copper

Temper	Rockwell Hardness		Tensile Strength p.s.i.	Yield Strength at½% elongation under stress p.s.i.	Elongation in 2" per cent	Shear Strength p.s.i.
	F	B				
0.040" Sheet — 0.015 mm Anneal	45	..	35,000	10,000	45	24,000
0.040" Sheet — 0.030 mm Anneal	40	..	32,000	10,000	45	22,000
0.040" Sheet — Hard	90	50	50,000	45,000	6	28,000
0.040" Sheet — Spring	94	60	55,000	50,000	4	29,000
1" x 0.049" Tube — 0.030 mm Anneal	40	..	32,000	10,000	45	22,000
1" x 0.049" Tube — Hard	90	.	50,000	45,000	12	28,000
No. 12 B&S Wire (0.081") 0.030 mm Anneal	.	..	32,000	10,000	45	24,000
No. 12 B&S Wire — Hard	.	..	60,000	55,000	8	30,000
1" Rod — Hard		45	40,000	33,000	30	22,000

NOTE: The above figures are typical and are not to be used for minimum specification requirements. Variations must be expected in practice.

(Courtesy *Chase Brass & Copper Co.*)

Composition and Properties of Zinc Alloys for Die Casting

DESIGNATION	ASTM SAE The New Jersey Zinc Company	XXI 921 Zamak-2	XXIII 903 Zamak-3	XXV 925 Zamak-5
COMPOSITION* % BY WEIGHT	Copper	2.5 to 3.5	.10 max.	.75 to 1.25
	Aluminum	3.5 to 4.5	3.5 to 4.3	3.5 to 4.3
	Magnesium	.02 to .10	.03 to .08	.03 to .08
	Iron max.	.100	.100	.100
	Lead max.	.007	.007	.007
	Cadmium max.	.005	.005	.005
	Tin max.	.005	.005	.005
	Zinc (99.99+% purity)	Remainder	Remainder	Remainder
MECHANICAL† PROPERTIES	Charpy Impact Strength, ft.lb., 1/4x1/4-in. bar, as cast	35	43	48
	Charpy Impact Strength, ft.lb., 1/4x1/4-in. bar, after 7 yrs. indoor aging	7	41	42
	Tensile Strength psi as cast	52,100	41,000	47,600
	Tensile Strength psi after 7 years indoor aging	48,100	33,800	38,300
	Elongation % in 2 in. as cast	8	10	7
	Elongation % in 2 in. after 7 years indoor aging	5	16	15
	Expansion (growth) inches per inch after 7 years indoor aging	.0055	.0006	.0004
OTHER PROPERTIES† AND CONSTANTS (AS CAST)	Brinell Hardness	100	82	91
	Compression Strength—Lb./Sq. In.	93,000	60,000	87,000
	Electrical Conductivity—Mhos./cm. cube at 20°C.	146,000	157,000	153,000
	Melting Point—°C.	379.5	380.9	380.6
	Melting Point—°F.	715.1	717.6	717.1
	Modulus of Rupture—Lb./Sq. In.	116,000	95,000	105,000
	Shearing Strength—Lb./Sq. In.	46,000	31,000	38,000
	Solidification Point—°C.	379.3	380.6	380.4
	Solidification Point—°F.	714.7	717.1	716.7
	Solidification Shrinkage—Inch/Foot	.15	.14	.14
	Specific Gravity	6.7	6.6	6.7
	Specific Heat—cal./gm./°C.	.10	.10	.10
	Thermal Conductivity—cal./Sec./sq. cm./cm./°C. at 18°C.	.25	.27	.26
	Thermal Expansion per °C.	.0000277	.0000274	.0000274
	Thermal Expansion per °F.	.0000154	.0000152	.0000152
	Transverse Deflection—In.	.22	.27	.16
	Weight (Lb.)/Cubic Inch	.24	.24	.24

*Composition as provided in ASTM and SAE specifications. The Zamak alloys meet these specifications but are held within closer tolerances.

†Properties and constants are as determined on Zamak alloys by The New Jersey Zinc Company. Values for impact strength, tensile strength and elongation, as cast, are well above the minimum ASTM and SAE requirements.

High-Permeability Materials

MATERIAL	FORM	APPROXIMATE PER CENT COMPOSITION					TYPICAL HEAT TREATMENT (°C.)
		FE	NI	CO	MO	OTHER	
Cold rolled steel	Sheet	98.5	—	—	—	—	950 Anneal
Iron	Sheet	99.91	—	—	—	—	950 Anneal
Purified iron	Sheet	99.95	—	—	—	—	1480 H_2 + 880
4% Silicon-iron	Sheet	96	—	—	—	4 Si	800 Anneal
Grain oriented*	Sheet	97	—	—	—	3 Si	800 Anneal
45 Permalloy	Sheet	54.7	45	—	—	0.3 Mn	1050 Anneal
45 Permalloy†	Sheet	54.7	45	—	—	0.3 Mn	1200 H_2 Anneal
Hipernik	Sheet	50	50	—	—	—	1200 H_2 Anneal
Monimax	Sheet	—	—	—	—	—	1125 H_2 Anneal
Sinimax	Sheet	—	—	—	—	—	1125 H_2 Anneal
78 Permalloy	Sheet	21.2	78.5	—	—	0.3 Mn	1050 + 600 Q**
4-79 Permalloy	Sheet	16.7	79	—	4	0.3 Mn	1100 + Q
Mu metal	Sheet	18	75	—	—	2 Cr, 5 Cu	1175 H_2
Supermalloy	Sheet	15.7	79	—	5	0.3 Mn	1300 H_2 + Q
Permendur	Sheet	49.7	—	50	—	0.3 Mn	800 Anneal
2V Permendur	Sheet	49	—	49	—	2 V	800 Anneal
Hiperco	Sheet	64	—	34	—	Cr	850 Anneal
2-81 Permalloy	Insulated powder	17	81	—	2	—	650 Anneal
Carbonyl iron	Insulated powder	99.9	—	—	—	—	— —
Ferroxcube III	Sintered powder		$MnFe_2O_4$ + $ZnFe_2O_4$				— —

*Properties in direction of rolling. †Similar properties for Nicaloi, 4750 alloy,

Permanent Magnet Alloys

MATERIAL	PER CENT COMPOSITION (REMAINDER FE)	HEAT TREATMENT* (TEMPERATURE, °C.)	MAGNETIZING FORCE $H_{max.}$ OERSTEDS
Carbon steel	1 Mn, 0.9 C	Q 800	300
Tungsten steel	5 W, 0.3 Mn, 0.7 C	Q 850	300
Chromium steel	3.5 Cr, 0.9 C, 0.3 Mn	Q 830	300
17% Cobalt steel	17 Co, 0.75 C, 2.5 Cr, 8 W	—	1,000
36% Cobalt steel	36 Co, 0.7 C, 4 Cr, 5 W	Q 950	1,000
Remalloy or Comol	17 Mo, 12 Co	Q 1200, B 700	1,000
Indalloy (sintered)	— Mo, — Co	— —	1,000
Alnico I	12 Al, 20 Ni, 5 Co	A 1200, B 700	2,000
Alnico II	10 Al, 17 Ni, 2.5 Co, 6 Cu	A 1200, B 600	2,000
Alnico II (sintered)	10 Al, 17 Ni, 2.5 Co, 6 Cu	A 1300	2,000
Alnico IV	12 Al, 28 Ni, 5 Co	Q 1200, B 650	3,000
Alnico V	8 Al, 14 Ni, 24 Co, 3 Cu	AF 1300, B 600	2,000
Alnico VI	8 Al, 15 Ni, 24 Co, 3 Cu, 1 Ti	— —	3,000
Alnico XII	6 Al, 18 Ni, 35 Co, 8 Ti	— —	3,000
Vicalloy I	52 Co, 10 V	B 600	1,000
Vicalloy II (wire)	52 Co, 14 V	CW + B 600	2,000
Cunife (wire)	60 Cu, 20 Ni	CW + B 600	2,400
Cunico	50 Cu, 21 Ni, 29 Co	— —	3,200
Vectolite	30 Fe_2O_3, 40 Fe_3O_4	— —	3,000
Silmanal	86.8 Ag, 8.8 Mn, 4.4 Al	— —	20,000
Platinum-cobalt	77 Pt, 23 Co	Q 1200, B 650	—
Hyflux	Fine powder	— —	2,000

(1) Value given is intrinsic H_c.

*Q - Quenched in oil or water. A - Air cooled. B - Baked. F - Cooled in magnetic field. CW - Cold worked.

†HR - Hot rolled or forged. drawn. M - Machined. G - P - Punched. C - Cast. Sn -

PERMEABILITY AT $B = 20$ GAUSSES	MAXIMUM PERMEABILITY	SATURATION FLUX DENSITY B_s GAUSSES	HYSTERESIS‡ LOSS, W_h ERGS PER CU.CM.	COERCIVE‡ FORCE H_c OERSTEDS	RESISTIVITY, MICROHM-CM.	DENSITY, G. PER CU.CM.
180	2,000	21,000	—	1.8	10	7.88
200	5,000	21,500	5,000	1.0	10	7.88
5,000	180,000	21,500	300	0.05	10	7.88
500	7,000	19,700	3,500	0.5	60	7.65
1,500	30,000	20,000	—	0.15	47	7.67
2,500	25,000	16,000	1,200	0.3	45	8.17
4,000	50,000	16,000	—	0.07	45	8.17
4,500	70,000	16,000	220	0.05	50	8.25
2,000	35,000	15,000	—	0.1	80	8.27
3,000	35,000	11,000	—	—	90	—
8,000	100,000	10,700	200	0.05	16	8.60
20,000	100,000	8,700	200	0.05	55	8.72
20,000	100,000	6,500	—	0.05	62	8.58
100,000	800,000	8,000	—	0.002	60	8.77
800	5,000	24,500	12,000	2.0	7	8.3
800	4,500	24,000	6,000	2.0	26	8.2
650	10,000	24,200	—	1.0	25	8.0
125	130	8,000	—	<1.0	10^6	7.8
55	132	—	—	—	—	7.86
1,000	1,500	2,500	—	0.1	10^8	5.0

Carpenter 49, Armco 48. ‡At saturation. **Q Quench or controlled cooling.

COERCIVE FORCE H_c OERSTEDS	RESIDUAL INDUCTION B_r GAUSSES	ENERGY PRODUCT $BH_{max.} \times 10^{-6}$	METHOD OF FABRICATION†	MECHANICAL PROPERTIES‡	WEIGHT, LB. PER CU. IN.
50	10,000	0.20	HR, M, P	H, S	0.280
70	10,300	0.32	HR, M, P	H, S	0.292
65	9,700	0.30	HR, M, P	H, S	0.280
150	9,500	0.65	HR, M, P	H, S	—
240	9,500	0.97	HR, M, P	H, S	0.296
250	10,500	1.1	HR, M, P	H	0.295
240	9,000	0.9	HR, M, P	H	0.290
440	7,200	1.4	C, G	H, B	0.249
550	7,200	1.6	C, G	H, B	0.256
520	6,900	1.4	Sn, G	H	0.249
700	5,500	1.3	Sn, C, G	H	0.253
550	12,500	4.5	C, G	H, B	0.264
750	10,000	3.5	C, G	H, B	0.268
950	5,800	1.5	C, G	H, B	0.26
300	8,800	1.0	C, CR, M, P	D	0.295
510	10,000	3.5	C, CR, M, P	D	0.292
550	5,400	1.5	C, CR, M, P	D, M	0.311
660	3,400	0.80	C, CR, M, P	D, M	0.300
1,000	1,600	0.60	Sn, G	W	0.113
6,000(1)	550	0.075	C, CR, M, P	D, M	0.325
2,600	4,500	3.8	C, CR, M	D	—
390	6,600	0.97	—	—	0.176

CR - Cold rolled or
Must be ground.
Sintered.

‡H - Hard. B - Brittle. S - Strong. D - Ductile.
M - Malleable. W - Weak.

Compiled by R. A. Chegwidden

(*Metal Progress Data Sheet,* November 1948)

Type	Filler	Colors	Applications	Ft. Lb. per In. Notch Impact	Flexural Psi.	Tensile Psi.	Water Absorption % 48 Hr.	Heat Resistance Continuous F	Dielectric Str., V. per Mil Step by Step Test in Oil ⅛-In. Spec.		Spec. Gravity	Shrinkage In. per In.	Bulk Factor
									25 C	100 C			
Phenolic	None	Amber green, ruby, turquoise, tortoise shell	Milking machine parts and sterilizable equipment also used for hard synthetic jewels	34-0.44	10,000-14,000	7,000-8,000	0.1	248	250-300	70-100	1.28	0.009-0.011	2.25
Phenolic	Wood-flour	All colors except pastels	General purpose molding applications	0.30-0.40	9,000-12,000	6,000-8,000	0.5-1.0	248	300-450	60-125	1.33-1.45	0.006-0.009	3
Phenolic	Wood-flour	Natural and black	General purpose high-dielectric applications	0.28	10,000	7,000-8,000	0.8-1.0	248	350-500	100-200	1.33-1.35	0.007-0.008	3
Phenolic	Wood-flour	Natural and black	Parts requiring good water resistance, minimum odor	0.30-0.35	9,000-11,000	5,000-7,000	0.5-0.8	248	250	50	1.40	0.008	3
Phenolic	Wood-flour, graphite	Gun metal	Bearings, cams, caster wheels, etc. requiring reduced friction	0.30	8,000-9,000	6,000	0.8-1.0	248	—	—	1.42	0.007-0.008	3
Phenolic	Asbestos, wood-flour	Most colors except pastels	Heater plugs and insulating pieces requiring good heat resistance	0.30	9,500-11,000	6,000	0.2-0.5	392	250-400	50-80	1.67-1.80	0.005	3
Phenolic	Short fibre asbestos	Black and brown	Parts requiring better heat resistance and for low power arc resistance	0.30	9,000-10,000	6,000	0.01-0.1	428	250-400	50-80	1.80-1.90	0.003-0.005	3
Phenolic	Long fibre asbestos	Black and brown	Best phenolic for heat resistance, low moisture absorption, low coefficient of expansion, maximum dimensional stability	0.36-0.40	9,000-9,500	5,000-6,000	0.01-0.1	428	250-400	50-80	1.80	0.003-0.004	3
Phenolic	Asbestos, graphite	Gun metal	Bearings, slides, valves, cams, etc requiring maximum heat-resistance, dimensional-stability good wear resistance	0.28	8,000-9,000	6,000	0.01-0.1	428	—	—	1.75	0.003-0.004	3
Phenolic	Asbestos	Natural and brown	High-heat and high impact applications	0.50	10,000	6,500	0.3	428	125	50	1.80-1.85	0.002-0.003	6
Phenolic	Asbestos	Natural and dark tan	High heat-low flame, high impact applications	3.40	10,000	6,200	0.8	392	70-100	50-70	1.60-1.70	0.003-0.004	5
Phenolic	Mica	Natural and black	Electrical applications requiring improved heat and low-moisture absorption	0.30	8,000	6,000	0.01-0.05	428	300-500	150-300	1.88-1.92	0.002-0.004	2.5
Phenolic	Cotton flock	Most dark colors	General purpose molding material with improved impact resistance	0.42-0.60	9,500-12,000	7,000-8,500	0.8-1.0	248	250-300	60-80	1.36-1.42	0.003-0.006	4
Phenolic	Cotton flock	Black	Combines good water resistance, minimum odor and improved-impact resistance	0.52	10,000	6,500	0.8-1.0	248	125	40-50	1.42	0.004-0.005	4
Phenolic	Fabric-short fibre	Natural, black, red, brown	Medium-high impact material with good flow for complex sections	1.00-1.80	10,000-12,000	6,000-6,500	1.0	248	200-250	50-80	1.38-1.42	0.003-0.004	5
Phenolic	Fabric-medium fibre	Black, brown, red	High-impact material used for bulky sections	3.00-3.50	10,000	6,000-6,500	1.0	248	200-250	50-80	1.38-1.42	0.003-0.004	8
Phenolic	Chopped cord	Black	Highest-impact phenolic material. Cannot be used for some complex sections	5.0	11,000	6,200	1.0	248	300	70	1.35	0.003	8

lastic Materials nd Uses

Type	Filler	Colors	Applications	Ft. Lb. per In. Notch Impact	Flexural Psi.	Tensile Psi.	Water Absorption % 48 Hr.	Heat Resistance Continuous F	Dielectric Str., V. per Mil Step by Step Test in Oil ⅛-In. Spec.		Spec. Gravity	Shrinkage In. per In.	Bulk Factor
									25 C	100 C			
Phenolic	Fabric, graphite	Gun metal	Cams, bearings, slides, etc. requiring high impact, reduced friction	0.70-0.80	8,000-9,000	6,000	0.8-1.0	248	—	—	1.45	0.003-0.004	4
Phenolic	Cotton flock and graphite	Gun metal	Cams, bearings, slides, etc. requiring medium-impact resistance, reduced friction	0.40	9,500	6,500	0.8-1.0	248	—	—	1.40	0.003-0.004	4
Phenolic	—	—	Used for the shielding of X-rays	0.30	9,500	6,000	0.5	248	—	—	—	0.005-0.006	3
Phenolic-Aniline	Wood-flour	Natural	Highest electrical properties with good arc resistance	0.30	10,000	6,000	1.25	248	300	300	1.34	0.006-0.008	3
Phenolic-Aniline	Mineral	Natural	Radio or similar parts requiring low dielectric losses. P.F. @ 1000 K.C. – 0.009	0.38	9,500	6,500	0.02	257	300-500	300-400	1.94	0.004	2.5
Phenolic-Aniline	Cotton flock	Natural	Highest electrical properties with improved-impact resistance	0.46	10,000	6,500	1.20	248	300	200-300	1.34	0.006-0.008	4
Urea	Cellulose	All colors including translucent and pastel shades	General purpose color work. Good arc resistance. Used for lamp shades, packages, radio cabinets, etc.	0.30	11,000	8,000	2.00	170	300	80	1.49	0.008	3
Melamine	Cellulose	All colors including translucent and pastel shades	General purpose color work with improved-temperature resistance. Good for dishes and buttons	0 28	12,000	6,000	1.7	210	230	250	1.50	0.008	3
Melamine	Mineral, cotton flock	Gray	Electrical applications requiring improved arc resistance. Excellent for ignition parts	0.44	8,000	5,000	0.25	284	300	200	1.80	0.006	2.5
Melamine	Fabric	Gray and black	Combines good impact resistance with improved-arc resistance	0.90	10,000	7,000	1.0	248	230	80	1.49	0.003-0.004	12
Cold Mold-Non-Refractory	—	Black and brown	Wiring device parts, cook-ware handles to withstand oven temperatures. Best cold mold for appearance	0.4	4,500	—	2.0	482	60	—	2.00	0 015	2.5
Cold Mold-Refractory	—	Gray	Arc deflectors, rheostat bases and other parts requiring maximum heat and arc resistance	0.6	5,000	—	0.05-15	1,292	60	—	2.20	Nil	2.5
Synthetic Hard Rubber	Mineral	Red	Electrical and ignition parts requiring good arc resistance and good dielectric at elevated temperatures	0.32	7,000	4,000	0.08	175	370	370	1.77	0.0195-0.0225	2
Mycalex	Mineral	Gray	Radio and other high frequency electrical applications requiring maximum heat and arc resistance. P.F. @ 1000 K.C. – 0.0023	—	10,000	—	0.0023	662	—	380	3.11	Nil	–
Mycalex	Mineral	Gray	General purpose electrical applications requiring low moisture absorption, high temperature and arc resistance. P.F. @ 1000 K.C. – 0.0018	—	12,000	—	0.001	482	—	325	3.70	Nil	—

* *Shrinkage. Molding materials shrink after they are molded. The values listed in the table give the amount of this shrinkage in in. per in. under average conditions. Allowance must be made in the mold design to compensate for this shrinkage.*

† *Bulk Factor. Mold designs must allow sufficient space for loading the molding compound. The ratio of the volume of compound before molding to the volume of the molded piece is called the bulk factor.*

Prepared from data submitted by the Shaw Insulator Co., Irvington, N. J.
(Courtesy *Materials & Methods,* December 1947, Engineering File Facts No. 153)

Properties of

	Type of Brick	Composition	P.C.E. or Fusion Point	True Specific Gravity	Approx. Weight in lbs. 9" Brick	Linear Coefficient of Expansion per °C
ACID	**Silica**	SiO_2 95–96%	31–33 Cone	2.3–2.4	6	See (A) Below
	High Heat Duty Fire Brick	Al_2O_3 35–42% SiO_2 52–60%	31–33 Cone	2.60–2.70	7½-8	53×10^{-7} 20 – 1200°C
	Super Duty Fire Brick	Al_2O_3 43–44% SiO_2 51–53%	33–34 Cone	2.65–2.75	7½–8	53×10^{-7} 20 – 1200°C
	High Alumina Fire Brick	Al_2O_3 50–80%	34–39 Cone	2.80–3.40	8–9	$53 - 65 \times 10^{-7}$ 20 – 1425°C
	Kaolin	Al_2O_3 44–45% SiO_2 51–53%	31–34 Cone	2.60	7½–8	53×10^{-7} 20 – 1425°C
	Mullite	Al_2O_3 62% SiO_2 38%	38 Cone	3.03	8½	45×10^{-7} 20 – 1320°C
	Zircon	ZrO_2 67.1% SiO_2 32.9%	approx. 4400°F	4.6	12	42×10^{-7} 20 – 1550°C
	Silicon Carbide	SiC 89–91%	dissoc. @4082°F	3.13–3.22	9.5	45×10^{-7} 20 – 1100°C
NEUTRAL	**Graphite**	C 100%	above 5432°F	2.25	8	20×10^{-7} 20 – 1000°C
	Chrome	Cr_2O_3 30–45% Al_2O_3 15–33% SiO_2 11–17% FeO 3–6%	3550–4000°F	3.8–4.1	11	80×10^{-7} 20 – 1000°C
	Fused Alumina	Al_2O_3 90–99.1%	38–41 Cone	3.80–4.00	11	70×10^{-7} 20 – 1000°C
BASIC	**Forsterite**	MgO 57.3% SiO_2 42.7%	40 Cone	3.3–3.4	9	110×10^{-7} 20 – 1500°C
	Magnesia-Alumina Spinel	MgO 28.2% Al_2O_3 71.8%	3875°F	3.6	10	80×10^{-7} 20 – 800°C
	Magnesite (Dead Burned)	MgO 83–93% Fe_2O_3 2–7%	3992°F	3.4–3.6	9½	147×10^{-7} 20 – 1425°C
	Magnesia (Electrically fused)	MgO 94–96% SiO_2 2–3% CaO 1–2%	3992–4532°F	3.60	10	150×10^{-7} 20 – 1475°C

* To change BTU units to C.G.S. units divide by 2903

(A) 430×10^{-7}, 20–300°C, 30×10^{-7}, *Refractories*

Thermal Conductivity BTU/Hr./Sq.Ft./In./°F.*	Mean Specific Heat (cgs)	Deformation Under Load 25#/sq. in.	Constancy of Volume	Remarks
13.0 390–1832°F	0.265 70–1832°F	No deformation at 2732°F, 50psi	Low Shrinkage. Rev.† exp. to Melting Point	Strongly resistant to acid slags. Readily attacked by basic materials and fluorides.
400–2400°F 9.5	0.26 70°–1830°F	4.0+% @ 2460°F	2.0% Shrink. @ 2550°F	Rapidly attacked by basic slags, particularly iron slags. Moderately resistant to acid slags.
Approx. same as High Heat Duty	Approx. same as High Heat Duty	2.5 to 4.0% @ 2460°F	1% Max. Shrink. at 2732°F	
Slightly more than High Heat Duty	Approx. same as High Heat Duty	Approx. same as Super Duty	0–3% Shrink. @ 2912°F	More resistant to alkali slags than fire clay brick; readily attacked by iron slags.
13.5 @2400°F	0.254 480–1832°F	1% @ 2800°F	0.5% Shrinkage @ 3000°F	Slightly more resistant than fire brick to slags, particularly basic slags.
8.5 200–2600°F	0.175 70°–1475°F	0 @ 2650°F., 50 psi: 2.0% @ 3000°F, 50 psi	No appreciable change to 3000°F	Low solubility in glasses and some slags. Attacked by high iron slags.
13.5 390°–1832°F	0.132 100°F	Fails @ 2820°–2910°F	No appreciable change to 2820°F	Not readily attacked by acid slags. Readily attacked by basic slags and fluorides.
66.0 @2000°F	0.186 70–1832°F	No deformation to 2732°F, 50 psi	No Shrinkage to 2732°F	Readily attacked by strongly basic slags, particularly those high in iron or calcium oxides.
220. @ 2000°F	0.29 70–1832°F	None	No Shrinkage	Strongly resistant to all slags except those containing oxides readily reduced.
12.1 @2400°F	0.22 @ 1832°F	No deformation @ 2600°F	1.3% Shrinkage at 2820°F	Neutral properties. Not readily attacked by acid or basic slags.
18.0–20.0 @ 2000°F	0.174–0.304 32°–1832°F	1–2% @ 2732°F, 50 psi	No Shrinkage at 2732°F	Very resistant to acid slags, moderately resistant to basic slags; tendency to absorb.
10.3 @ 2400°F	0.22 70–200°F	No deformation to 2732°F, 50 psi	Negligible Shrinkage to 3000°F	Not readily attacked by basic slags; readily attacked by acid slags.
14.5 @ 2400°F	0.25 70–1832°F			Moderate resistance to basic slags; low resistance to acid slags. Magnesia spinel sometimes shows slag absorption.
13. 2400°F	0.278 70–1832°F	Poor load bearing property above 2450°F	No Shrinkage below 2900°F	Not readily attacked by basic slags; readily attacked by acid slags.
20.0 2000°F	0.292 32–2375°F	Poor load bearing property above 2732°F	Less than 1% below 3250°F	

† Reversible

300–1100° C.

(Courtesy *American Foundryman,* May 1947)

Temperature Conversions

Albert Sauveur type of table. Look up reading in middle column; if in degrees Centigrade, read Fahrenheit equivalent in right hand column; if in degrees Fahrenheit, read Centigrade equivalent in left hand column. Values as printed in "Bethlehem Alloy Steels."

−459.4 to 0			0 to 100						100 to 1000						1000 to 2000						2000 to 3000					
C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F	C		F
−273	*−459.4*		−17.8	*0*	32	10.0	*50*	122.0	38	*100*	212	260	*500*	932	538	*1000*	1832	816	*1500*	2732	1093	*2000*	3632	1371	*2500*	4532
−268	*−450*		−17.2	*1*	33.8	10.6	*51*	123.8	43	*110*	230	266	*510*	950	543	*1010*	1850	821	*1510*	2750	1099	*2010*	3650	1377	*2510*	4550
−262	*−440*		−16.7	*2*	35.6	11.1	*52*	125.6	49	*120*	248	271	*520*	968	549	*1020*	1868	827	*1520*	2768	1104	*2020*	3668	1382	*2520*	4568
−257	*−430*		−16.1	*3*	37.4	11.7	*53*	127.4	54	*130*	266	277	*530*	986	554	*1030*	1886	832	*1530*	2786	1110	*2030*	3686	1388	*2530*	4586
−251	*−420*		−15.6	*4*	39.2	12.2	*54*	129.2	60	*140*	284	282	*540*	1004	560	*1040*	1904	838	*1540*	2804	1116	*2040*	3704	1393	*2540*	4604
−246	*−410*		−15.0	*5*	41.0	12.8	*55*	131.0	66	*150*	302	288	*550*	1022	566	*1050*	1922	843	*1550*	2822	1121	*2050*	3722	1399	*2550*	4622
−240	*−400*		−14.4	*6*	42.8	13.3	*56*	132.8	71	*160*	320	293	*560*	1040	571	*1060*	1940	849	*1560*	2840	1127	*2060*	3740	1404	*2560*	4640
−234	*−390*		−13.9	*7*	44.6	13.9	*57*	134.6	77	*170*	338	299	*570*	1058	577	*1070*	1958	854	*1570*	2858	1132	*2070*	3758	1410	*2570*	4658
−229	*−380*		−13.3	*8*	46.4	14.4	*58*	136.4	82	*180*	356	304	*580*	1076	582	*1080*	1976	860	*1580*	2876	1138	*2080*	3776	1416	*2580*	4676
−223	*−370*		−12.8	*9*	48.2	15.0	*59*	138.2	88	*190*	374	310	*590*	1094	588	*1090*	1994	866	*1590*	2894	1143	*2090*	3794	1421	*2590*	4694
−218	*−360*		−12.2	*10*	50.0	15.6	*60*	140.0	93	*200*	392	316	*600*	1112	593	*1100*	2012	871	*1600*	2912	1149	*2100*	3812	1427	*2600*	4712
−212	*−350*		−11.7	*11*	51.8	16.1	*61*	141.8	99	*210*	410	321	*610*	1130	599	*1110*	2030	877	*1610*	2930	1154	*2110*	3830	1432	*2610*	4730
−207	*−340*		−11.1	*12*	53.6	16.7	*62*	143.6	100	*212*	413.6	327	*620*	1148	604	*1120*	2048	882	*1620*	2948	1160	*2120*	3848	1438	*2620*	4748
−201	*−330*		−10.6	*13*	55.4	17.2	*63*	145.4	104	*220*	428	332	*630*	1166	610	*1130*	2066	888	*1630*	2966	1166	*2130*	3866	1443	*2630*	4766
−196	*−320*		−10.0	*14*	57.2	17.8	*64*	147.2	110	*230*	446	338	*640*	1184	616	*1140*	2084	893	*1640*	2984	1171	*2140*	3884	1449	*2640*	4784
−190	*−310*		− 9.4	*15*	59.0	18.3	*65*	149.0	116	*240*	464	343	*650*	1202	621	*1150*	2102	899	*1650*	3002	1177	*2150*	3902	1454	*2650*	4802
−184	*−300*		− 8.9	*16*	60.8	18.9	*66*	150.8	121	*250*	482	349	*660*	1220	627	*1160*	2120	904	*1660*	3020	1182	*2160*	3920	1460	*2660*	4820
−179	*−290*		− 8.3	*17*	62.6	19.4	*67*	152.6	127	*260*	500	354	*670*	1238	632	*1170*	2138	910	*1670*	3038	1188	*2170*	3938	1466	*2670*	4838
−173	*−280*		− 7.8	*18*	64.4	20.0	*68*	154.4	132	*270*	518	360	*680*	1256	638	*1180*	2156	916	*1680*	3056	1193	*2180*	3956	1471	*2680*	4856
−169	*−273*	−459.4	− 7.2	*19*	66.2	20.6	*69*	156.2	138	*280*	536	366	*690*	1274	643	*1190*	2174	921	*1690*	3074	1199	*2190*	3974	1477	*2690*	4874
−168	*−270*	−454	− 6.7	*20*	68.0	21.1	*70*	158.0	143	*290*	554	371	*700*	1292	649	*1200*	2192	927	*1700*	3092	1204	*2200*	3992	1482	*2700*	4892
−162	*−260*	−436	− 6.1	*21*	69.8	21.7	*71*	159.8	149	*300*	572	377	*710*	1310	654	*1210*	2210	932	*1710*	3110	1210	*2210*	4010	1488	*2710*	4910
−157	*−250*	−418	− 5.6	*22*	71.6	22.2	*72*	161.6	154	*310*	590	382	*720*	1328	660	*1220*	2228	938	*1720*	3128	1216	*2220*	4028	1493	*2720*	4928
−151	*−240*	−400	− 5.0	*23*	73.4	22.8	*73*	163.4	160	*320*	608	388	*730*	1346	666	*1230*	2246	943	*1730*	3146	1221	*2230*	4046	1499	*2730*	4946
−146	*−230*	−382	− 4.4	*24*	75.2	23.3	*74*	165.2	166	*330*	626	393	*740*	1364	671	*1240*	2264	949	*1740*	3164	1227	*2240*	4064	1504	*2740*	4964
−140	*−220*	−364	− 3.9	*25*	77.0	23.9	*75*	167.0	171	*340*	644	399	*750*	1382	677	*1250*	2282	954	*1750*	3182	1232	*2250*	4082	1510	*2750*	4982
−134	*−210*	−346	− 3.3	*26*	78.8	24.4	*76*	168.8	177	*350*	662	404	*760*	1400	682	*1260*	2300	960	*1760*	3200	1238	*2260*	4100	1516	*2760*	5000
−129	*−200*	−328	− 2.8	*27*	80.6	25.0	*77*	170.6	182	*360*	680	410	*770*	1418	688	*1270*	2318	966	*1770*	3218	1243	*2270*	4118	1521	*2770*	5018
−123	*−190*	−310	− 2.2	*28*	82.4	25.6	*78*	172.4	188	*370*	698	416	*780*	1436	693	*1280*	2336	971	*1780*	3236	1249	*2280*	4136	1527	*2780*	5036
−118	*−180*	−292	− 1.7	*29*	84.2	26.1	*79*	174.2	193	*380*	716	421	*790*	1454	699	*1290*	2354	977	*1790*	3254	1254	*2290*	4154	1532	*2790*	5054
−112	*−170*	−274	− 1.1	*30*	86.0	26.7	*80*	176.0	199	*390*	734	427	*800*	1472	704	*1300*	2372	982	*1800*	3272	1260	*2300*	4172	1538	*2800*	5072
−107	*−160*	−256	− 0.6	*31*	87.8	27.2	*81*	177.8	204	*400*	752	432	*810*	1490	710	*1310*	2390	988	*1810*	3290	1266	*2310*	4190	1543	*2810*	5090
−101	*−150*	−238	0.0	*32*	89.6	27.8	*82*	179.6	210	*410*	770	438	*820*	1508	716	*1320*	2408	993	*1820*	3308	1271	*2320*	4208	1549	*2820*	5108
− 96	*−140*	−220	0.6	*33*	91.4	28.3	*83*	181.4	216	*420*	788	443	*830*	1526	721	*1330*	2426	999	*1830*	3326	1277	*2330*	4226	1554	*2830*	5126
− 90	*−130*	−202	1.1	*34*	93.2	28.9	*84*	183.2	221	*430*	806	449	*840*	1544	727	*1340*	2444	1004	*1840*	3344	1282	*2340*	4244	1560	*2840*	5144
− 84	*−120*	−184	1.7	*35*	95.0	29.4	*85*	185.0	227	*440*	824	454	*850*	1562	732	*1350*	2462	1010	*1850*	3362	1288	*2350*	4262	1566	*2850*	5162
− 79	*−110*	−166	2.2	*36*	96.8	30.0	*86*	186.8	232	*450*	842	460	*860*	1580	738	*1360*	2480	1016	*1860*	3380	1293	*2360*	4280	1571	*2860*	5180
− 73	*−100*	−148	2.8	*37*	98.6	30.6	*87*	188.6	238	*460*	860	466	*870*	1598	743	*1370*	2498	1021	*1870*	3398	1299	*2370*	4298	1577	*2870*	5198
− 68	*− 90*	−130	3.3	*38*	100.4	31.1	*88*	190.4	243	*470*	878	471	*880*	1616	749	*1380*	2516	1027	*1880*	3416	1304	*2380*	4316	1582	*2880*	5216
− 62	*− 80*	−112	3.9	*39*	102.2	31.7	*89*	192.2	249	*480*	896	477	*890*	1634	754	*1390*	2534	1032	*1890*	3434	1310	*2390*	4334	1588	*2890*	5234
− 57	*− 70*	− 94	4.4	*40*	104.0	32.2	*90*	194.0	254	*490*	914	482	*900*	1652	760	*1400*	2552	1038	*1900*	3452	1316	*2400*	4352	1593	*2900*	5252
− 51	*− 60*	− 76	5.0	*41*	105.8	32.8	*91*	195.8				488	*910*	1670	766	*1410*	2570	1043	*1910*	3470	1321	*2410*	4370	1599	*2910*	5270
− 46	*− 50*	− 58	5.6	*42*	107.6	33.3	*92*	197.6				493	*920*	1688	771	*1420*	2588	1049	*1920*	3488	1327	*2420*	4388	1604	*2920*	5288
− 40	*− 40*	− 40	6.1	*43*	109.4	33.9	*93*	199.4				499	*930*	1706	777	*1430*	2606	1054	*1930*	3506	1332	*2430*	4406	1610	*2930*	5306
− 34	*− 30*	− 22	6.7	*44*	111.2	34.4	*94*	201.2				504	*940*	1724	782	*1440*	2624	1060	*1940*	3524	1338	*2440*	4424	1616	*2940*	5324
− 29	*− 20*	− 4	7.2	*45*	113.0	35.0	*95*	203.0				510	*950*	1742	788	*1450*	2642	1066	*1950*	3542	1343	*2450*	4442	1621	*2950*	5342
− 23	*− 10*	14	7.8	*46*	114.8	35.6	*96*	204.8				516	*960*	1760	793	*1460*	2660	1071	*1960*	3560	1349	*2460*	4460	1627	*2960*	5360
− 17.8	*0*	32	8.3	*47*	116.6	36.1	*97*	206.6				521	*970*	1778	799	*1470*	2678	1077	*1970*	3578	1354	*2470*	4478	1632	*2970*	5378
			8.9	*48*	118.4	36.7	*98*	208.4				527	*980*	1796	804	*1480*	2696	1082	*1980*	3596	1360	*2480*	4496	1638	*2980*	5396
			9.4	*49*	120.2	37.2	*99*	210.2				532	*990*	1814	810	*1490*	2714	1088	*1990*	3614	1366	*2490*	4514	1643	*2990*	5414
						37.8	*100*	212.0				538	*1000*	1832				1093	*2000*	3632				1649	*3000*	5432

Approximate Critical Temperatures for S.A.E. Steels by M. J. R. Morris, R. Sergeson and G. W. Gable; Central Alloy Division, Republic Steel Corp.

In most instances found by examining microstructure of quenched ⅝-in. discs of 1-in. round, taken from furnace at 20°F. increments. Grain size of steel unknown. Rate of heating and cooling about same as in furnace-cooling for commercial annealing.

Number	On Slow Heating			On Slow Cooling		
	Ac_1	Ac_2	Ac_3	Ar_3	Ar_2	Ar_1
	Carbon Steels					
1010	1350	1405	1605	1570	1400	1255
1015	1355	1410	1585	1545	1395	1265
X1015						
1020	1355	1410	1570	1535	1395	1260
X1020						
1025	1355	1405	1545	1515	1405	1255
X1025						
1030	1350	1405	1495	1465	1405	1250
1035	1345		1475	1455	1395	1275
1040	1340		1455	1415		1275
X1040	1340		1450	1340		1270
1045	1340		1450	1405		1275
X1045	1335		1420	1330		1270
1050	1340		1425	1390		1275
X1050	1335		1400	1330		1270
1055	1340		1425	1390		1275
X1055	1335		1400	1330		1270
1060	1340		1410	1370		1275
1065	1340		1385	1345		1285
X1065	1335		1380	1330		1280
1070	1345		1370	1340		1280
1075	1350		1365	1340		1280
1080			1360	1285		
1085						
1090			1360	1285		
1095			1360	1290		
10150*			1355	1290		
	Free Cutting Steels					
1112	1355	1410	1590	1545	1395	1265
X1112						
1115						
1120	1355	1405	1550	1510	1400	1255
X1314						
X1315	1345	1420	1520	1495	1370	1245
X1330						
X1335						
X1340						
	Manganese Steels					
T1330	1325		1480	1340		1160
T1335	1315		1460	1340		1165
T1340	1315		1435	1310		1160
T1345	1315		1410	1300		1160
T1350	1310		1400	1255		1105
T1360*	1305		1405	1200		1095
	Nickel Steels					
2015	1375	1475	1575	1450	1400	1215
2115	1345	1455	1525	1475	1380	1195
2315	1300	1350	1440	1350	1260	1100
2320	1285	1345	1420	1235	1160	920
2330	1275	1315	1400	1180		1050
2335	1275		1375	1180		1050
2340	1280		1360	1180		1060
2345	1280		1350	1180		1060
2350	1280		1340	1180		1070
2515	1250	1335	1420	1220	1140	825
2520*	1240	1340	1390	1175	1025	825

*This number not in the official S. A. E. list

Number	On Slow Heating			On Slow Cooling		
	Ac_1	Ac_2	Ac_3	Ar_3	Ar_2	Ar_1
	Nickel-Chromium Steels					
3115	1355	1400	1500	1470	1380	1240
3120	1350	1400	1480	1455	1380	1230
3125	1350	1395	1465	1400	1380	1220
3130	1345	1380	1460	1360		1220
3135	1340		1445	1300		1220
3140	1355		1415	1295		1220
X3140	1350		1430	1300		1240
3145	1355		1395	1295		1220
3150	1355		1380	1275		1215
3215	1350	1410	1465	1415	1350	1240
3220	1350	1415	1460	1405	1355	1240
3230	1340		1435	1395		1240
3240	1335		1425	1280		1240
3245	1345		1400	1270		1225
3250	1340		1375	1255		1200
3312	1330	1370	1435	1240		1160
3325	1335	1365	1400	1230		1160
3330*	1320	1360	1380	1225		1145
3335	1310		1360	1200		1100
3340	1290		1380	1180		1100
3415	1330	1370	1425	1340	1300	1220
3435	1290		1380	1200		1150
3450	1290		1360	1200		1100
	Molybdenum Steels					
4130	1395	1435	1485	1405	1395	1280
X4130	1395	1435	1480	1405		1250
4135	1395	1440	1475	1380	1360	1280
4140	1380		1460	1370		1280
4150	1365		1395	1355		1280
4340	1350		1425	875		725
4345	1345		1415	875		725
4615	1335	1400	1485	1400	1320	1200
4620	1335		1470	1390		1175
4640	1320		1430	1300		1125
4650*	1315		1410	1260		1125
4815	1300		1440	1310		800
4820	1300		1440	1260		760
	Chromium Steels					
5120	1410	1460	1540	1470	1420	1295
5140	1370		1440	1345		1280
5150	1330		1420	1280		1220
52100	1340		1415	1315		1280
	Chromium-Vanadium Steels					
6115	1420	1460	1550	1450	1380	1300
6120	1410	1460	1545	1440	1380	1300
6125	1400	1440	1490	1390	1360	1295
6130	1390	1440	1485	1370	1340	1285
6135	1390		1480	1370		1280
6140	1390		1455	1375		1295
6145	1390		1450	1375		1290
6150	1385		1450	1375		1270
6195	1370		1425	1360		1300
	Tungsten Steels					
7260	1360		1430	1370		1310
	Silicon-Manganese Steels					
9255	1400		1500	1380		1320
9260	1400		1500	1380		1315

(Courtesy *Metal Progress*)

Properties of Soft Solders

Composition per cent					Liquidus (° C.)	Solidus (° C.)	Tensile strength (psi)	Bond strength of lapped joints (psi)	Spread of ½ gr. in sq. in.	Creep rate in per cent per year at 30 deg. C.			
Pb	Sn	Ag	Bi	Sb						200 (psi)	400 (psi)	600 (psi)	800 (psi)
60	40				238	183	5,660	6,270	1.30	10.9	92.0	300	
97.5		2.5			304	304	4,980	3,740	0.19	0.10	0.15		0.50
95		5.0			375	304	4,915	4,340	0.20	0.18	0.22		0.45
90	10				298	183	4,850	4,960	0.27	2.5	12.0		
87.75	10	2.25			290*		4,950	5,000	0.41		2.3	8.0	
80	20				275	183	4,940	5,680	0.37	6.7	18.7		
78	20	2.0			267*		5,620	5,550	0.57				
70	30				257	183	5,390	5,770	0.83	10.0	50.0		
69	30	1.0			251*		8,810	5,620	0.86		4.0	20.0	
78.5	15	1.5	5		264*		4,960	5,310	0.47				
77.5	15	1.5	5	1.0	258*		8,000	5,090	0.29				
74.85	20	1.5	3	0.5	258*		8,120	5,380	0.39				

Note: Bond and spread tests were made on copper sheet.
Tensile and creep tests were made on chill cast strips of the alloys.
* Determined in this investigation from cooling curves—other temperatures from literature.

Comparison of Wire Gages

Gage No.	American or Browne & Sharpe's A. W. G. or B. & S.	Birmingham or Stubs' B. W. G.	Washburn & Moen S. W. G.	British Standard S. W. G.	London or Old English	United States Standard	Manufacturers' Standard for Sheet Steel	Gage No.
0000000			.4900	.500		.500		0000000
000000	.5800		.4615	.464		.469		000000
00000	.5165		.4305	.432		.438		00000
0000	.4600	.454	.3938	.400	.454	.406		0000
000	.4096	.425	.3625	.372	.425	.375		000
00	.3648	.380	.3310	.348	.380	.344		00
0	.3249	.340	.3065	.324	.340	.312		0
1	.2893	.300	.2830	.300	.300	.281		1
2	.2576	.284	.2625	.276	.284	.266	.2391	2
3	.2294	.259	.2437	.252	.259	.250	.2242	3
4	.2043	.238	.2253	.232	.238	.234		4
5	.1819	.220	.2070	.212	.220	.219	.2092	5
6	.1620	.203	.1920	.192	.203	.203	.1943	6
7	.1443	.180	.1770	.176	.180	.188	.1793	7
8	.1285	.165	.1620	.160	.165	.172	.1644	8
9	.1144	.148	.1483	.144	.148	.156	.1495	9
10	.1019	.134	.1350	.128	.134	.141	.1345	10
11	.0907	.120	.1205	.116	.120	.125	.1196	11
12	.0808	.109	.1055	.104	.109	.109	10.46	12
13	.0720	.095	.0915	.092	.095	.0938	.0897	13
14	.0642	.083	.0800	.080	.083	.0781	.0747	14
15	.1571	.072	.0720	.072	.072	.0703	.0673	15
16	.0508	.065	.0625	.064	.065	.0625	.0598	16
17	.0453	.058	.0540	.056	.058	.0562	.0538	17
18	.0403	.049	.0475	.048	.049	.0500	.0478	18
19	.0359	.042	.0410	.040	.042	.0438	.0418	19
20	.0320	.035	.0348	.036	.035	.0375	.0359	20
21	.0385	.032	.0317	.032	.0315	.0344	.0329	21
22	.0253	.028	.0286	.028	.0295	.0312	.0299	22
23	.0226	.025	.0258	.024	.0270	.0281	.0269	23
24	.0201	.022	.0230	.022	.0250	.0250	.0239	24
25	.0179	.020	.0204	.020	.0230	.0219	.0209	25
26	.0159	.018	.0181	.018	.0205	.0188	.0179	26
27	.0142	.016	.0173	.0164	.0188	.0172	.0164	27
28	.0126	.014	.0162	.0148	.0165	.0156	.0149	28
29	.0113	.013	.0150	.0136	.0155	.0141	.0135	29
30	.0100	.012	.0140	.0124	.0138	.0125	.0120	30
31	.0089	.010	.0132	.0116	.0123	.0109	.0105	31
32	.0080	.009	.0128	.0108	.0113	.0102	.0097	32
33	.0071	.008	.0118	.0100	.0103	.00938	.0090	33
34	.0063	.007	.0104	.0092	.0095	.00859	.0082	34
35	.0056	.005	.0095	.0084	.0090	.00781	.0075	35
36	.0050	.004	.0090	.0076	.0075	.00703	.0067	36
37	.0045		.0085	.0068	.0065	.00664	.0064	37
38	.0040		.0080	.0060	.0058	.00625	.0060	38
39	.0035		.0075	.0052	.0050			39
40	.0031		.0070	.0048	.0045			40

Properties of Ceramic Materials

Materials	Dense Steatites ($MgO.SiO_2$)	Rutile Bodies (TiO_2)	Cordierite Bodies ($2MgO2Al_2O_3.5SiO_2$)	Natural Lava	Porcelain	
					Dry Process	Wet Process
Mechanical Properties						
Hardness, Moh's scale	7.5	8	7	6	...	...
Tensile strength, lb./sq. in.	7,500–10,000	7,500	1,500–3,500	2,000–2,500	1,000–2,000	5,000–8,000
Compressive strength, lb./sq. in.	65,000–85,000	80,000	30,000–40,000	20,000–30,000	30,000–50,000	45,000–90,000
Modulus of rupture, lb./sq. in.	18,000–22,000	20,000	4,000–8,000	8,000–9,000	6,000–8,000	10,000–18,000
Impact resistance, ft. lb./sq. in. (Charpy)	1.8–2.1	2.4	0.9	1.3–1.4	...	...
Electrical Properties						
Dielectric strength, volts/mil	210–240	100	...	80–100	40–100	250
Dielectric constant; 60 cycles	6.3–6.5	...	...	...	...	...
1,000 kc.	5.8–6.2	85	4.1–5.0	5.3–5.6	6.0–7.0	6.0–7.0
10,000 kc.	5.7–6.0	85	4.0–5.0	5.3–5.5	(1 to 1,000 kc.)	(1 to 1,000 kc.)
Power factor, percent; 60 cycles	0.14–0.30	...	...	...	1.70–2.50	1.70–2.50
1,000 kc.	0.02–0.20	0.08	0.40	0.30–1.00	0.80–1.00	0.80–1.00
10,000 kc.	0.01–0.18	0.06	0.30	0.25–0.90	0.60–1.00	0.60–1.00
Loss factor, percent; 60 cycles	0.88–1.95	...	...	...	10.20–17.50	10.20–17.50
1,000 kc.	0.13–1.24	...	1.64–2.00	1.68–5.30	4.80–7.00	4.80–7.00
10,000 kc.	0.06–1.08	...	1.20–1.50	1.37–4.77	3.60–7.00	3.60–7.00
Volume resistivity, ohms/cc.						
at 25 deg. C.-(77 deg. F.)	$>10^{14}$	$>10^{12}$	$>10^{14}$	$>10^{12}$	$>10^{13}$	$>10^{13}$
at 100 deg. C. (212 deg. F.)	$2.1x10^{12}$– $>10^{14}$	$9.8x10^{11}$	$6.1x10^{12}$–$4.0x10^{13}$	$3.2x10^{11}$	(at 75°C.)	(at 75°C.)
at 500 deg. C. (932 deg. F.)	$3.2x10^{5}$–$3.5x10^{10}$	$1.7x10^{6}$	$4.8x10^{6}$–$2.0x10^{7}$	$1.7x10^{6}$–$2.6x10^{8}$		
at 900 deg. C. (1,652 deg. F.)	$<10^{11}$–$2.5x10^{7}$	$<10^{4}$	$7.0x10^{4}$–$2.2x10^{5}$	$2.0x10^{4}$–$1.8x10^{6}$		
Thermal Properties						
Softening point, deg. F.	2,550–2,630	3,000	2,570–2,600	2,700–3,000	...	...
Heat resistance, deg. F.	1,830	1,830	2,280	2,000–2,190	...	...
Coef. of expansion, per deg. C. (20–100 deg. C.)	7.8–$10.4x10^{-6}$	8.6–$8.7x10^{-6}$	2.5–$2.8x10^{-6}$	3.4–$10.5x10^{-6}$	3.0–$6.0x10^{-6}$	3.0–$6.0x10^{-6}$
Thermal Conductivity						
Cal. per sec. per cm. per deg. C.	0.006	...	0.003	0.003–0.005	...	...
General Properties						
Specific gravity	2.6–2.7	4.0	2.1	2.3–2.8	2.3–2.5	2.3–2.5
Weight, lb./cu. in.	0.094–0.098	0.144	0.076	0.085–0.102	...	...
Chemical resistance	Resistant to all common acids and alkalies except hydrofluoric acid					
Water absorption, percent	1.00–0.00	0.05–0.00	8.0–1.0	2.5–1.0	1.0–0.5	0.00

(Courtesy *Product Engineering,* June 1942)

Index