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OF STEEL

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THE
HEAT-TREATMENT
OF STEEL

BY

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WITH A FOREWORD
BY THE LATE
MR. C. K. EVERITT

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FOREWORD

I AM sure readers of this book on "The Heat-treatment of Steel" will benefit by the practical manner in which the subject is put forward. It will certainly be of interest to all steel users.

I had the pleasure of knowing that eminent scientist, the late Dr. H. C. Sorby, F.R.S., who followed up his investigation of the structure of rocks by studying the crystalline formation of iron and steel, and in the year 1886 I supplied him with samples of various carbon and alloy steels. One of the conditions of steel brought about by heat-treatment, the "sorbitic" structure, is named after him. It is on the foundation of his work that the heat-treatment of steel has been so wonderfully built up.

I have no doubt this book will be of interest to all who work on steel and steel tools.

C. K. EVERITT.

TO THOSE
WHOSE PATIENCE AND CARE FOR US
MADE THIS BOOK POSSIBLE—
OUR WIVES

PREFACE

OUR three previous series of simplified accounts of metallurgical methods and operations inevitably touched here and there on matters of heat-treatment. Notably in *The Structure of Steel* we gave brief outlines of the main heat-treating operations and principles. In *Steel Manufacture* we dealt in some detail with the heat-treatment of steel castings. Finally, in *The Mechanical Working of Steel*, we dealt incidentally with such processes as "spheroidizing" and the treatment of steel wire.

It became evident, however, as our work proceeded, and from letters received, that far more need existed for simple instruction and exposition in regard to heat-treatment than our earlier series had satisfied. We set to work, therefore, to compile as full and informative a book on "The Heat-treatment of Steel" as our experience and abilities would allow. In many respects this is the most ambitious of all our efforts. It has required a vast amount of time and patience to compile the essential data, and an equal amount to reduce the often complex laws and processes to simple and clear statements suitable for both layman and engineer. It has been necessary in the course of this book to repeat or refer to matter contained in the earlier books. This, however, was inevitable, but does not in any way invalidate or render superfluous the earlier works, all of which stand on their own feet, and, though inter-related, are quite independent of one another.

A work of this type presents many difficulties, and the authors do not claim to have achieved perfection. They rely to some extent on their readers to detect and point out errors, omissions, or failure to make sufficiently clear some knotty point in the exposition that follows. Letters indicating difficulties or doubts will be welcomed.

In conclusion, the authors express in advance thanks for the help they have received from Dr. H. Alex. Fells and the Sheffield and District Gas Company, who have "vetted" the sections on gas furnaces and atmosphere control; to The Incandescent Heat Co., Ltd., Smethwick; Birmingham Electric Furnaces, Ltd., Birmingham; Wild-Barfield Electric Furnaces, Ltd., Watford; British Furnaces, Ltd., Chesterfield; and Mr. H. Southern, of Messrs. G. P. Wincott, Ltd., of Sheffield, for illustrations and valuable help in connection with the sections on furnaces; Mr. T. R. Lynam and the Oughtibridge Silica Firebrick Co., Ltd., Oughtibridge, and General Refractories, Ltd., Sheffield, who have provided data on refractories; Mr. A. E. Frost, of Messrs. William Griffith & Sons, Ltd., Sheffield, Mr. T. Hewitt, of Messrs. George Turton Platts & Co., Ltd., Sheffield, and Mr. H. Singleton, of the Tempered Spring Co., Ltd., who gave us the benefit of their first-hand experience in the treatment of steel springs; Mr. A. J. Beeley and Messrs. Edgar Allen & Co., Ltd., who have allowed us to borrow freely from their store of information on treating tool steels, particularly mining tool steels, and have generously lent most of the blocks, as well as given us permission to reproduce the textual material, which appeared serially in their technical journal, *The Edgar Allen News*; the late Mr. A. E. Shorter, M.B.E., M.I.Mech.E., of the Shorter Process Co., Ltd., Sheffield, who carefully supervised our comments on the flame-hardening process with which his name is so intimately associated; and Mr. Ambrose Shardlow, of Messrs. Ambrose Shardlow & Co., Ltd., Sheffield, who has been most helpful in providing information and photographs in connection with the induction hardening process.

EDWIN GREGORY
ERIC N. SIMONS

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THE
HEAT-TREATMENT OF STEEL

CHAPTER I

Temperature Measurement

Before steel can be heat-treated, we must know what condition and effects we wish to produce in it, whether these concern structure, mechanical properties, performance in service, or finished appearance. We may have this knowledge, and yet not obtain satisfactory results, either because of inadequate skill and experience, or, more probably, because our methods of measuring the heat-treatment temperatures are imperfect.

Many old hands can, as the result of a lifetime in the heat-treatment shop, and under reasonably constant conditions of lighting, determine temperatures to within a few degrees by the eye alone. Nevertheless, while the accuracy of these men is something to marvel at, and in the days before efficient temperature-measuring devices existed was invaluable, better results will be obtained in heat-treatment if proper scientific temperature-measuring appliances are used. Every steel maker knows that even the old hands turn out better work when their remarkable judgment is supported by the pyrometer, while the less expert cannot safely do without one.

The necessity for accurate measurement and control of temperatures exists at almost every stage in the manufacture and treatment of steels. The range involved may be wide, since it includes melting at temperatures as high as 1650° C., and tempering at temperatures as low as 150° C. Between these limits lie the hardening, normalizing, annealing, softening, tempering, case-hardening, and nitriding temperatures of steels of specified chemical compositions. All these terms will be explained later.

In general, the difficulties met with in accurate temperature measurement are greater at the higher temperatures than at the lower. This is largely because temperature has no definite physical dimensions, and cannot be expressed except in relation to something else. There are no basic fundamental units of temperature.

and to measure it we have to fix, quite arbitrarily, some definite standard with which it can be compared. Thus, one degree on the centigrade scale is defined as one hundredth of the *apparent* expansion under heat of a column of mercury (in a tube) at temperatures anywhere between the melting point of ice and the boiling point of water, under a pressure of 760 millimetres of mercury, i.e. the equivalent pressure of a 760 mm. column of mercury. There are other scales of temperature measurement besides the centigrade, e.g. the Fahrenheit and the Réaumur. All these involve some purely arbitrary standard for comparison, based on physical phenomena due to heat. None of them obeys any specific law relating temperature to its physical effects in the sense of an absolutely regular increase or addition of these effects per unit of temperature measured. Thus, before we can safely adopt any system, we must have some standard temperature scale to which it can be referred, just as the draper's yard stick can, if necessary, be checked by the Imperial yard in London.

This analogy must not be taken too far, and the reader should realize the difference between heat and temperature. Thus, a small piece of steel may be at one and the same temperature, say 800° C., as a much larger piece, but the amount of heat (energy) contained in the latter considerably exceeds that in the smaller piece. Again, although two single yard sticks are together equal to a 2-yard stick, two substances at 800° C. when placed together do not give something at 1600° C.

The Thermodynamic Scale

To this end Lord Kelvin devised the thermodynamic scale of temperature based on a theoretically perfect heat engine. One of the laws governing the physical universe is that any transformation of one form of energy into another can produce heat. Heat is simply a form of energy, and is produced by the motion or vibration of the ultimate particles of matter. This energy can be produced as a result of either mechanical action, as when a brake acts upon the tyre of a locomotive wheel, or chemical action, as when the oxygen of the air blast combines with metallic impurities such as silicon in the molten metal in the Tropenas steel converter. The heat energy produced by particular agencies can, by a reversal of the process, be used to produce motion, as in a heat engine, and if such an engine lifts ten pounds of corn to a given height when the heat is at a certain degree, twenty when the heat is greater, and so on, we can work out a fundamental scale by which to measure the temperatures concerned, and this scale will be independent of what material or method for producing the heat is adopted. The standard is the actual work done by the heat, and not the particular effect of heat on some arbitrarily chosen substance. It can be proved, thermodynamically, that the quantity of heat a substance possesses is proportional to its "absolute" temperature, and, in the instance given above, the temperatures would be expressed in terms of pounds of corn lifted through the given height. This, of course, is not Kelvin's unit of measurement, but it will serve as an example of the principle involved. We should then express the temperature as 10 ft.-lb., 20 ft.-lb., etc., meaning the temperatures at which so much work could be done, i.e. the heat required to lift 10 or 20 lb. of corn through 1 ft. of height.

ABSOLUTE ZERO

If the melting point of ice and the boiling point of water are accepted as 0° C. and 100° C. respectively, it can readily be shown that *the absolute zero on the thermodynamic scale is* — 273° C. (*actually* — 272·85° C.). Absolute zero has no real existence. What does it mean?

In scientific research an instrument known as the *air thermometer* is used for measuring temperatures. Instead of a column of mercury, as in the ordinary thermometer for normal temperature measurement, there is a column of air, and the graduations or unit markings begin with a point known as "absolute zero" and work upwards. It is known that the effect of heat on gases is to cause their expansion. Conversely, cold, or the withdrawal of heat, causes their contraction. If one can imagine a state of cold so intense that the volume of air in the air thermometer has shrunk to absolutely nothing, then this would represent absolute zero, since no lower temperature is imaginable. All the italicized statement above means, then, is that on Kelvin's scale, whereby heat is measured in terms of work done, absolute zero (i.e. the lowest conceivable temperature, when no heat-motion exists) is regarded as equivalent to a temperature on our workaday thermometers of 273 degrees centigrade *below* zero, zero being the melting point of ice. On the scientist's air thermometer, then, or the *absolute scale*, as it is termed, the melting point of ice and the boiling point of water under atmospheric pressure would be marked at 273° and 373° respectively, and not at 0° and 100° as on our ordinary centigrade thermometers. This gives us a permanent independent standard of comparison.

The thermodynamic—or heat-in-terms-of-work-done—scale is of theoretical value only and has little bearing on practical heat-treatment, but another scale based on a set of laws of great practical importance has been shown to be in almost perfect agreement with it. These are the laws formulated by Boyle and Charles for perfect gases.

CHARLES'S LAW

Charles proved that the volumes of gases under constant pressure increase by equal fractional amounts, i.e. regularly, when heated, no matter what the nature of the gases. For those who like these laws expressed symbolically, he declared that $V_t = V_0 (1 + ct)$ where V_0 is the volume of a given mass of gas at the melting point of ice, i.e. 0° C., V_t its volume at a temperature t° C., and c the temperature coefficient of volume, i.e. the fraction by which the volume at 0° C. increases for each degree of temperature. We thus have again a means of temperature measurement that is not affected by the material or method for producing the heat.

By experiment the value 1/273 was obtained for c, which means that when the volume of such a mass of gas shrinks to absolutely nil, i.e. its power of motion (kinetic energy) vanishes, then $1 + ct = 0$, whence $t = - 273°$ C.

This temperature thus constitutes the zero or starting point on the gas scale of temperatures (based on expansion under heat), and because it agrees with the absolute or thermodynamic scale, gas scale temperatures *are now everywhere accepted as standards* with which all others may be compared. Moreover, although there is a specific upper limit of temperature beyond which the gas pyrometer (i.e. temperature measurer) cannot be used, certain laws of heat and light radiation, deduced by mathematics on a thermodynamic basis, can, as we shall see, be used in measuring temperatures far above the working range of the gas pyrometer.

EXTRAPOLATION

The gas pyrometer is not, however, an instrument suitable for industrial use. In consequence, other instruments are employed that measure entirely different phenomena. The question at once arises: how closely do the temperatures they indicate agree with gas scale temperatures? It is often desired to measure temperatures outside the range of the gas pyrometer, but if a pyrometer whose construction is based on some quite other physical law yields temperature readings agreeing closely with true gas-scale temperatures, extrapolation may often be used with little risk of inaccuracy. Extrapolation means that if a certain point on a curve or graph is known to lie within limits *actually determined*, and another point is known to lie *outside* the actually determined limits, a value can with reasonable safety be given to this second point on the assumption that there will be no sharp alteration in the character of the curve or its form, or in the corresponding values.

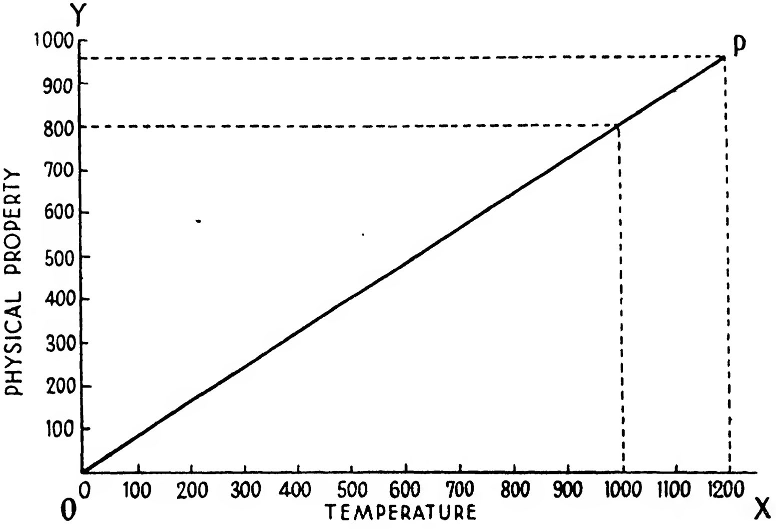


FIG. 1

Fig. 1 may make this a little clearer. Let us assume that with every ten degrees of increase in temperature shown on the axis OX, there is an eight-units increase shown on the axis OY in some physical property in an imaginary metal. Up to 1000° C., these facts may have been definitely established, but beyond 1000° C. no actual proved figures exist. It will be seen that the curve (in this instance, a straight line) showing the correlation of temperature with the particular property does not fluctuate in direction and regularity between 0° and 1000° C. It is desired to know what the value will be at 1200° C. No figures exist, but the assumption is that the line will still continue its regular course, and that the value will be that indicated by the point *P*, corresponding to 960 units increase in the relevant physical change. This is the method of assigning values by *extrapolation.*

In the standardization of pyrometers, based on the observance of the alteration of these other physical phenomena with temperature, fixed points, accurately determined by the gas pyrometer, are employed, e.g. the boiling points of pure liquids and the melting or freezing points of pure substances and *eutectics* (which are mixtures of elements or compounds freezing at constant temperatures). The following list of fixed points is useful in this connection.

TABLE I

	Freezing (or Melting) Point (° C.)	Boiling Point (° C.)
Ice	0	—
Diphenylamine	54	—
Naphthalene	79	—
Water	—	100
Tin	232	—
Lead	327	—
Zinc	419	—
Sulphur	—	444·7
Antimony	631	—
Aluminium	658	—
Silver-copper eutectic	779	—
Sodium chloride (common salt)	801	—
Silver	961	—
Copper oxide-copper eutectic	1063	—
Copper free from oxide	1083	—
Nickel	1455	—
Iron	1535	—

Almost every physical property that changes with temperature has been exploited in the construction of instruments designed to yield trustworthy and reproducible temperature indications, and it is possible to classify these instruments according to the particular physical phenomenon measured.

The principles on which the various measuring instruments are constructed differ greatly, and it is therefore important that some of these should be considered, together with the advantages and limits of usefulness of instruments of each type, since no one instrument will serve all purposes. Indeed, in choosing a pyrometer consideration must be given not merely to the range of temperature involved, wherein accurate readings may be relied upon, but also to the working conditions under which the instrument is used.

Although at one time the term "pyrometer" related to instruments designed to measure temperatures above the range of the ordinary mercury "thermometer," it is now generally recognized that the two terms are interchangeable.

The temperature-measuring instruments important to science and industry are: (1) Gas thermometers; (2) expansion thermometers; (3) electrical resistance thermometers; (4) thermoelectric pyrometers; (5) radiation pyrometers; (6) optical pyrometers; (7) calorimetric pyrometers; (8) fusion pyrometers.

CHAPTER I

Pyrometers

THE GAS THERMOMETER

IT will be evident from the considerations outlined that a gas thermometer could be constructed to measure (i) the increase in volume occurring when a given mass of gas is heated, the pressure being kept constant, or (ii) its increase in pressure when the volume is made constant. In practice, when changes in volume are being measured, it is exceedingly difficult to keep all parts of the measuring apparatus at the same uniform temperature, and it is therefore much more convenient to use the "constant volume" gas thermometer, i.e. one in which the *volume* of the gas is kept constant, changes in *pressure* caused by heat being used as the basis of measurement. Use is thus made of the fact that the pressure of a given mass of gas at any specific temperature equals the pressure at zero centigrade (0° C.) multiplied by the sum $(1 + ct)$, where c is now the coefficient of pressure and t is the corresponding temperature in degrees centigrade. This relation is expressed thus

$$P_t = P_o \quad (1 + ct)$$

where P_t and P_o are the pressures of a given volume of gas at $t°$ and 0° C. respectively and c is the temperature *coefficient of pressure*, which is also equal to 1/273rd. (A *coefficient* is the numerical value of one factor corresponding to a particular value of some other factor with which it is related. Temperature coefficient of pressure thus means the increase in pressure corresponding to a particular increment of temperature, usually 1° C.)

Even so, however, the gas pyrometer can only be regarded as a research and laboratory instrument. Elaborate precautions must be taken to avoid distortion of the gas-containing bulb and to avoid diffusion of the gas through its walls. The bulb is usually made of an alloy of platinum and iridium, two of the rarer metals. The latter alloy is harder than pure platinum, and resists deformation caused by internal pressure to a much greater degree. For very high temperature work the thermometer bulb is enclosed inside a similar but larger bulb, the space between being filled with the same gas under identical pressure. This almost completely prevents distortion of the inner bulb.

In reality, gas scale temperatures would only be in perfect agreement with corresponding absolute or thermodynamic temperatures if an ideal or perfect gas could be used in the thermometer, a perfect gas being defined as one obeying in every respect the laws of Boyle and Charles, which the reader can study for himself in a handbook of chemistry or physics. No such perfect gas is known, however, so that what are termed *correction factors* must be employed. This means that certain pre-established numerical values must be added to the actual values recorded by the instrument to make the final value correct. The more the gas deviates from the perfect, the bigger numerically must be the correction factor added. When hydrogen and helium, two extremely light and tenuous gases, are used, the deviations from true temperatures are very small, even at 1000° C., and correction is unnecessary. For this reason fixed points determined by the *standard hydrogen gas thermometer* are everywhere accepted as representing true thermodynamic temperatures.

EXPANSION THERMOMETERS

The only expansion pyrometers that need consideration are the mercury-in-glass and the mercury-in-steel types. In the gas thermometers, the metal of the bulb containing the gas expands so little in volume that this volume expansion can be largely ignored as compared with the expansion of the gas inside it. In liquid mercury thermometers, on the other hand, the expansion of the bulb itself exerts a real effect that cannot be ignored. It is thus important to remember that in measuring temperature with these mercury thermometers it is only the *apparent* (as distinct from the real) expansion of the mercury when heated that is used to measure temperature. In consequence, for accurate work, bulbs *must* be used that will retain their original dimensions even after many prolonged reheatings to elevated temperatures. (It will be seen later that certain metals "grow," i.e. permanently enlarge, when frequently reheated.) Mercury thermometers whose bulbs are not each one made from the same glass cannot, for this reason of differing rates of expansion under heat, be compared with one another, and in consequence most modern mercury thermometer bulbs meant for accurate work are made from a special boro-silicate glass, i.e. one largely composed of fused borax and silica. Thermometers of this type are then singularly free from the fault known as *zero depression*, quite common among thermometers made of ordinary glass. Zero depression means that the zero point is shown lower by the thermometer than it actually should be.

Mercury boils at 357° C. and a mercurial thermometer, in its common form, cannot be used to measure temperatures above this limit. If the space above the mercury in the thermometer tube is filled with an *inert gas* such as nitrogen, the upper limit of measurement can be extended to temperatures as high as 540° C., since the pressure exerted by the gas raises the boiling point of the mercury. (An inert gas is one that does not readily combine with other substances.) To ensure that the thermometers shall accurately indicate temperature, the makers usually anneal them, i.e. heat them to a specific, suitable temperature and keep them at this heat for many hours, afterwards letting them cool down slowly. The temperature to which they are heated is the *maximum* temperature at which they are intended to operate. This treatment is given before the thermometers are graduated (given their correct markings), and it has the effect of stabilizing the volume of the glass, so that the inaccuracies due to zero depression are minimized, if not entirely eliminated. Glass thermometers are also allowed to stand for long periods before being graduated so as to allow the glass to contract to its lowest volume.

Mercury-in-glass thermometers are necessarily fragile, and should be handled with care. To minimize this fragility, the bulb may be encased in an outer protecting shield or sheath. This has the disadvantage that it decreases the sensitivity of the instrument, which will then not indicate abrupt temperature changes so readily as an unprotected thermometer. To lessen this defect the space between the bulb and its shield is sometimes filled with copper dust. This, being a good conductor, rapidly conducts the heat to the bulb, so that the interval between the sharp temperature change and its indication by the thermometer is considerably reduced.

In the mercury-in-steel thermometer the bulb is made of steel instead of glass. Cast iron may also be used for the bulb chambers. Cast iron, however, "*grows*" when subjected to prolonged reheatings to elevated temperatures, so that it will not give the same constancy of indication as a steel bulb. *Growth* is merely the technical term for *permanent* as distinct from *temporary* expansion in grey cast iron (it does not occur in white cast iron). It is mainly caused by the oxidation of the iron silicide and some of the iron, which oxidation occurs along the graphite flakes. There are other minor causes into which we need not go.

Steel bulb thermometers possess the advantage that they can easily be rendered self-recording. The mercury is caused to travel, by reason of its expansion under heat, along a steel tube with a fine "bore" or internal diameter. It then comes into contact with a gauge that records the pressure exerted by the expanding mercury. This gauge, of what is known as Bourdon type, consists of a dial with a pointer actuated by a bent spring, against which the mercury presses. The dial is graduated in suitable *temperature* units, although, of course, the instrument really records the *pressure*. The pointer may also take the form of a pen moving over a circular rotating chart, like those barometric pressure recorders thoughtful seaside corporations place at suitable points for the interest and convenience of visitors.

Steel is much stronger than glass, so that mercury-in-steel thermometers can be used for much higher temperatures with little risk of bulb distortion, even though the tube contains nitrogen or some other inert gas under high pressure. It is possible that in the near future modern alloy steels possessing a high degree of resistance to "creep" may be utilized with still more satisfactory results. (*Creep* is the slow movement of one part of a structure or piece of metal relative to another part. It is usually applied to the continued lengthening of a piece of metal when a load is placed upon it at elevated temperatures. Its occurrence in a steel part may mean fracture if the load is prolonged at these temperatures, so that steels with high creep limits, i.e. those with high strength under prolonged load at high working temperatures and capable of resisting this tendency to fracture, are continually being sought after.)

If true temperature readings are to be obtained from a mercury thermometer, we must take into account the depth of immersion of the instrument in the liquid or chamber whose temperature is to be measured. The correction formula generally used for mercury-in-glass thermometers is

$$t = t_o + 0{\cdot}00013\ (t_o - t_e)\,n$$

where t is the corrected temperature, t_o the observed temperature, t_e the temperature of the emergent stem taken at a point $(t_o - \frac{1}{2}n)$, n being the number of degrees of unheated emergent stem.

The makers generally *calibrate*, i.e. allow for the amount of variation from absolute accuracy of, these mercury-in-steel thermometers used for industrial purposes, for a given depth of immersion, e.g. 3 in., and the thermometer should be used under these conditions if good results are to be expected and correction formulae avoided.

Mercury-in-steel thermometers quite suitable for oil, lead and salt baths for tempering operations, tinning baths, galvanizing baths, etc., are obtainable. These cover a range of temperature from 100°–540° C. (212°–1000° F.).

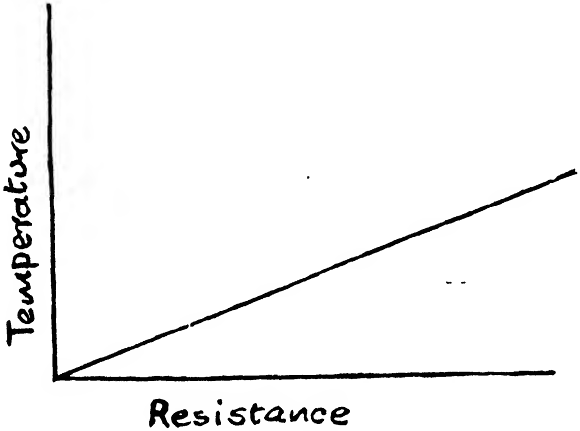


Fig. 2

ELECTRICAL RESISTANCE THERMOMETERS

The electrical resistance thermometer is based on the fact that, in general, the resistance offered by a metal conductor to an electric current increases as its temperature rises.

This form of thermometer is capable of yielding more accurate temperature readings than any other really practical instrument, and, indeed, is often used for the standardization of other thermometers or pyrometers, although the temperatures it indicates have to be corrected by a formula deduced by Callendar. This correction is necessary because the resistance offered to the electric current by the wire (usually of platinum) is not a *linear function* of its temperature. In other words, the rise of resistance with temperature does not yield a straight line (Fig. 2) but a curve (Fig. 3) and an equation is again used to express this symbolically—

$$R_t = R_0 \quad (1 + \alpha t + \beta t^2)$$

Here, R_t is the resistance of the wire at its temperature t° C.; R_0 is its resistance at the temperature of melting ice, i.e. 0° C., while α and β are constants whose values depend on the particular metal used for the wire.

There is no need to be alarmed by this row of symbols, containing letters from the Greek alphabet. All it means is that the dead accurate temperature is arrived at by multiplying the electrical resistance of the wire at 0° C. (expressed numerically) by a second figure. This second figure is obtained by adding together the product of, or result of multiplying, the constant α and the temperature in degrees, the product of constant β and the temperature squared (i.e. multiplied by itself), and to these adding unity.

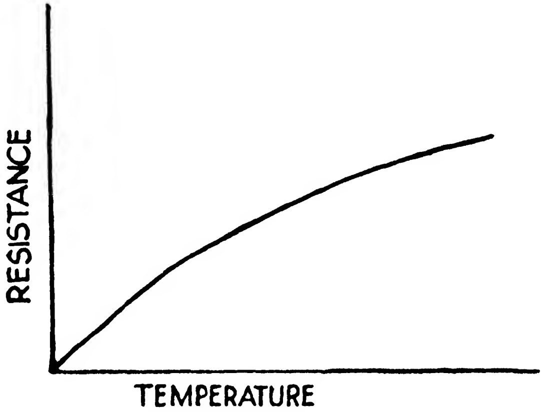


Fig. 3

In practice, however, it would be a long-winded business to establish a proper temperature-resistance relation, so that in constructing and graduating instruments designed to give direct temperature indications, much difficulty is avoided by using the simpler, but somewhat less accurate, linear equation $R_t = R_0 (1 + \alpha t)$.

As before, R_t and R_0 are the resistances of the wire at t° and 0° C. respectively, and α is a constant, characteristic of the metal used. α is thus the temperature coefficient of resistance, i.e. the increased resistance value expressed as a fraction of the resistance at 0° C. produced by a specific rise in temperature, usually 1° C. For pure platinum this has the value 1/260th.

We shall not henceforth expound these various equations. It should now be clear, even to the novice with no mathematical training, that an equation or formula is only a kind of shorthand to express briefly a mathematical calculation.

If the value of 1/260th is substituted in the above equation for the symbol α, a simple calculation will show that the temperature at which the resistance of platinum theoretically vanishes is − 260° C. This temperature is known as the *fundamental zero* for platinum.

The increase in resistance between the freezing and boiling points of water under atmospheric pressure is known as the *fundamental interval*, and for convenience the length and cross-section of the wire are so arranged that, for pure platinum, this increase is exactly one *ohm*. (An ohm is the unit of electrical resistance, i.e. the resistance necessary to allow an electromotive force—the mechanical force of electrically produced movement —of one *volt* in strength to pass a current of 1 *ampere*. A volt is the unit of electromotive force, i.e. the force that would carry one ampere of current against one ohm of resistance. An ampere is the amount of current that one volt of electromotive force can send through one ohm of resistance, hence it is the unit of electric current.)

Thus, an increase in resistance of 0·01 ohm represents a rise in temperature of 1°, the accurate measurement of which is easily made, even with industrial forms of resistance thermometers.

The temperatures based on the above linear relation are known as *platinum scale temperatures*, and, as already indicated, these must be converted into true gas scale temperatures by means of Callendar's correction formula. This is expressed as follows—

$$t - p = \delta\left[\left(\frac{t}{100}\right)^2 - \frac{t}{100}\right]$$

where t is the true gas scale temperature for the indicated platinum scale temperature p, and δ is a constant whose value depends solely on the purity of the platinum used.

For pure platinum δ has the value 1·5.

The platinum constant is determined from values, obtained by experiment, of the resistance of the platinum bulb at the freezing and boiling points of pure water, and at the boiling point of sulphur, the latter being known with extreme accuracy, namely 444·7° C.

Examples of the determination of δ and the application of the above relation are given below.

A platinum wire having a resistance of 2·6 ohms at 0° C. and a *fundamental interval* of one ohm is found to have a resistance of 6·815 ohms at the boiling point of sulphur.

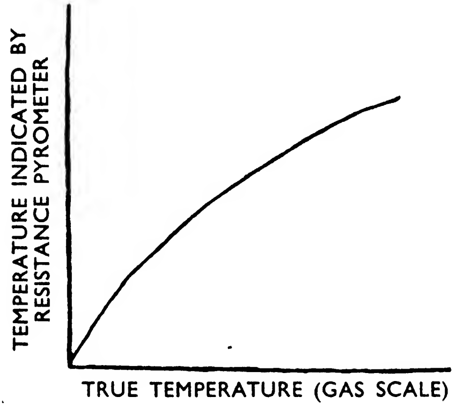


FIG. 4

This gives a platinum scale temperature of $(6{\cdot}815 - 2{\cdot}6) \times 100 = 421{\cdot}5^\circ$. Substituting the appropriate values in Callendar's formula, we obtain

$$444{\cdot}7 - 421{\cdot}5 = \delta\left[\frac{444{\cdot}7^2}{100^2} - \frac{444{\cdot}7}{100}\right]$$

Working out this sum, we find that $\delta = 1{\cdot}5$.

Once this value has been obtained, it is simple to convert indicated values to true temperatures by means of a graph (Fig. 4) constructed from a series of calculated values. In determining points on the curve, much labour is saved if the platinum scale temperatures corresponding with specified gas scale temperatures are calculated, since if a series of true temperatures is to be calculated from the corresponding platinum scale values, this involves the tedious solution of several *quadratic equations*, i.e. those in which square roots are involved and two different values are obtained.

Corresponding temperatures are given in the following table and the relation between the two scales represented graphically in Fig. 5.

TABLE II

(True) Gas Scale	Platinum Scale	(True) Gas Scale	Platinum Scale
25°	25·28°	300°	291°
50	50·38	400	382
75	75·28	500	470
100	100	600	555
200	197	700	637
		1000	865

It will be observed that platinum scale temperatures are higher than gas scale temperatures between 0° and 100°, but lower than those above 100°, the discrepancy between the two sets of values increasing as the temperature rises, as indicated by the departure from the straight line shown in Fig. 5.

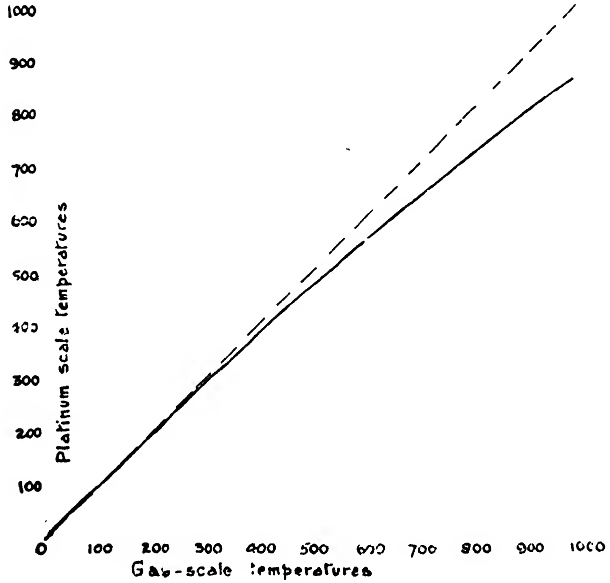


Fig. 5

The more impure the platinum, the greater the value of the platinum constant. Platinum scale temperatures then differ still further from true gas scale temperatures, as shown by Table III, page 17.

For measuring the resistance of the platinum wire, a special instrument is required. This is known as a *Wheatstone bridge.*

Radio has made most readers familiar with electrical diagrams, and Fig. 6 shows the principle of this bridge.

TABLE III

(True) Gas Scale Temperatures	Platinum Scale Temperatures		
	$\delta = 1{\cdot}6$	$\delta = 1{\cdot}7$	$\delta = 1{\cdot}8$
500°	468°	466°	464°
750	672	667	662
1000	856	847	838

It is an electrical circuit. A, A_1, A_2, and X are electrical resistances, the values of three of which are known, the value of X being unknown. 2 and 4 are opposite junctions or "business ends" of the circuit to which electric cells are connected. 1 and 3 are the remaining junctions to which a *galvanometer* is connected, this being an instrument for detecting and measuring very small currents. If the resistances are regulated in such a way that *no* current passes through the galvanometer, the points 1 and 3 must be at equal *potentials*, i.e. they are at identical electrical pressures or voltages. Hence if X is divided by A_2 (which is a known quantity), it must equal A divided by A_1, so that the value of X can be found if A and the ratio A/A_1 are known.

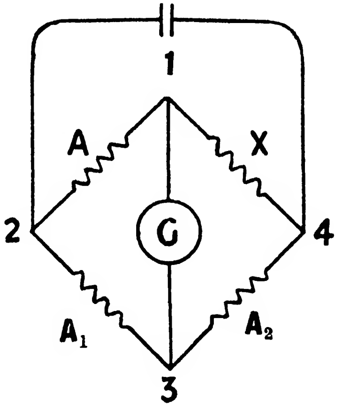


FIG. 6

In the form of Wheatstone bridge used for measuring platinum wire resistance, the wire, whose cross-section is necessarily rather thin, is wound upon an insulating bobbin made of some such material as ***mica*** or ***obsidian.*** It then constitutes what is known as the platinum bulb. (Mica is a scaly or flaky mineral composed of silicate of aluminium oxide with other silicates. Obsidian is a dark, glassy lava or volcanic rock rather like bottle glass.) The wire is wound on the bobbin *non-inductively*, i.e. is bent double before being made into a coil or spiral.

Platinum wires are used to connect the bulb to the *bridge* (or combination of resistances), and to compensate for the increased resistance of these wires with increasing temperature compensating *leads* (conductors of electric current) having the same length and cross-section are inserted in the thermometer tube as shown in Fig. 7, and are inserted into opposite arms of the bridge, as indicated in Fig. 8.

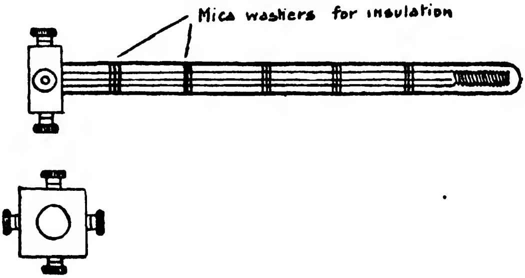


FIG. 7

At any instant, as the temperature of the "bulb" increases, its increase in resistance is readily determined by adjusting the variable resistance *R* until the bridge is *in balance*, i.e. until there is no difference in electrical potential between the points *S* and *T*.

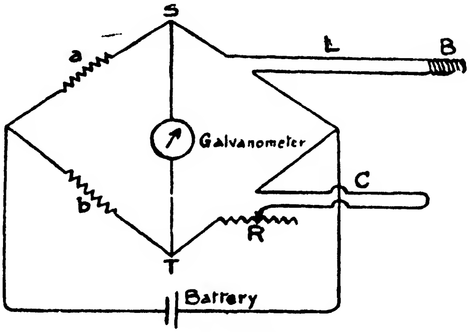


FIG. 8

a and *b* are generally two fixed resistances of equal magnitude made from some such alloy as manganin (copper 84, nickel 4, manganese 12 per cent). This alloy has a negligible temperature coefficient of resistance, i.e. its resistance to an electric current is little affected by temperature variation. At the point of balance, indicated by no deflection (i.e. no pointer movement) on the galvanometer the following relation obtains—

$$\frac{a}{b} = \frac{L + B}{C + R}$$

Since "a" is equal to "b" in magnitude, and C has the same resistance as L it follows that the resistance of the bulb (B) is identical with that of R.

From the increase in the resistance of the "bulb" its platinum scale temperature can at once be determined and its true temperature readily calculated by employing Callendar's correction formula. (See page 14.)

Practical forms of the resistance thermometer are generally designed to give direct temperature readings. Thus, in the well-known *Whipple indicator*, manufactured by the Cambridge Instrument Co., Ltd., London, the adjustable resistance R is in the form of a spiral attached to a cylindrical drum around which is a paper scale graduated in degree of temperature. Since a *null method*—i.e. one in which no electric current flows through the galvanometer of the Wheatstone bridge—is employed, the readings are practically independent of the battery voltage, which is furnished by dry cells that serve for a long period without renewal. The four leads from the thermometer to the bridge are well insulated, although contained in the same outer sheath or cable, and, as a result of the method of compensation adopted, any desired length of cable may be used. The galvanometer, although sensitive, is also robust enough in construction to allow the instrument to be carried from place to place with little risk of damage during transit.

The Wheatstone bridge principle and the "null" method have also been employed in the construction of resistance thermometer recorders. One of the earliest recorders, and perhaps the best known, was designed by Callendar. In this instrument the balancing of the bridge is automatic, the balancing mechanism operating a pen in contact with a graduated chart, driven by clockwork mechanism in a direction at right angles to the movement of the pen. By this means autographic time-temperature curves are obtained. Further details of this recorder and others are given in catalogues issued by the instrument manufacturers, and need not be considered here.

In other forms of resistance thermometer, temperature indications are obtained without balancing the bridge, the *out of balance* current flowing through the galvanometer being utilized in moving the galvanometer pointer over a graduated temperature scale. This method of measurement suffers from the disadvantage that a constant battery voltage must be maintained if reliable temperature indications are to be had. This necessitates a preliminary adjustment of the battery circuit before a temperature reading can be secured.

A disadvantage associated with some resistance thermometers is that platinum scale temperatures are *indicated*, and the corresponding true temperatures only obtained by reference to tables or graphs.

The platinum bulb is also extremely fragile, and the connecting wires must be protected from the action of hydrocarbons (compounds of hydrogen and carbon) and carbon monoxide (CO — carbon and oxygen), since platinum is readily attacked by these gases. The bulb is therefore generally protected by a porcelain sheath, which, in turn, is enclosed in an iron sheath. In consequence, the instruments respond rather sluggishly to temperature variations. In the University of Sheffield it was found that a resistance thermometer had a time-lag of about 10 minutes behind a thermo-electric pyrometer (see later) whose junction or "business end" was placed in approximately the same position as that of the resistance thermometer bulb inside a furnace at a temperature of about 700° C. The resistance thermometer is thus unsuitable for most industrial operations, but, as already indicated, is an extremely useful instrument for purposes of standardization. Prolonged heating at high temperatures is liable to introduce errors due to distortion of the bulb and grain growth in the platinum. For this reason the resistance thermometer should not be used continuously above 700° C.

THERMO-ELECTRIC PYROMETERS

Thermo-electric pyrometers are based on the principle, discovered by Seebeck, that when two dissimilar metals are joined together and the junction is heated and forms part of a *closed circuit,* it becomes the seat of an electromotive force (see page 14) whose magnitude varies with the temperature of the heated junction. (A closed circuit is the unbroken path of a circulating electric current.) If a sensitive galvanometer (see page 17) or *millivoltmeter* which is also an instrument for measuring very small electric current pressures) is placed in the circuit without breaking it, just as a circular chain can be enlarged by adding extra links, the magnitude of the *electromotive force*—for which we shall henceforward use the customary abbreviation e.m.f.—may be determined at several accurately known fixed points such as those given on page 6, and thus a relation between temperature and e.m.f. established.

The simplest form of thermo-electric (i.e. heat in relation to electricity) circuit is shown in Fig. 9. The wires of the *thermo-couple*, which is the short way of saying the two dissimilar elements forming a junction, are connected directly to the galvanometer. Such an arrangement is not always practical, however, particularly when platinum and its alloys are employed, because the first cost is too great.

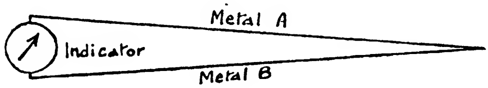


FIG. 9

In such instances the arrangement represented in Fig. 10 is used, the thermo-couple wires then being connected to the galvanometer by means of a copper lead or conductor or some other type of metallic lead.

The junctions of the thermo-couple wires and the connecting leads then constitute the *cold junction* of the circuit, which is not subjected to heat, being kept at a constant temperature, generally by insertion in some substance at an already known temperature. It links up the galvanometer or other measuring device with the entire circuit. In the circuit represented by Fig. 9 the *cold* junction is at the galvanometer itself. That junction of two dissimilar metals which is placed in the furnace whose temperature is to be measured is called the *hot junction*. The wires of this are preferably welded or fused together.

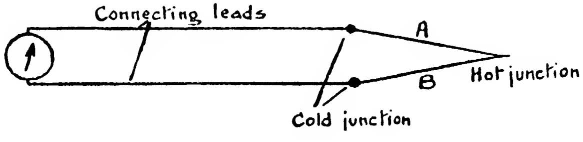


FIG. 10

It is important to note that the e.m.f. set up in a *thermo-electric circuit* of this type is simply proportional to the *difference* in temperature between the hot and cold junctions. This is perhaps the most vital principle of thermo-electricity, since, for the galvanometer deflections or actual e.m.f. values to have any real significance, the cold junction must obviously be kept at a constant temperature during calibration (see page 11) *and when used.*

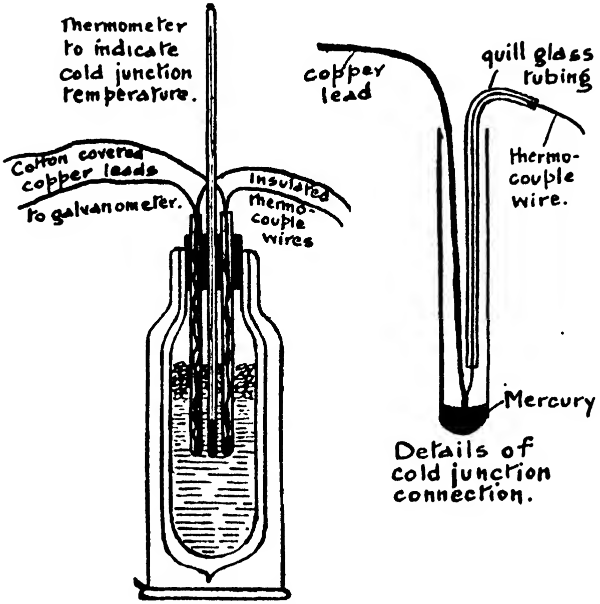


FIG. 11

In laboratory installations the cold junction is conveniently maintained at 0° C. by means of a vacuum flask (on the principle of a thermos flask) containing melting ice, as shown in Fig. 11. In industrial installations this is, for obvious reasons, impracticable, and the instrument is usually calibrated with its cold junction at the normal temperature of use. The true temperature of the cold junction is then added to that corresponding with the e.m.f. set up in the circuit.

With most installations, however, the actual thermo-couple is comparatively short, and if placed in, for example, a heat-treatment furnace, the cold junction will be heated by radiation from the furnace, and will then be liable to considerable temperature fluctuations, which will obviously affect the temperature readings. If the cold junction temperature differs much from that of calibration, and this temperature is added to the indicated temperature, serious errors may result.

In this connection the use of compensating leads, originally designed by Peake for use with the platinum series of thermo-couples, has proved invaluable in industry. Consider, for instance, a thermo-couple having one wire of platinum and the other of an alloy of platinum with 10 per cent of *rhodium* (a hard white metal of the platinum group). If ordinary copper leads are used to connect this "couple" (short for "thermo-couple") to its indicator, two opposing e.m.f.'s will be generated at the junctions copper-to-platinum-rhodium and copper-to-platinum.

These two e.m.f.'s are of opposite sign, i.e. one can be regarded as positive and the other negative, but they are not necessarily of equal magnitude at any given temperature, so that they do not cancel each other out, so to speak. If, however, the two junctions that together make up the cold junction of the circuit are always maintained at some constant temperature, this will be immaterial, since their algebraic sum (i.e. the net result of adding up the positive and negative values) is taken into account during calibration. But if the cold junction temperature alters, these two e.m.f.'s vary in different degrees. In consequence, the net e.m.f. of the cold junction differs from that obtained during calibration.

Peake's leads consist of two different nickel-copper alloys whose compositions are so arranged that the e.m.f. set up at the junction of one lead with the platinum wire is, *for all cold junction temperatures*, equal in magnitude and of opposite sign to that generated at the junction of the other lead and the platinum-rhodium wire. By "opposite sign" is meant that if one e.m.f. is positive (or +), the other will be negative (or —).

In effect, this transfers the cold junction to the actual indicator, which is usually situated at a considerable distance from the furnace, and is much less liable to temperature fluctuations than the true cold junction, because out of range of radiation from the furnace.

METALS AND ALLOYS FOR THERMO-COUPLES

Metals available for the construction of thermo-couples are divisible into two classes—"rare" metals such as platinum, rhodium, and iridium, and "base" metals such as iron, copper, nickel, etc. This classification is based entirely on first cost, and it does not necessarily follow that the more expensive rare-metal thermo-couples will always yield better results in temperature measurement than those constructed from the cheaper metals and alloys. Indeed, in certain circumstances, a base metal thermocouple may give better service.

In choosing a thermo-couple, a most important consideration is obviously the maximum temperature to be measured, since the upper limit to which the thermo-couple may be used is determined by the melting point of one or other of its wires. This, however, is by no means the sole consideration. For instance, some metals oxidize (i.e. combine with the oxygen of the surrounding atmosphere) more readily than others, oxidation being swifter at higher temperatures. This oxidation, with its accompanying scaling, or formation of flaky scales on the surface, alters the resistance of the thermo-couple to the electric current, and therefore alters that of the entire circuit. This, of course, affects the total e.m.f. of the circuit and, in consequence, its temperature indications. Again, some metals rapidly deteriorate when exposed to the action of certain gases, and if these are used in the thermocouple, suitable protection must then be given to them when used in such atmospheres.

Certain combinations of metals, notably iron and nickel, when used for thermo-couples, yield curves of e.m.f. in relation to temperature on which appear well-defined *points of inflection*, i.e. points where the curve changes from convex to concave. These points represent temperatures at which certain structural transformations in one or other of the metals due to heat take place, and are known as *allotropic changes*. An *allotropic transformation* is a change in the properties of an element without any change in its chemical nature. It is always accompanied by a change in internal energy, recorded by the curve of the inflection point, due, on the whole, to a change in the number or arrangement of atoms in the molecule or unit cell. The existence of such a transformation or *change-point* within the range of temperature over which temperature measurements are desired renders such a metal altogether unsuitable for the purpose, because the temperature indications will vary from the true temperature whenever these internal changes of structure occur.

Finally, the phenomenon known as *thermo-electric inversion* must be considered. This is common to all thermo-couples, although it occurs within different temperature ranges. Within such a temperature range the e.m.f. rises, up to a certain degree of heat, then falls, and may become zero or even negative, i.e. a minus quantity. If a thermo-electric temperature curve is drawn, therefore, it is generally a parabola (see Fig. 12).

Thus there is a highest (or lowest) point or value beyond which the e.m.f. generated as a result of heat cannot rise (or fall) and once this is attained, the value begins to drop until it reaches nil, after which it may go on falling to below zero. The temperature corresponding to this highest point or maximum value of the curve is known as the neutral temperature or *neutral point.* It always occurs at one and the same temperature when the same two thermo-elements are employed. The *inversion point,* i.e. the point where the current changes from + to — (positive to negative), corresponds with the temperature of the hot junction, which is just as much above the neutral point as the cold junction is below it.

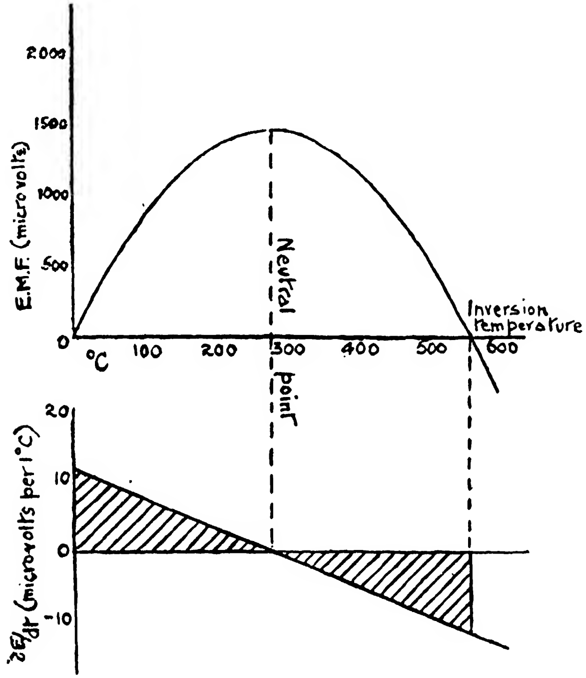


FIG. 12

A curve that, over limited ranges approximately represents the relation between the temperature and the e.m.f. generated by a thermo-couple is the parabola: $E = at + bt^2$ where E is the e.m.f. in microvolts (i.e. millionths of a volt) generated by the couple whose hot junction is at a temperature $t°$ C. and cold junction at 0° C., and where a and b are constants having characteristic values for each pair of metals (or alloys) used.

There is a way of using this simple equation to give us still more knowledge. In a parabolic curve of this type, the various values, taken at stated intervals, which may be regular or irregular, represent a continuously varying quantity, and the mathematics of the *differential calculus* can be employed in dealing with them. This means simply that certain other quantities, whose precise value is governed by the law of variation (the law on which the comparative magnitude of these varying terms depends), can be mathematically calculated, frequently with great accuracy, from the values already known, without special reference to the law of variation itself. This is done by a mathematical process known as *differentiating the equation.*

We do not propose to outline here the mathematics involved, which the student can study independently of this work. It suffices to say that the equation: $E = at + bt^2$, when "differentiated," yields an equation which, represented by a graph or curve, would be not of parabolic but of linear (or straight line) type.

This equation is written $\frac{dE}{dt} = a + 2\,bt$, and it measures something the first does not. It gives the *rate of increase of e.m.f. for each degree of increase in temperature*, and this is known as the *thermo-electric power.* When the maximum point in the e.m.f.-temperature curve is reached, the value $\frac{dE}{dt} = 0$. This really means that the rate of increase of e.m.f. per 1° C. at this point is equal to zero, and thus the neutral point may be defined as the temperature at which the thermo-electric power becomes zero. At the neutral point, therefore—

$$a + 2\,bt = 0, \text{ i.e. } t = -\frac{a}{2b}$$

If, now, a and b have the same sign (i.e. are either both positive or both negative), the neutral point occurs at some temperature below 0° C., since t then has a negative value, but if these constants are of opposite sign (i.e. one positive and the other negative) the neutral temperature will have a positive (or +) value, and the inversion temperature may occur in a range within which temperature measurement is desired. Thus, if the couple consists of one wire of copper and the other of iron, the following relation holds—

$$E = 10{\cdot}6t - 0{\cdot}019t^2, \text{ whence } \frac{dE}{dt} = 10{\cdot}6 - 0{\cdot}038t$$

The neutral point for the copper-iron couple thus occurs at $\frac{10{\cdot}6}{0{\cdot}038} = 279°$ C., while the inversion temperature, i.e. the temperature at which the e.m.f. is zero, and therefore at which the current flowing in the circuit changes direction, is $\frac{10{\cdot}6}{0{\cdot}019} = 558°$ C. (but only when the cold-junction temperature is 0° C. (see later).

The above curves are plotted in Fig. 12, and it will be observed that the thermo-electric power gradually decreases to zero at the neutral temperature, and that between 0° C. and the inversion temperature (see page 25) a given e.m.f. may have two corresponding temperature values. The copper-iron couple is, therefore, unsuitable for the measurement of temperature within the range 0°—558° C. This does not necessarily imply that this couple is valueless. On the contrary, it may yield exceedingly satisfactory results in very low temperature work, where even platinum thermo-couples would be unsuitable.

It has already been indicated that the e.m.f. in a thermo-electric circuit is proportional to the *difference* in the temperatures of the hot and cold junctions. This influences the inversion temperature, since from the symmetrical shape of the parabolic curve (Fig. 12) it is clear that the inversion temperature is always as much above the neutral temperature as the cold junction is below it. Thus, if a cold junction temperature of 20° C. is employed with a copper-iron couple, the neutral point again occurs at 279° C., but the current changes its direction at about 538° C.

It has been shown that, approximately, the thermo-electric power of a given thermo-couple is a linear function (i.e. can be drawn out as a straight line curve) of the temperature of its hot junction. The ideal thermo-couple would have a constant thermo-electric power at all temperatures. Such a couple has never been even experimentally achieved, and from what has already been written it will be obvious that a thermo-couple will not be satisfactory in the measurement of temperature unless the thermo-electric power increases progressively as its hot-junction temperature increases throughout a given range. Fortunately, several couples fulfilling this requirement are available, e.g. nearly all the platinum group of metals and those having the alloy *constantan* (copper 50 per cent, nickel 50 per cent, or copper 60 per cent, nickel 40 per cent) as one element of the couple.

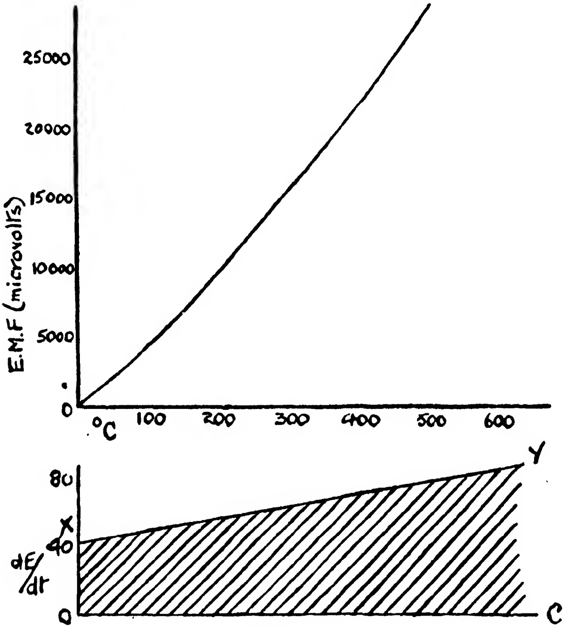


FIG. 13

The thermo-electric curve for the copper-constantan couple taken over a limited range corresponds to the equation

$$E = 40{\cdot}5t + 0{\cdot}036t^2$$

whence by differentiation (see page 26) we get

$$\frac{dE}{dt} = 40{\cdot}5 + 0{\cdot}072t$$

These curves are shown in Fig. 13. The relations are only approximately true, and in this instance cannot be used as a means of finding the values for the neutral and inversion temperatures. The point at which the thermo-electric power line XY shown in Fig. 13 if taken backwards would intersect the temperature axis

OC suggests at once, however, that these temperatures are low in the temperature scale. The platinum series of thermo-couples yields similar curves.

It will now be evident that great care is necessary in choosing a pair of metals or alloys for use as thermo-couples.

Rare Metal Thermo-couples

Rare metal couples do not melt or oxidize below 1600° C., and are thus particularly suitable for measuring very high temperatures. The platinum alloys are, however, readily attacked by furnace atmospheres containing hydrogen, sulphur dioxide, carbon monoxide, and metallic vapours. Suitable protection must therefore be given to them, or the wires will become exceedingly brittle, and their thermo-electric properties be considerably altered. Otherwise, the accompanying changes in these and other physical properties would adversely influence the e.m.f.'s developed and, in consequence, the indicated temperature values.

A glazed porcelain or silica sheath of good quality is perhaps the best means of protecting a rare metal couple from the injurious effects of furnace gases, and enables temperatures at least as high as 1400° C. to be measured. Unfortunately, however, slow and uniform heating of a porcelain tube is essential, or it will crack. In this respect sheaths of fused silica are much better because they withstand rapid changes of temperature without cracking. They have, however, the disadvantage that they cannot be used *continuously* above 1600° C., because they lose their vitreous or glassy property, become porous, and finally disintegrate.

Porcelain and silica sheaths are unsuitable for immersion in molten salt baths. In such circumstances an outer protecting sheath of iron may be used, although in the long run it is more economical to use a sheath of some heat-resisting nickel-chromium alloy.

With any thermo-couple, short-circuiting, i.e. a fault in the circuit allowing part or all of the current to escape, must be avoided by insulating one wire, or both. This means their enclosure in some material that does not conduct electricity and so prevents the current from escaping. For this purpose single or twin-bore (having two passages bored through them) silica or fireclay tubes are used. Twin-bore beads made of unglazed porcelain or fireclay are sometimes used with these tubes to render the couple more flexible when the insulation is complete.

Although fireclay tubes cannot be bored so evenly as silica, they are much cheaper and withstand high temperatures without deterioration, although the platinum is attacked if in contact with fireclay for a long time at high temperatures.

For a heat-treatment furnace, and if the temperature does not exceed 900° C., the arrangement shown in Fig. 14 is quite satisfactory when the couple is vertically suspended. This eliminates the fragile silica or porcelain protecting sheath and the couple responds more readily to temperature alterations in the furnace.

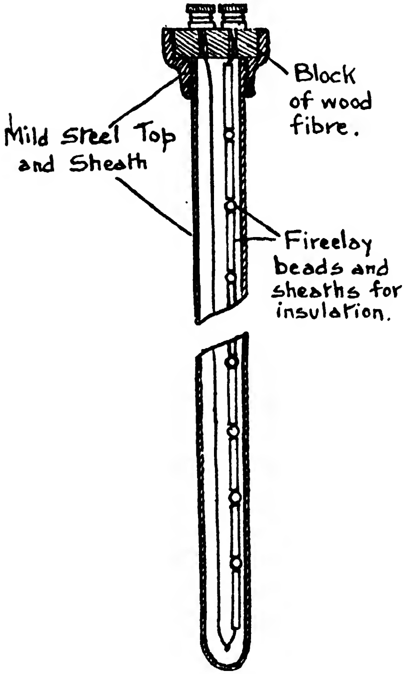


FIG. 14

The best-known rare metal couples comprise one wire of pure platinum and the other of an alloy of platinum with 10 or even 20 per cent of rhodium or iridium. Platinum to platinum-iridium couples yield higher e.m.f. values than platinum to platinum-rhodium couples of similar type. Prolonged heating above 1000° C., however, results in the volatilization (or vaporization) of the iridium and contamination of the pure platinum wire. This alters the e.m.f.-temperature relation, and may also render the pure platinum wire unsuitable for further use. For these reasons platinum-rhodium alloys are always more satisfactory in very high temperature work.

The rare metals are expensive, and in order to reduce the first cost to a minimum the thermo-couple usually consists of thin wires having a diameter of about 0·5 millimetre (1/50th of an inch). The first resistance of such a couple is high, so that its change in resistance during heating when the couple is inserted in a furnace is also large. To minimize the effect of this increase in resistance on the temperature indications, the resistance of the whole circuit must be large in comparison with that of the couple itself. Any change, therefore, in the electrical resistance of the thermo-couple caused by its heating then becomes almost insignificant as far as the total e.m.f. (and, therefore, its temperature indications) is concerned.

This may be accomplished by using a high resistance galvanometer incorporating an additional "ballast" resistance.

The need of a high total circuit resistance when a rare metal couple is used, together with the very low e.m.f. generated—about one-hundredth of a volt at 1000° C.—renders it essential to use a highly sensitive galvanometer. In consequence, such installations suffer from two distinct disadvantages: they cost a lot to buy, and the measuring instrument is extremely delicate.

All thermo-couples should be welded or fused together at their junctions wherever possible. The platinum couples are readily and conveniently fused together by introducing the extremities of the wires at the twisted junctions into the hottest zone of a small oxy-hydrogen or oxy-coal-gas blowpipe flame for a moment only. If they are kept too long in the flame a bigger bead of metal than is desirable will be formed or the wires may separate.

Platinum and its alloys are often supplied in the hard-drawn state, i.e. the wire is made by drawing rods through the tapered hole in a die (see *The Mechanical Working of Steel*), which, in addition to reducing the section down to wire form, hardens the metal as a result of what is termed *work-hardening*. When these alloys are heated, recrystallization gradually occurs, i.e. the crystals of the metal deformed and disintegrated by the wire-drawing operation return to their original form and arrangement. This change is accompanied by an alteration in the thermo-electric properties of couples constructed from them. Even the twisting of the wires to form the hot junction may set up a condition of local physical heterogeneity (the reverse of uniformity), later influencing the temperature indications. In other words, the mechanical action of twisting may set up local deformations of the crystalline structure of the wire, so that its physical properties are different at different points, and this will alter the temperature indications of the instrument, since the resistance will vary from point to point. A new couple, unless obtained directly from the makers of the entire pyrometric installation, should therefore always be rendered as uniform in physical properties as possible by a process known as *electric annealing*. This consists in passing a current of about 10 amps. through the couple-wires of 0·5 mm. diameter, the current being kept on until the wires present an even glow. The full effects and explanation of annealing can best be gathered from *The Structure of Steel* and from Chapter XV of this book. For any other diameter of wire the current strength has to be stronger if the wire is thicker, and vice versa.

After prolonged use, physical heterogeneity may be induced in platinum couples as a result of repeated and non-uniform heatings and coolings. This again is a phenomenon of structural type known as *heat-embrittlement*, dealt with later. Electric annealing will often restore such wires to their original state. Bad places when heated are then readily revealed as dull spots, since they offer a different resistance to the passage of the current. The current must be kept on until they disappear and the whole length of wire glows evenly with the same tint.

CHAPTER III

Base-metal Thermo-couples

BASE-METAL thermo-couples are cheaper than the platinum series, and in consequence the wires may be made thicker and stronger —for standard types, 3 mm. diameter. The first resistance of a base-metal couple to an electric current is, therefore, much lower because the electrical resistance of a conductor is inversely proportional to its area of cross-section. The specific resistance (the resistance of a centimetre "cube" of a base metal) is also less than that of a centimetre cube of platinum or its alloys, so that, in general, the increase in the resistance of the circuit due to the heating of the thermo-couple wires is considerably less than that occurring with rare metal couples. Generally, also, a larger e.m.f. is developed (approx. 3-4 times greater than that of a platinum couple) with the result that a less delicate, but far more robust, indicator or recorder can be used. The indicator may, indeed, be as robust as an ammeter (or instrument for measuring electrical amps.), an important point in industrial work. In this respect the following data for rare metal (platinum to platinum-rhodium) and base-metal (Hoskin's alloys—a series of proprietary alloys invented by Hoskin) are of interest.

Couples consisting of one wire of a copper-nickel alloy of the constantan (see page 28) type with another wire of copper, silver, nickel or iron, yield good results if used within their appropriate temperature ranges. The e.m.f.'s generated depend on the character of the material of the other wire, but almost any constantan couple develops relatively high e.m.f. values, those given on page 40 for the iron-eureka couple being quite typical. (Eureka is an alloy of the "constantan" type consisting essentially of copper and nickel in the proportions 60/40.)

The highest temperature measurable by a particular couple depends largely on the resistance of its wires to oxidation during heating. Iron-eureka couples give good results below 700° C. Above this temperature the iron oxidizes rapidly and scales.

Resistance to oxidation at elevated temperatures is a useful property of the silver-constantan couple, which gives exceedingly satisfactory results for temperatures below 800° C.

For temperatures above 1000° C., few reliable base-metal couples are available. The most satisfactory are those of the *Hoskin's metal* or *chromel-alumel* type, the latter comprising one wire of a nickel-chromium alloy (nickel 90 per cent, chromium 10 per cent) and the other wire of nickel containing 2 per cent of aluminium. These couples may be employed to measure temperatures up to 1300° C. The wires oxidize very slowly, and are almost uninfluenced by metallic vapours, but need protection from carbon monoxide, sulphurous and other reducing (oxygen-removing) gases, particularly in the region of 800° C. Suitable protection is given by an iron or mild steel sheath below 900° C., while between 900 and 1000° C. a nickel-chromium alloy sheath may be used. For still higher temperatures it is necessary to use a fireclay (heat-resisting) sheath with, perhaps, a lining of silica if the attack of the gases is likely to become severe.

In general, the need of protection is less with a base-metal couple than with one of rare metal, and mostly a metal sheath to prevent free access of air or direct contact with flames is all that is required.

One particular use of a base-metal thermo-couple merits special mention, i.e the measurement of the temperatures of

TABLE IV

	Rare Metal	Base Metal
Resistance of thermo-couple stem when cold	2 ohms	0·1 ohm
Probable variation of thermo-couple resistance due to insertion to different depths and into furnaces at different temperatures	1 ohm	0·01 ohm
Resistance of copper cable . . .	1 ohm	0·25 ohm
Resistance of copper coil in indicator . .	24 ohms	2 ohms
Probable change in resistance of cable and coil due to change in atmospheric temperature	1 ohm	0·09 ohm
Therefore probable total change in circuit resistance	2 ohms	0·1 ohm
Minimum total resistance by addition of ballast in order that above change in resistance does not exceed 1% of the total resistance	200 ohms	10 ohms
E.m.f. of thermo-couple at 1000° C. . .	10 millivolts	40 millivolts
Current flowing in moving coil of indicating millivoltmeter, generating the operating force, in milliamperes (thousandths of an ampere)	$\frac{10}{200} = 0{\cdot}05$ mA.	$\frac{40}{10} = 4$ mA.

molten non-ferrous alloys just before they are poured. Here a suitable couple may be inserted directly into the molten metal without any protecting sheath. Thermal lag, i.e. delay is registering the change in temperature, ascribable to the sheath, in thus avoided, and the junction quickly attains the temperature of the liquid metal. "Snap" or instantaneous readings of the temperature of the liquid metal are then easily obtained. Even though the original fused or welded junction may be dissolved by the heat of the molten metal, the e.m.f. remains unchanged, as does the indicated temperature. This is because a well-known law of thermo-electricity—*the Law of Successive Contacts*—comes into operation. This law states that the e.m.f. developed by a thermo-couple is unaffected if the wires are joined by a third metal or alloy, so long as the two junctions, which together then constitute the hot junction, are at the same temperature. In the instance under consideration, the molten alloy serves to connect the thermo-couple wires together.

Data relative to the thermo-couples commonly employed are given in Table IV.

CONVERSION OF E.M.F. INTO TEMPERATURE

The only really satisfactory method of calibrating (checking for accuracy) a thermo-electric pyrometer is to determine the e.m.f.'s corresponding with a series of accurately-known "fixed points," the cold junction of the circuit being maintained at some constant temperature throughout the whole series of experiments. If the fixed point is the freezing point (or eutectic) of a pure metal below 500° C., the metal may be melted in the *plumbago* crucible (i.e. one made from a mixture of clay and graphite), using a good gas burner of the *Meker* type. (A "Meker" burner is a modified and improved burner of the "Bunseh" type, see page 66.)

For temperatures up to 1000° C. a vertical resistance furnace, wound with *nichrome* wire to carry the current, is useful and relatively cheap. Nichrome is a nickel-chromium-iron alloy (60 per cent nickel, 14 per cent chromium, the balance being iron) specially developed for parts exposed to high temperatures because of its freedom from oxidation and distortion. In this type of furnace the heat is provided by a metal wire wrapped round the heating chamber, the resistance it offers to the electric current providing the requisite heat to the chamber.

For still higher temperatures, furnaces wound with platinum wire or tape, or molybdenum wire, may be used. The first cost of a platinum-wound furnace is relatively high, but it has several advantages over the cheaper, molybdenum-wound furnace. Molybdenum rapidly oxidizes if heated in air or water vapour, and if used as a heating element must be protected by being heated in a neutral or reducing atmosphere only, i.e. either one consisting of an inert gas having no action at all on the metal, or one containing an absolute minimum of oxygen, thus lessening the risk of oxidation. This atmosphere is conveniently obtained by passing "*cracked*" or *dissociated* ammonia (ammonia whose atoms have been broken up into simpler groups, so that it is split into its separate components, nitrogen and hydrogen) over the heating coil (the coil of wire wound round the furnace). Ammonia vapour under pressure is generated from cylinders, and passed through a tube-shaped furnace at a temperature of about 500° C. Here it is largely dissociated into its components, nitrogen and hydrogen. The mixed but uncombined gases are next passed through dilute sulphuric acid solution to remove any ammonia left undissociated (because the ammonia is then trapped as ammonium sulphate in the solution), then through concentrated sulphuric acid, to remove most of the moisture carried over from the dilute sulphuric acid solution, and, finally, through a tube containing phosphorus pentoxide (P_4O_{10}). This last is a white powder combining very readily with water, and therefore much used for drying gases by removing completely any water vapour they contain. Hence its employment here.

The temperature coefficient (see page 33) of molybdenum is large—1/200th—and the resistance of the winding rapidly increases as the temperature rises. Since the temperature coefficient of resistance is large and therefore its rate of rise in resistance with rise in temperature rapid, the current correspondingly decreases, which determines the amount of heat generated. To compensate for this we have to start with a large external resistance, which can be reduced as the temperature and resistance of the molybdenum winding increase. An ordinary regulating resistance would need to be very large to allow the current strength to be properly adjusted, and would dissipate too much electrical energy as heat. The amperage is best regulated by means of a *choking coil,* which enables easy adjustment of the current to be made without wasting much electrical energy.

A current strength of about 50 amps. per square millimetre of cross-section will maintain a temperature of 1650° C.

Carbon ring furnaces, in which the necessary heat is generated by passing the current through close-packed graphite, previously crushed, and contained in an outer cylindrical chamber, are also employed for high temperature work. The graphite must be packed with great uniformity, otherwise local heat "spots" will be generated, i.e. there will be intense heat at certain isolated points and a lower temperature elsewhere.

About 100 grams of metal should be used in determining its freezing point. With much smaller quantities there may be a considerable thermal lag (see page 35) resulting from the insulation of the couple by the silica or fireclay sheaths protecting it against the corrosive or erosive attack of the molten metal. The thermo-couple will then show a temperature lower than the true freezing point.

During calibration, the couple and its protecting sheath are inserted in the molten material, and galvanometer deflections or millivolt readings observed as the temperature falls. When the freezing point is reached, the temperature remains constant for an appreciable time, if the quantity specified above is used. This makes it almost unnecessary to plot cooling curves, since the "halt" in the rate of cooling is generally obvious.

A series of e.m.f. values corresponding with fixed points is obtained in this way, and a calibration curve then plotted from the results. This curve is afterwards used to convert millivolt readings into their corresponding temperatures. It must again be emphasized that the e.m.f. is proportional only to the *difference* in temperature between the hot and cold junctions. If the cold junction is always held at some constant temperature, the origin or starting point of the curve is then at the cold junction temperature. If, however, the cold junction is subject to temperature

TABLE V

Couple	E.M.F. in millivolts—Cold junction at 0° C.											
	100°	200°	300°	400°	500°	600°	700°	800°	900°	1000°	1100°	1200°
Iron-eureka .	5·25	10·9	16·5	22·0	27·6	33·4	39·4	45·5	51·6	57·7	63·8	—
Chromel-alumel .	4·08	8·2	12·3	16·5	20·8	25·0	29·2	33·3	37·3	41·2	44·9	48·5
Pt-Pt (10% Rh)	0·70	1·46	2·40	3·38	4·44	5·56	6·70	7·94	9·18	10·5	11·8	13·19
Pt-Pt (10% Ir) .	1·30	2·60	4·10	5·80	7·40	9·10	10·7	12·2	14·0	15·7	17·3	19·0

fluctuations, it is more usual to plot the e.m.f., or its corresponding net galvanometer reading, against the *difference* between the hot and cold junction temperatures. The cold junction temperature existing at the time of a later determination is then added to that obtained from he curve.

In industrial installations, the indicator is generally calibrated directly in degrees of temperature, with the cold junction at the average room temperature—about 15° C. When a temperature reading is desired, the pointer of the indicator is then "set" at this cold junction temperature, the adjustment being made on an "open" circuit, i.e. with the leads disconnected. If compensating leads (see page 23) are used, this method introduces no serious error, since in general the existing cold junction temperature will differ little from that of calibration.

A highly convenient automatic cold junction compensating device—originally devised by Darling—is particularly valuable in industrial installations where the indicating instrument itself is liable to temperature fluctuations. It consists of a spiral made of a compound or bi-metallic strip of two metals, each having a different coefficient of expansion, i.e. whose rates of expansion under heat are different at one and the same temperature. This is attached to the pointer of the indicator. As the temperature falls or rises, this spiral coils or uncoils, and causes the pointer to move over its scale in exactly the reverse direction to that caused by the actual fluctuation in the indicator temperature. In short, when a temperature change pushes the pointer forward (or back) the spiral returns it promptly to its original position. Thus, if the indicator temperature rises, a smaller e.m.f. and, therefore, an apparently lower temperature, is recorded, but the uncoiling of the spiral negatives this.

If compensating leads are not used and the cold junction temperature is subject to considerable variation, serious error may be introduced if the existing cold junction temperature is simply added to the net temperature indicated. In laboratory installations, where a calibration curve is employed, a true mathematical correction is possible, the correction factor per degree being given by the ratio of the tangents of the curve at the cold and hot junction temperatures, i.e. the ratio of the thermo-electric powers at these temperatures.

Thus, a platinum-platinum-rhodium (10 per cent rhodium) thermo-couple gives an e.m.f. of 7·94 mV (millivolts) with its hot junction at 800° C., and cold junction of 0° C. Suppose an e.m.f. is obtained, but with the cold junction at 20° C. From the data on page 37 the thermo-electric powers at 20° and 800° C. for this couple are 0·007 and 0·0124 mV per 1° C. respectively. Thus, the correction to be applied is

$$\frac{0{\cdot}007}{0{\cdot}0124} \times 20 = 11{\cdot}3^\circ \text{ C.}$$

giving a corrected temperature of 811·3° C. instead of 820° C. obtained by the addition of the cold junction temperature to that corresponding with e.m.f. of 7·94 mV.

USE OF FORMULAE IN CALIBRATION

Several attempts have been made to deduce a mathematical expression, applicable to all thermo-couples, connecting e.m.f. with temperature. With certain base-metal couples, the e.m.f. is approximately a linear function, i.e. a straight line relationship (see page 12) of the temperature of the hot junction. Generally, however, the e.m.f.-temperature relation is more accurately expressed by the parabolic equation (see page 26) deduced by Holborn and Day

$$E \doteq a + bt + ct^2$$

where E is the e.m.f. in micro- or millivolts, t the corresponding temperature of the hot junction in degrees centigrade, and a, b, and c are constants whose values vary with different thermo-couples.

For the evaluation of these constants three determinations of the e.m.f. at known temperatures become necessary. A general expression commonly employed and deduced by Holman is

$$E = bt^a$$

where E is the e.m.f. in micro- or millivolts, t the temperature in degrees centigrade, and a and b are constants evaluated by determining the e.m.f. at two fixed points only. The symbols bt^a mean only that b is multiplied by t raised to the power "a" so that if "a" is 2, the product is that of b multiplied by "t" squared, or, as we say, $b \times t \times t$, i.e. bt^2.

This equation of Holman's can be written in another way, known as the *logarithmic form*. The reason for re-writing it is that its values are more quickly discovered by simply referring to the printed, standard logarithmic tables. (These are numerical tables used for shortening calculation, enabling addition and subtraction to be substituted for multiplication and division, and these for more complicated calculations.) The logarithmic form of Holman's equation is written

$$\log_{10} E = a \log_{10} t + \log_{10} b$$

This is the form in which, for convenience of calculation, it is generally used, and in order to avoid logarithms with negative characteristics (involving minus quantities), the e.m.f. is often expressed in microvolts, instead of millivolts, since a millivolt is a thousand times greater than a microvolt. Thus, a positive value is obtained on the left-hand side of the above equation.

This equation is not accurate enough for wide temperature ranges, but if the constants are evaluated independently over limited ranges, say 0–500° C. and 500–1000° C., the error is small, and may for most purposes be neglected. Such formulae are useful when the number of fixed points is limited and a rapid check on the original calibration is desired. E.m.f.-temperature relations for commonly used thermo-couples are—

TABLE VI

Couple	Range	Formula (E.M.F. in millivolts)
Chromel-alumel . .	0° – 500° C. 500° – 1000° C.	$\log_{10} E = 1\cdot011 \log_{10} t - 1\cdot4113$ $\log_{10} E = 0\cdot987 \log_{10} t - 1\cdot3466$
Iron-eureka . .	0° – 500° C. 500° – 1000° C.	$\log_{10} E = 1\cdot031 \log_{10} t - 1\cdot3418$ $\log_{10} E = 1\cdot0608 \log_{10} t - 1\cdot4216$
Pt-Pt (10% Rh) .	0° – 500° C. 500° – 1000° C.	$\log_{10} E = 1\cdot1470 \log_{10} t - 2\cdot4489$ $\log_{10} E = 1\cdot2418 \log_{10} t - 2\cdot7042$
Pt-Pt (10% Ir) . .	0° – 800° C.	$\log_{10} E \doteq 1\cdot0820 \log_{10} t - 1\cdot8729$

USE OF STANDARD THERMO-COUPLES

In industrial work, a standard thermo-couple, if used exclusively for this purpose, affords a ready and reliable means of calibrating a new or used thermo-couple. The hot junction of the couple under test and that of the standard should be placed as close together as possible, and the furnace temperature slowly raised, so that there is no real difference in the temperatures of the two heated junctions. Corresponding readings are then taken every fifty degrees or so.

MEASUREMENT OF ELECTROMOTIVE FORCE

The e.m.f. developed by a thermo-couple is extremely small. The most accurate determination of its magnitude, that generally used in the laboratory, is made by the *potentiometer*, the principle of which is illustrated in Fig. 15. This instrument is actually designed to measure differences of electrical *potential* or pressure.

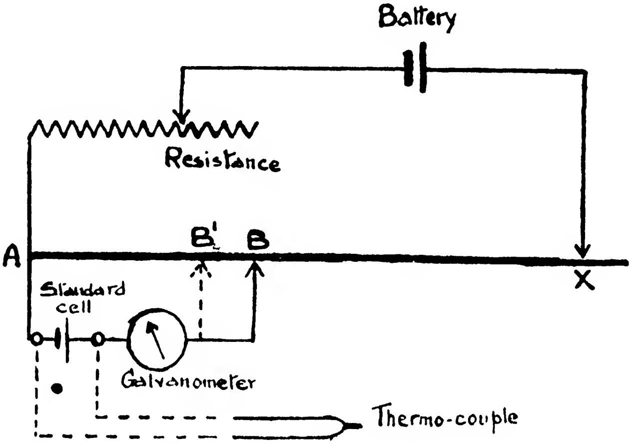


FIG. 15. MEASUREMENT OF ELECTROMOTIVE FORCE

The potentiometer wire is first standardized in terms of e.m.f. (*AX*) per unit length, i.e. is arranged to represent so many units (micro- or millivolts) of e.m.f. per unit of length (inch, centimetre, millimetre, etc.). For this purpose the positive terminal (the end of the lead carrying positive, or +, electric current) of a standard Clark or Weston *cell* (one unit of an electric battery) is connected to *A* and its negative (—) terminal to *B*. The battery current is thus opposed to that of the cell. By altering the position of *X*, a point may be reached at which the galvanometer pointer is not deflected, i.e. no current flows in the lower circuit. The fall in potential between *A* and *B* is then equal to the e.m.f. of the standard cell, which is proportional to the length of *AB*. Each unit length of *AB* thus represents a definite e.m.f. if the resistance and e.m.f. in the battery circuit are kept constant. If, now, the standard cell is replaced by a thermo-couple, but the position of X maintained, the contact B may be altered until, again, there is no deflection on the galvanometer. When this new point of contact, say B^1, is obtained, the e.m.f. generated by the thermo-couple is $\frac{AB^1}{AB}$ times that of the standard cell. In more practical forms, such as the Tinsley potentiometer, the wire AB is replaced by a series of small coils that may be successively inserted or removed from the thermo-couple circuit.

In practical pyrometry the e.m.f. is often measured by galvanometers of the D'Arsonval type, consisting essentially of a *moving coil*, or wire spiral for the passage of electric current, which can be moved at will. This coil is placed between the *poles* or terminal (end) points of a *permanent magnet* (a magnet whose magnetic force is inherent in its constitution, heat-treatment, and previous magnetizing treatment, rather than created by the temporary magnetism induced in the steel by surrounding it with an electromagnetic field generated by passing an electric current through a surrounding, exciting or search coil). When a current passes through the moving coil, the coil is turned in a horizontal plane through an angle proportional to this current.

In laboratory instruments the coil is suspended by a thin strip of phosphor-bronze, a copper-tin alloy, and the twisting of this strip generates the restoring force of the coil. It is an axiom in mechanics that action and reaction are equal and opposite, and in this particular case the force required to twist the strips generates a force equal and opposite in the strip, which brings it back to zero when the original force is removed.

In this way, no frictional force is involved during the movement of the coil, i.e. no energy is absorbed in overcoming the frictional resistance of the coil to the movement, and therefore maximum sensitivity is obtained. Suspended coil instruments have several disadvantages. They must be mounted on firm supports, the coils must be locked in position whenever the instruments are moved, and careful levelling is necessary before they can be used. Otherwise, there is a grave risk that the suspension will be damaged and the coil "stick" (not be free to move when the instrument is in actual use). In consequence, galvanometers of this type are unsuitable for industrial work. In modern industrial millivoltmeters the coil is mounted on one or two conical jewels, which have great hardness and resistance to wear, and are held in place by spiral springs. To the coil is rigidly attached a light pointer which moves over a scale graduated directly in degrees of temperature, and sometimes also in millivolts, as shown in Fig. 16. Even with this method of mounting, a millivoltmeter is necessarily a delicate instrument and should always be so regarded.

Accurate readings are obtainable only if the *magnetic flux* between the poles of the magnet remains constant. (The magnetic flux is the quantity of magnetism or magnetic force threading through a specific area.) This flux is influenced by "stray" (scattered or casually encountered) magnetic *fields*, just as the audience at an open-air meeting may be influenced by another nearby, and wander off to it. These "fields" are the regions in which magnetic forces are encountered or existent. Because of this influence, indicators and recorders should never be fixed side by side on steel stanchions or near cables carrying heavy currents unless protected by an iron case or some other suitable internal magnetic shield. Otherwise the magnetic fields existent in each other and in the surroundings will interfere with the constancy of their flux and so falsify their readings. Permanent magnet manufacturers take into account that the magnetic properties of their magnets may change with time and may, moreover, be seriously impaired by any damage they receive in transit.

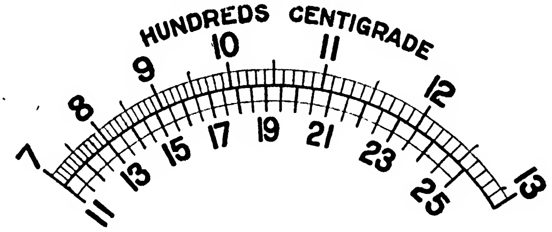


FIG. 16. MILLIVOLTMETER SCALE

RECORDERS

In certain instances, such as annealing, it is often desirable to have a permanent record of variations in temperature during the process. For this purpose several self-recording instruments, of different types, are available. The simplest recorder has a chart in the form of a disc revolving once in 24 hours, but this suffers from the disadvantage that both time and temperature divisions on the chart are curved and the time-temperature curve is consequently less easily interpreted than those obtained with rectangular co-ordinates or straight lines from the plotting of the curves.

The recorders most often used have the chart either wrapped round a drum, rotating once in, say, 25 hr. (Fig. 17) or as a long continuous strip lasting for perhaps one month. In both instances the chart usually has rectangular co-ordinates, and is marked by the action of a chopper bar which drops at regular intervals (usually one minute) and presses against an inked thread stretched across, and just above, the chart. Alternatively, a stylus pen replaces the combination of knife edge and inked thread. Recorders of the galvanometer type work with exceedingly small deflecting forces, too feeble to move a pen kept continuously in contact with the chart, so that in every instance the pointer is periodically depressed in order to leave a dot on the chart. In practice, however, most of the dots join up to yield an almost continuous line.

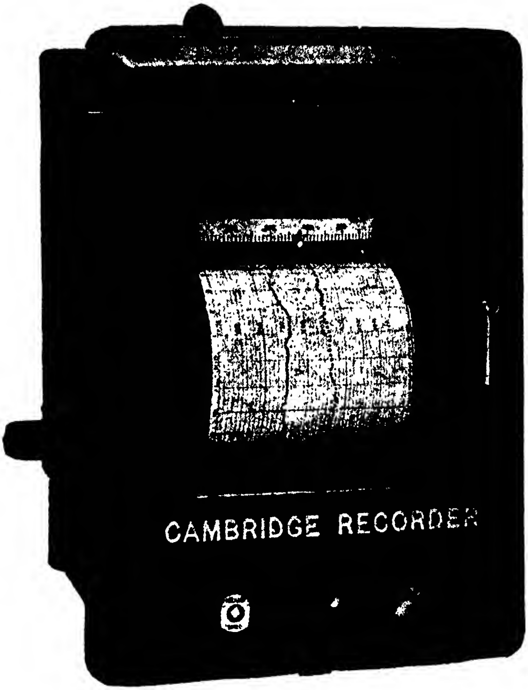


FIG. 17. DRUM TYPE RECORDER

Within recent years thermo-electric installations have been designed capable of automatically indicating correct and incorrect treatment temperatures. Thus, in one, a white bulb is illuminated if the furnace is at the correct temperature, a green bulb means temperature too low, and a red bulb means temperature too high.

FIG. 18. PORTABLE INDICATOR OR MILLIVOLTMETER

In electrically heated furnaces the temperature may be automatically controlled. An auxiliary pointer is attached to the galvanometer, which may be adjusted to any desired value, and when the temperature indicator comes in contact with it this operates a *relay*, which cuts off the current supply to the furnace. (A relay is a device controlling the electric supply to power or heating equipment in response to quantitative variations of a relatively feeble actuating force or current.)

It cannot be too strongly emphasized, however, that even with the most elaborate automatic thermo-electric apparatus, *periodic calibration or checking for accuracy is essential.*

CHAPTER IV

Radiation Pyrometers

ANY body at temperatures above absolute zero (see Chapter I) radiates energy in the form of heat and, at higher temperatures, light also, to its surroundings, which also radiate energy back to it. The *rate* at which energy is radiated as heat, and as light also when the heated body glows, can be used as a measure of temperature. If the energy radiated by the body exceeds what it receives from its surroundings, it is hotter than the surroundings, and vice versa. When the energy it radiates is exactly equal to what it receives, it and its surroundings are at the same temperature. A hot body, when it ceases to be heated, goes on cooling down until this condition of equal temperature with its environment, known as *dynamic equilibrium*, is eventually reached.

All radiation pyrometers are based on the *fourth power law*, deduced thermodynamically (see Chapter I) by Stefan and experimentally verified by Boltzmann. This law states that the energy radiated by a hot body is proportional to its temperature multiplied by itself four times, so that the energy given out increases at a rapidly increasing rate as the temperature rises. Expressed mathematically, the Stefan-Bóltzmann law is as follows: $E = KT^4$, where K is a constant and T^4 is the temperature raised to the fourth power. (A "power" is the number of times a number must be multiplied by itself to satisfy specified conditions. Thus, 2 raised to the fourth power, i.e. 2^4, is sixteen.) In this equation E is the intensity of the energy radiated by a hot body at a temperature T degrees absolute and K is a constant whose value depends on the units chosen for the measurement of the energy. By differentiation (see Chapter II) $dE/dT = 4\,KT^3$, i.e. the rate of increase of the energy radiated by the body is proportional to its absolute temperature cubed. Therefore, the radiation pyrometer is most suitable for very high temperature work, since a more open scale is then obtained, the higher the temperature the greater being the increase in the rate of energy emission. If, now, the body at a temperature of $T_1°$ is radiating energy to surroundings at $T_0°$, the following relation holds: $E - E_0 = E_1$ (say) $= K\,(T_1^4 - T_0^4)$, where E_1 is the *net* amount of energy radiated and so lost by the hot body. Let us suppose two radiating sources at temperatures $T_1°$ and $T_2°$ respectively, with, in each instance, surroundings at a temperature $T_0°$. The following relation clearly holds—

$$\frac{E_1}{E_2} = \frac{T_1^4 - T_0^4}{T_2^4 - T_0}$$

where E_1 and E_2 are the net energies radiated by the bodies at temperatures $T_1°$ and $T_2°$ respectively. In practical pyrometry

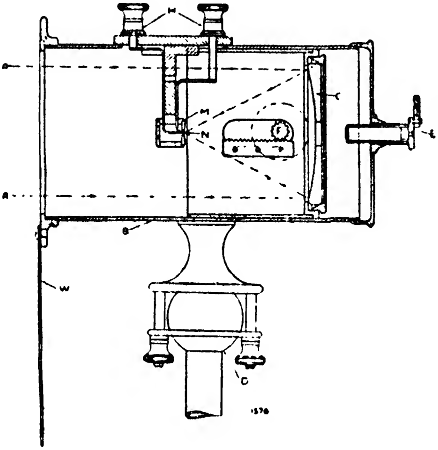


Fig. 19

T_0 is generally much lower than either T_1 or T_2 and, therefore, its fourth power is exceedingly small in comparison with T_1^4 or T_2^4 and may be neglected. Thus, in comparing the energies emitted by two hot bodies at different temperatures, we may write

$$\frac{E_1}{E_2} = \frac{T_1^4}{T_2^4}$$

If, now, E_1 and E_2 can be measured, and one temperature, say T_1, is known, the other is easily calculated.

The commonest way of measuring the energy radiated is by a *blackened* thermo-couple situated at the focus (or point at which the beams of light and heat it reflects meet) of a concave "silvered" or stainless steel mirror, as represented in Fig. 19. The radiant light and heat are thus converted into electrical energy, which is readily measured by connecting the thermo-couple leads to a delicate galvanometer. The maximum temperature of the couple rarely exceeds 80° C., and by using compensating leads (see page 23) the readings are practically uninfluenced by any variation in the temperature of the receiving instrument.

Under these conditions

$$\frac{\text{E.m.f. at } T_1}{\text{E.m.f. at } T_2} = \frac{T_1^4}{T_2^4} = \frac{(t_1 + 273)^4}{(t_2 + 273)^4}$$

there t_1 and t_2 are the centigrade temperatures corresponding with the absolute temperatures T_1 and T_2, from which an e.m.f.-temperature relation is readily established, and any indicated e.m.f. converted into its corresponding centigrade temperature reading. This principle is involved in the well-known Féry pyrometer (Fig. 19). The heat (and light) rays emitted by the hot body are focused on to the couple (N) by means of the mirror C. The thermo-couple *must* be completely enclosed by the cone of rays reflected from the surface of the mirror, and in the Féry instrument the correct conditions are obtained by means of an extremely simple focusing device involving two small wedge-shaped mirrors (M).

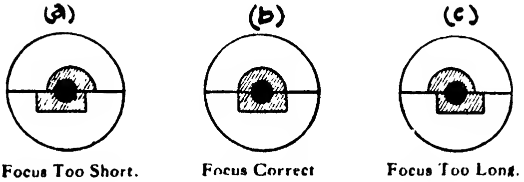


Fig. 20

On looking through the eyepiece E, the observer sees an image of the heated object in the mirror M. If the eyepiece is correctly focused, the appearance will be as shown in Fig. 20 (b), where the black centre represents the image of the couple, and the shaded portion the reflected image of the hot body. Incorrect focusing is indicated by a divided image as represented by either (a) or (c). By rotating the knurled or milled head attached to the pinion F, the upper and lower half-images slide over one another until they coincide and correct focus is obtained.

In the Foster *fixed focus* radiation pyrometer this preliminary focusing is obviated by using a relatively long and narrow receiving tube. (The reader must accept this statement as a fact.)

As already stated, the e.m.f. generated by the couple is measured by a scale, calibrated in both degrees centigrade and millivolts.

Theoretically, temperature readings should be independent of the distance of the pyrometer from the object whose temperature is being sought, since although the intensity of the radiated energy impinging on the mirror surface varies inversely (i.e. the one quantity increases while the other decreases) as the square of its distance from the radiating source, the number of light rays received per unit area (i.e. per square inch or square millimetre) of surface is directly proportional to the square of this distance. In actual practice, however, the hot body or aperture should be at least 1 in. diameter for each 2 ft. of distance between it and the pyrometer, in order that the reflected cone of rays shall completely overlap the thermo-couple.

Since as a rule the radiated energy is measured in terms of e.m.f., it is clear that this type of radiation pyrometer may be used in conjunction with the thread and other recording instruments commonly used in thermo-electric pyrometry.

CONDITIONS FOR CORRECT READING OF RADIATION PYROMETERS

It must be realized that the Stefan-Boltzmann law, upon which all radiation pyrometers are based, is only strictly applicable to true *black bodies,* i.e. substances absorbing all the radiant energy falling upon them. A hot body emits only the same kind of radiation as it absorbs at a given temperature. (This is a well-known and established fundamental law of physics.)

Thus a black body is the only perfect radiator. In actual fact, there is no perfect black body, although carbon in the forms of graphite and lamp-black (a pigment made from soot), as well as certain metallic oxides, closely approximate to it.

The rate at which energy is radiated by a hot body depends on the material of which it is composed, and on its surface condition. Thus, if a radiation pyrometer is focused, *in the open,* on a block of carbon, a higher reading will be obtained than if it is focused on a piece of porcelain under similar conditions. A still lower reading will be obtained with, for example, polished platinum. This is because the emissive powers (ability to emit rays) of porcelain and platinum are considerably less than those of graphite, a consequence of their different chemical and physical properties. Indicated temperatures, always low, are sometimes known as *black body temperatures*, since they are the values indicated by a pyrometer that has been calibrated or checked under true black body conditions. The term is unfortunate and apt to be misleading, since at first sight one would naturally assume, from what has been said, that a black body temperature should be a correct temperature.

If the emissivity, or ability to radiate energy, of a perfect black body is taken as unity (1), clearly the emissive powers of other substances, not so effective in this respect, must be fractions of 1. The emissive power (e) is the ratio of arithmetical relation of the intensity of the energy emitted by a body at an absolute temperature T° to that emitted by a perfect black body at the same temperature. Clearly from the fourth-power law we have

$$\frac{E_0}{E_1} = e = \frac{T_0^4}{T_1^4}$$

where E_1 and E_0 are the energy intensities emitted by any substance and a black body at one and the same temperature, and T_1 and T_0 are the indicated and true temperatures respectively. From this the following logarithmic relation is readily obtained—

$$\log_{10} e = 4 \ (\log_{10} T_0 - \log_{10} T_1)$$

whence, if T_0 is known (say, by means of a thermo-couple) and T_1 is the indicated temperature, e may be evaluated and afterwards used to convert indicated into true temperatures. Emissive powers of several substances are given in the following table—

TABLE VII

Aluminium	0·20
Graphite	0·95
Molten copper	0·15
Copper oxide	0·60
Molten brass	0·28
Molten iron	0·28
Iron oxide	0·85
Nickel oxide (at 1000° C.)	0·80
Zinc oxide	0·10

It has been shown that the emissivities of hot bodies more nearly approach the figure 1 when they are at higher temperatures. The amount of correction needed to convert indicated into true temperatures thus becomes less as the temperature rises. The same correction cannot be used, however, for observations taken in both a well lighted and a poorly lighted shop. In consequence, mathematical corrections to radiation pyrometer readings taken in the open can only be applied under definitely known conditions. If, however, external conditions are always kept fairly constant, a radiation pyrometer can be extremely useful if its readings are regarded as relative rather than absolute. Correction then becomes unnecessary.

Black body conditions can be experimentally realized, since it has been shown that the interior of a closed furnace functions as a true black body. Further, the radiation emanating from a small hole in the side of such a heated chamber is practically true black-body radiation. Thus, pieces of graphite, porcelain, or polished platinum within a furnace, and at the same temperature, cannot be distinguished from one another. A radiation pyrometer, sighted in turn on each of these three materials, would give the same true temperature reading. The radiation pyrometer is, therefore, more suitable for determining temperatures within an enclosed space, e.g. inside a furnace, than in the open. At the same time, flame, dust, smoke and fumes within the furnace may seriously affect the temperature readings, since they affect the intensities of the heat and light emitted. To obviate error arising from these sources, a porcelain or fireclay tube may be inserted in the furnace and the pyrometer sighted on the closed end.

CHAPTER V

Optical Pyrometers

Most optical pyrometers in use to-day are of one of two kinds: (*a*) the disappearing filament, or (*b*) the polarizing type. In each of these the intensity of the light emitted by the heated object is matched against that from a standard source.

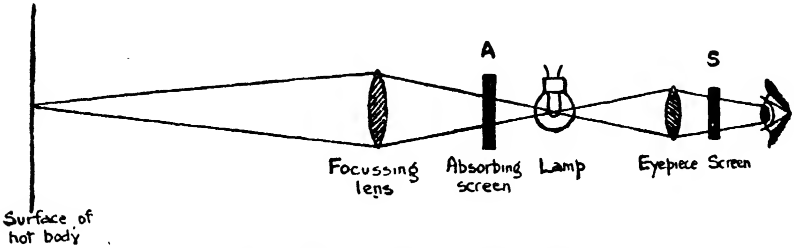


Fig. 21. Typical Optical Arrangement

In the disappearing filament pyrometer a hairpin filament lamp (one whose filament is shaped like a hairpin) is used as the standard, the electric current passing through it being adjusted until the image of the filament, seen through the eyepiece, just disappears into the *field* or area illuminated by the body whose temperature is being sought. The temperature is then indicated by a milliammeter or voltmeter graduated to read in degrees centigrade.

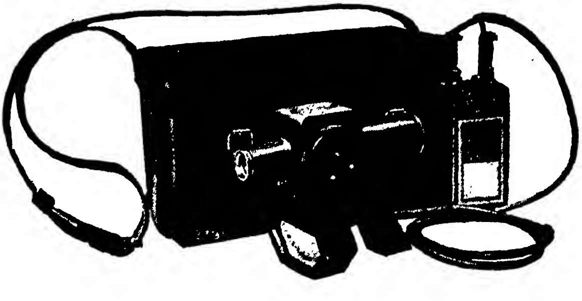


Fig. 22. External View of Disappearing Filament Pyrometer

A typical optical arrangement is indicated in Fig. 21, while Fig. 22 shows an external view of an instrument of this type.

Below 800° C. the red rays of the visible spectrum predominate, and the exact point of disappearance of the image of the heated filament is readily adjusted by varying the resistance. (The visible spectrum is, of course, the image formed by coloured rays of light, or when white light is split up into its component primary colours by a glass prism, usually triangular, or by water drops as in the rainbow.) When *too much* current passes through the lamp circuit, the filament appears as a bright line upon a darker background, since, of course, the excess current will make the filament glow more brightly than the hot body. With *insufficient* current, it will show as a dark line on a lighter background. When the current is *correctly adjusted* the tip of the filament will merge into and be indistinguishable from the background. These conditions are indicated in Fig. 23. From Fig. 21 it will be seen that the image of the heated object is brought into the same surface or plane as that of the filament by the lens system comprising an objective and an eyepiece.


Decrease Rheostat *Increase Rheostat* *Matched*

FIG. 23

For temperatures above 800° C., screens are used to minimize glare and so facilitate comparison. Between 800° C. and 1400° C. the monochromatic (of one colour only) screen S is interposed between the eye and both images. This renders the light from both sources almost monochromatic, but does not influence the readings taken without the screen, since both intensities are reduced by the same amount. For still higher temperatures it is usual, in order to avoid over-heating of the filament, to interpose an absorbing screen A between the hot body and the filament. This diminishes the intensity of the light received *from the hot body only*, and therefore a different calibration (or system of marking) and scale must be employed. The instrument is thus fitted with a double scale, as shown in Fig. 24. In some instruments the lamp is connected *in series* with a milliammeter and a *rheostat.* (To be connected in series means that the several instruments are connected in sequence—one after the other—as distinct from connecting in parallel, where groups of conductors or instruments are independently connected to the same positive and negative terminals of the same main circuit. A rheostat is a resister of electric current in which is embodied means for regulating the value or amount of its resistance.)

In other instruments, a voltmeter is used to measure the potential drop, or fall in electrical energy, across the filament and is then graduated to read temperature degrees. This method yields a more open scale, since the motive force operating the needle of the instrument exerts a more powerful effect.

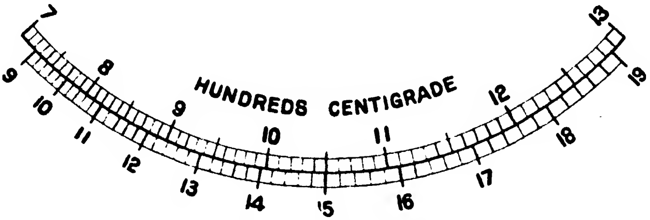


Fig. 24. Double Scale Instrument

With either circuit, calibration and checking for accuracy are easily accomplished by applying the relation

$$C = a + bt + ct^2$$

where C is the current flowing through the circuit (or the fall in voltage across the filament's terminals), t is its temperature in centigrade degrees under black body conditions, and a, b, and c are constants. Three determinations at known temperatures suffice to evaluate the constants, a, b, and c, which may then be employed to convert any current reading into its corresponding temperature. A similar relation to the above will obviously hold for instruments measuring the voltage drop across the filament terminals.

In the polarizing type of optical pyrometer, a chosen ray of monochromatic light (generally of wavelength $0{\cdot}6\mu$) from the hot body is adjusted to the same intensity as that emitted by a standard electric lamp illuminated by the current derived from an *accumulator* (a series of storage cells charged with electricity by an electric dynamo or motor, and storing up electrical energy until such time as it is required). In reality, this pyrometer is a kind of photometer or light-measurer. The first successful instrument was devised by Wanner, of which the Leskole and Cambridge pyrometers are improved forms. Wanner's optical system, which may be regarded as typical, is represented diagrammatically in Fig. 25. It consists essentially of a direct vision *spectroscope*, a Rochón (*tourmaline*) *prism*, a Nicol prism which serves as an analyser, and a series of lenses.

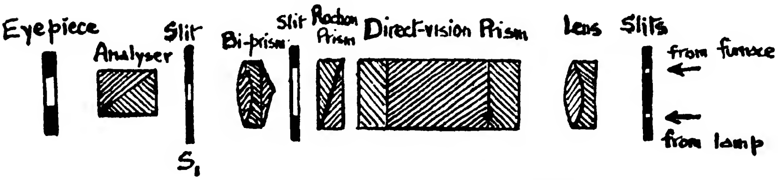


Fig. 25. Wanner's Optical System

As this string of new and curious terms may puzzle the reader, we will simplify them. A spectroscope is simply an instrument that determines what a substance is, or contains, from the colour or colours of the "flame" it gives when heated until incandescent or white-hot. A prism is a solid body whose ends or sides are plane figures, i.e. those lying in a plane, or perfectly flat, surface, e.g. triangles. The ends of a prism usually employed in optical pyrometry are equal to and parallel with one another, and the sides plane parallelograms, as in Fig. 26.

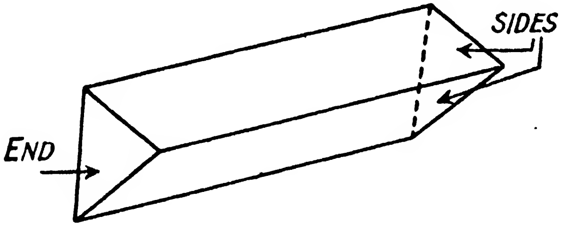
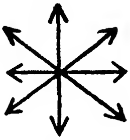


Fig. 26

If ordinary white light, e.g. daylight, is passed through a prism, it is broken up into a fan-shaped beam of component *primary* colours, made up of rays of light of different wavelengths, thus producing on the eye of the beholder the effect of different primary colours, in bands gradually merging into one another, as in the rainbow. This is termed the visible spectrum. When heated, many substances produce a flame of distinctive colour, and this colour is invariably found somewhere in the visible spectrum. The colours corresponding to different substances have been tabulated, so that by means of a direct vision spectroscope we can determine from the colour of the light given off by an incandescent body to what substance in the table it corresponds, i.e. what it is. A Rochón prism is made of tourmaline, a mineral of complex type which, in the form here used, is transparent and colourless, and polarizes ordinary and extraordinary rays at right angles to each other. These rays are explained later. In other words, the Rochón prism has certain useful optical characteristics whose explanation would take us far from our present subject. A Nicol prism consists of two wedges of the mineral calcite, joined together by a cement known as *Canada balsam*, and its function is to convert all light passing through it into plane polarized light, i.e. light whose vibrations are all in the same direction,

thus ↔ instead of 

By the combination of these various prisms and lenses and the spectroscope, each red ray from the heated object and the lamp is split up into two rays, an ordinary and an extraordinary ray, *polarized at right angles to each other*, but the optical system of lenses is so arranged that the ordinary ray of the one source and the extraordinary ray of the other source are deflected from the optical train, so that we are left with an ordinary ray, say from the heated object, and an extraordinary ray from the standard lamp. These two rays are polarized at right angles to each other, so that by rotating the analyser, or Nicol prism, a greater or less amount of either ray passes through the instrument, and it is thus possible to obtain a balance in the colours seen through the eyepiece of the instrument.

Each of these rays is made to illuminate half of a circular field when viewed through the eyepiece of the instrument, so that by rotating the Nicol prism interposed between the slit *S* and the eyepiece the intensity of one semi-circular field is diminished and that of the other increased, until at last the entire circle is uniformly bright. Should lamp and source emit red light of the same intensity, then obviously the eye will see a uniform red field when the analyser is at an angle of 45° with the two planes of polarization. For any other angular rotation (ϕ) necessary to bring both half-fields to the same tint, the following relation holds: $\frac{I_1}{I_0} = \tan^2 \phi$ where I_1 and I_0 are the first intensities of the two sources of light. If, now, I_0 is kept constant, it will be evident that the angle of rotation of the analyser is a measure of the intensity I_1. The intensity of the light emitted by a hot body, however, is a function of (has a definite relation to) its absolute temperature, and thus an angular scale attached to the analyser may be calibrated to read degrees of temperature. Optical instruments of this type are based on *Wien's Displacement Law* for monochromatic radiations (rays of light of pure or simple wavelengths).

This is represented by

$$I = C_1\lambda^{-5} \,.\, \varepsilon - \frac{C_2}{\lambda T}$$

where I is the energy corresponding to wavelength λ emitted by a black body at absolute temperature T, C_1 and C_2 are constants, and ε is the base of the Napierian system of logarithms ($= 2{\cdot}71828$). In the determination of temperatures, we are concerned with the measurement of intensity *ratios* only. Clearly we then have

$$\frac{I_1}{I_0} = \frac{\varepsilon^{-\frac{C_2}{\lambda T_1}}}{\varepsilon^{-\frac{C_2}{\lambda T_0}}} = \frac{\varepsilon^{\frac{C_2}{\lambda T_0}}}{\varepsilon^{\frac{C_2}{\lambda T_1}}} = \tan^2 \phi$$

where I_1 and I_0 are the intensities corresponding to absolute temperatures T_1 and T_0, and ϕ, as before, is the angular rotation of the analyser required to bring chosen red rays from these two sources to equality. By logarithms we have

$$\log_{10} \tan^2 \phi = \frac{C_2}{\lambda} \log_{10}\varepsilon \left(\frac{1}{T_0} - \frac{1}{T_1}\right)$$

which may be rewritten thus—

$$\log_{10} \tan \phi = K_1 - K_2 \,.\, \frac{1}{T_1}$$

where K_1 and K_2 are constants if T_0 is kept constant as by a standard electric lamp. These constants may therefore be evaluated by two determinations at known temperatures other than T_0. The above relation is obviously linear, and if its curve is plotted, a straight line is obtained connecting $\log_{10} \tan \phi$, and the *reciprocal* of the absolute temperature. (A reciprocal of a number is that quantity which, when multiplied by the number, produces unity. Thus $4 \times \frac{1}{4} = 1$, so that 4 and $\frac{1}{4}$ are reciprocals. The same is true of 5 and 0·2.) It is therefore a simple matter to graduate the instrument to read degrees of temperature.

Since the standard lamp forms part of an accumulator circuit, the brightness of its filament may vary, as the electric current originating in an accumulator is not always uniform in flow. To overcome this difficulty the intensity of the light is standardized against that of an *amyl-acetate* flame. Amyl-acetate ($CH_3COOC_5H_{11}$) is a colourless liquid with a powerful smell like that of pear drops, and is made by the distillation of a mixture of amyl alcohol and sulphuric acid with sodium acetate. Burnt in a special lamp, it gives a flame whose intensity and apparent black body temperature are constant and definitely known. In carrying out the standardization, which should be done frequently, the procedure is as follows: with an amyl-acetate flame of given length and at a given distance from the receiving end of the instrument, the analyser is "set" at an angle specified by the instrument makers and the adjustable resistance in the lamp circuit is then varied by a rheostat (see page 54) until the half-field illuminated by the filament has the same intensity or colour as that of the amyl-acetate flame.

The current flowing through the filament is indicated by a milliammeter, and the reading must be kept constant at this value when the pyrometer is afterwards used to determine the temperatures of heated bodies. By this means also, the gradual deterioration of the filament with time, or ageing, is compensated. Incidentally, the lamp is usually artificially aged by "over-burning" for a considerable time before it is placed in the instrument.

Black Body Conditions and Corrections

Wien's law is applicable to true monochromatic or single black body radiation only. When determining temperatures within an enclosed space, through a small peephole, where smoke, flame, and fume are absent, little or no correction is needed, and the indicated temperatures may be accepted as true. For the determination of temperatures in the open, however, correction factors must be used if the true temperature is to be estimated. The extent of this correction depends on the character of the hot body and on the conditions under which the determination is made.

Generally, however, the amount of the correction is considerably less than when a total radiation pyrometer is employed, since, with the latter, light and heat rays of *all* wavelengths are used, whereas in a true optical pyrometer the radiation measure is essentially monochromatic. The *emissivities*, or rates at which heat or light is radiated, differ considerably for monochromatic light from those for total radiation at the same temperatures. Let us assume that the monochromatic emissivity for light of wavelength λ is e_m for a hot body at a temperature of T and its black body temperature as indicated by an optical pyrometer is T_1. If I_2 and I_1 are the intensities emitted by a true black body and the hot body respectively at the temperature T_2, we have from Wien's law—

$$\frac{I_1}{I_2} = \frac{\varepsilon^{\frac{-C_2}{\lambda T_1}}}{\varepsilon^{\frac{-C_2}{\lambda T_2}}} = \varepsilon^{\frac{C_2}{\lambda}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)} = e_m$$

(The emissive power for monochromatic light)

By logarithms $\log_{10} e_m = \frac{C_2 \log_{10} \varepsilon}{\lambda}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$

$\log_{10}\varepsilon = 0{\cdot}4343$ and for red light of wavelength $0{\cdot}65\mu$, the constant $C_2 = 14{,}500$, hence

$$\log_{10} e_m = 1{\cdot}032 \times 10^{-4}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

The emissivity e_m is thus readily determined, under given conditions, from the indicated temperature T_1 and the correctly known temperature T_2 (measured by means, say, of a thermocouple), and its calculated value may then be used to convert the indicated temperatures. The emissivities of some important materials for monochromatic red light ($0{\cdot}65\mu$) are as follows—

TABLE VIII

Graphite	0·95
Molten copper	0·15
Copper oxide	0·70
Molten iron and steel	0·40
Iron oxide	0·95
Molten nickel	0·37
Nickel oxide	0·90
Molten silver	0·10
Molten gold	0·22
Molten platinum	0·38

Much useful work on the determination of high temperatures has been done by a Pyrometric Sub-Committee of the Iron and Steel Institute (Fourth Report on Heterogeneity of Steel Ingots, 1932). It has been shown that the wavelengths of the light transmitted by screens in several pyrometers of the polarizing type may differ considerably, thus accounting to some extent for the discrepancies when different instruments are used.

The Committee's recommendation of the disappearing filament pyrometer as the most suitable for measuring high temperatures such as those of molten steel has since been rescinded, and the Schofield thermo-electric couple has now been established in practice for this purpose. See *Steel Manufacture*, third edition, for a description of this thermo-couple.

As already indicated, optical and radiation pyrometers show true temperatures only when used under true black body conditions. If used under other conditions, such as to determine temperatures in the open, correction factors must be utilized to convert indicated into true temperature readings. Such corrections are unnecessary however, if an instrument is always used under similar conditions, and if the indications are regarded as relative only.

One of the chief advantages of both these types of pyrometers is their portability. They may be easily carried from place to place.

OTHER PYROMETERS

Of other methods used to measure temperature, the only pyrometers that need be considered are the so-called fusion pyrometers. The most important of these are the *Seger cones* and Brearley's *Sentinel pyrometers.* The former are triangular pyramids composed of silicates, which begin to melt or soften at previously determined temperatures. At the softening temperature, the apex of the cone bends over towards the triangular base. These cones have been found exceedingly useful in the study of refractoriness or heat resistance in materials used for crucibles (pots in which steel and other metals are melted) and furnace linings.

Sentinel pyrometers are cylinders of compressed salts, with wax coatings to avoid deliquescence (liquefaction, due to absorption of moisture from the atmosphere). Both pure salts and eutectic mixtures are used, and each cylinder, contained in a small porcelain dish placed on or near the articles to be heat-treated, melts completely at the specified temperature. These pyrometers are particularly useful when thermo-couples temporarily break down in heat-treatment furnaces, and as a means of checking thermo-electric pyrometer readings.

CHAPTER VI

Furnaces

HEAT-TREATMENT involves, at all events in its main stages, raising the steel to a correct temperature in a furnace fired or heated by various methods. The fuel used may be coke, coal, gas (town, blast-furnace, or natural), fuel oil, or electricity. Which is used depends mainly on the particular form of treatment required, the availability of the fuel, and the economics of the process. At the same time, however, the most economical furnace for a particular operation is not necessarily that costing the least to run. It is quite possible for a furnace to be cheap in cost per unit of heat and dear in spoiled steel, upkeep of equipment, labour charges, and other factors. The proper and only satisfactory basis for judging a furnace is, therefore, the quality and cost of the finished product. The efficiency of a fuel for heat-treatment furnaces depends mainly on the extent to which that fuel lends itself to control so as to yield enough heat to suit the furnace charge. It is the difficulty of control that makes coal-fired or coke-fired furnaces, when these solid fuels are burned on a grate or stoker, unsuitable for all except a few heat-treatment operations such as those carried out in the blacksmith's coke-fired hearth, where the highest accuracy is not essential, and, incidentally, not obtainable. Attention should, however, be paid to the notes in Chapter VII.

A heat-treatment furnace should, in principle, give a specific temperature that will not vary outside certain defined limits. This temperature should be uniform over the whole area of the furnace during the entire heat-treating period, or, if desired, graded conformably to requirements. The furnace must be trustworthy, readily controllable, needing the bare minimum of attention and upkeep cost. It should be quick and easy to heat to the desired temperature, and the atmosphere of the furnace chamber should be appropriate to the work and controllable, so that the proper surface condition may be obtained on any steel to be heat-treated. Finally, the furnace should be satisfactory in cleanliness and working conditions for the operator. (Atmosphere control is so important in modern heat-treatment that it has been given a separate chapter.)

The temperature variation permissible is largely affected by the character of the operation, but is usually in the region of plus or minus 5 degrees C. where great accuracy is required.

Most modern heat-treating furnaces are either gas, oil, or electrically-fired.

GAS-FIRED FURNACES

For those forms of heat-treatment demanding exact control, gas is, perhaps, the most suitable fuel because the temperature can be held to close limits, while the furnace atmosphere can be regulated and maintained, an important factor whose significance will be apparent in due course. Oil, used chiefly in the United States, and to a less extent in this country, is equally capable of temperature and atmosphere control, but for the best results special attention has to be paid to the furnace design, and rather more careful working is needed. Electricity is principally used where the temperatures required are not above 1040° C. The factor limiting its employment to this range is the relatively rapid deterioration of the resistance elements with higher heats. There are, however, exceptions to this statement, and these will be dealt with in the chapter on electric heat-treatment furnaces.

Gas as a heat-treatment fuel can be natural (occurring in nature) or artificial. It can be obtained from blast furnaces, where the waste gases given off during the process (see *Steel Manufacture*) are economically utilized for furnace firing, although the upper limit of temperature, when blast-furnace gas is used, is about 900° C. Up to this temperature, when properly cleaned, blast-furnace gas is almost the ideal fuel. Gas may be made in gas producers (again see *Steel Manufacture*), or can be taken from the town supply. Where such supply is economical, efficient, and trustworthy, this is the commonest and probably most effective method, because the gas undertaking has already done all the necessary work on the raw materials. The consumer has only to kindle the fuel supplied to him. He has not to provide plant for its manufacture or storage.

The convenient form in which *town gas* is supplied and its constant value in terms of effective units (its *calorific value*) enable it to be burned in the widest variety of different burners, controllable either individually or as a set to give a constant supply of heat capable of distribution as desired.

Furnaces fired by town gas will give, without difficulty, the temperature constancy required for accurate heat-treatment, so long as they are correctly designed. This constancy can be virtually guaranteed, subject to certain conditions, if a suitable system of automatic temperature control is employed. This, however, is not a matter of simply watching the pyrometer to see that it does not go above or below the limits set. The major factor is the furnace charge, i.e. the quantity and type of steel introduced for treatment into the furnace chamber. It is quite possible for the *pyrometer* to show a correct temperature within the required working limits, but if the *charge* is not uniformly heated throughout to this temperature, some parts being hotter than others, the steel, after being cooled or quenched, will be inconsistent in hardness.

Temperature uniformity of the entire charge depends on proper furnace design, and careful and accurate adjustment of the burners and flues, so that by proper and even distribution and regulation of the heat in the chamber, the charge is evenly heated and maintained at the right temperature. Since these adjustments and regulations themselves depend on uniformity in the fuel, important advantages are derived from a fuel of high quality.

Town gas has the advantage that it can be burned in burners of almost any size, so that if it proves difficult to obtain the necessary heat distribution with a single burner or combustion chamber, a series of burners can be employed, each burner being individually adjustable.

Other virtues of town gas are that it provides a greater amount of heat in a given time in a given furnace volume than does electricity; it enables control of the furnace atmosphere (see later) to be more readily obtained than with any other fuel; and it is a clean fuel, producing satisfactory operating conditions.

FACTS ABOUT GAS COMBUSTION

Choice of a suitable gas furnace for heat-treatment cannot be effective unless the different types of burner systems are understood. A given volume of town gas will need approximately four times this volume of air to ensure its thorough combustion. The gas does not, of course, provide the requisite heat until mixed with the correct volume of air. This mixing can be done in various ways and at various points. For example, if pure, i.e. unmixed, gas is allowed to travel along a pipe, and is ignited at the open end of the pipe, the mixture with air will only begin at the edges of the flame, since that is the first contact with the atmosphere.

The ordinary naked gas-jet still to be found in some country and town houses is an example of this. Another method is to mix the gas and air before lighting the mixture at the burner or nozzle. This is the method employed in the modern domestic gas cooking-stove. Alternatively, both methods may be combined. Assuming the combustion of the gas to be complete, or as nearly complete as is practicable, the same amount of heat will be produced whichever mixing method is adopted. This amount will correspond to the calorific value of the gas, though the character, intensity, and temperature of the flame may differ with each separate form of burner.

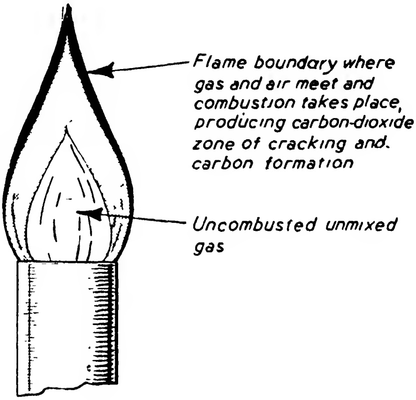


Fig. 27

If air is mixed with the gas in advance of combustion, it is termed *primary air.* If mixed during combustion, it is termed *secondary air.* The ordinary naked gas burner, in which the gas is combusted at the end of a tube, uses no primary air, and, being simple and stable, has a degree of usefulness for certain operations in which low temperatures only are involved. (Outside the realm of steel treatment, one may mention the slow drying of crucibles for steel manufacture by means of the heat produced by naked gas jets.) Some heat-treatment furnaces use no primary air, but only secondary air, and will be dealt with later.

If a burner using only secondary air is employed, it is important that the flame should not encounter any surface at a low temperature. To understand the reason for this, examine what happens when a flame of this type is created by igniting the unmixed gas issuing from the open end of a tube. The pressure of the gas drives it out to a certain extent, and it does not begin to burn until it meets the air in the room or chamber. Then, at the boundaries, having lost some of its force, the gas mingles with the air and combustion takes place. This combustion produces heat, and this heat partly *cracks* (breaks up into its separate constituents) a portion of the uncombusted gas. The cracking produces particles of carbon (one of the constituents of the gas) which are made incandescent (luminous) by the heat, thus giving the characteristic "gas light."

These particles should normally pass outwards into the actual zone of combustion, where they are burned to carbon dioxide (CO_2). But if the flame impinges on a cool or cold surface, this carbon combustion is arrested by the chilling effect, and the uncombusted carbon is deposited on the surface encountered. Gas combustion is then incomplete.

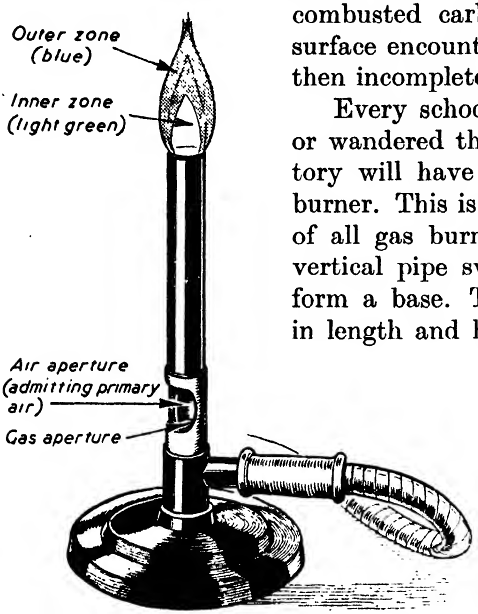


Fig. 28

Every schoolboy who has worked in or wandered through a chemical laboratory will have used or seen a Bunsen burner. This is probably the commonest of all gas burners, comprising a metal vertical pipe swelling out externally to form a base. This pipe is about 10 cm. in length and has an orifice in the side slightly less than 1 mm. in diameter, through which the gas is admitted, passing first along a rubber tube. Another orifice, this time *variable* in diameter, in the side of the pipe admits air as desired. The air mingles with the gas stream, and the resulting mixture is ignited and combusted at the open top of the pipe. The flame produced is non-luminous, and hotter than a luminous flame. It will be seen that this type of burner employs both primary and secondary air, the former being admitted into the pipe, the latter meeting the flame at its boundaries. The actual flame comprises two zones, an inner one, coloured a light green, and an outer, coloured blue, or bluish violet. The first effect of ignition is the partial burning of the mixture of gas and primary air in the inner cone. This burning leaves still available for combustion a proportion of carbon monoxide (CO) and hydrogen (H_2). These are finally combusted with the secondary air in the outer zone.

The striking difference between this type of burner and the first described is that if the outer zone of the flame impinges on a cold surface, there is no arrest of combustion, and consequently no deposit of carbon. It is only when the inner zone is brought into contact with the chilling surface that combustion is once more arrested, though here the end products will contain not pure carbon, but carbon monoxide and other gases. This drastic impingement, which would mean virtually ramming a surface into the burner mouth, is unlikely and, in consequence, these Bunsen flames, termed *aerated*, can be safely used even if their contact with cool surfaces cannot be obviated. It is also possible to use these flames in comparatively cramped heat-treating furnace chambers, while a third important point is that, being hotter than luminous flames, they give higher temperatures.

The reason for making the air aperture variable is that the temperature and intensity of the flame are directly affected by the air-gas ratio. In the ordinary luminous flame, as stated, a ratio of 4 : 1 is necessary, i.e. four volumes of air to one of gas. In the aerated flame, the ratio for primary air only, assuming normal mains pressure for the gas supply, is lower, and unless specially constructed burners are used, should never be greater than 2½ : 1. The reason is that otherwise the speed with which the flame spreads is greater than that with which the mixture passes through the vertical pipe or tube. Consequently the flame spreads into the burner tube itself, an obviously undesirable result. Secondary air is used later.

One way of overcoming this is to raise the gas pressure, i.e. increase the force with which it is driven through the burner. This overcomes the undesired extension of the flame, and also gives a flame of great intensity. Such a flame is of great value in cramped space, where the amount of secondary air entering the chamber is, or may become, inadequate. A disadvantage, however, is that this type of flame, being less stable than the normal aerated flame, depends for its efficiency on maintenance of the air-gas ratio and pressure within somewhat close limits. If the air proportion becomes too high or the velocity too low, the flame will go backwards into the burner. If the gas proportion or velocity is too high the flame may be blown out completely. These troubles may be partly overcome by breaking up the single gas jet into a number of smaller jets, using a nozzle in which not one orifice alone exists, but a series of smaller orifices or slits. In heat-treatment furnaces, tunnel burners are employed for the same reason.

Another method is to direct the combustible mixture on to layers of broken refractory (heat-resisting) material. We shall explain these procedures later.

There is another way of increasing the intensity of a gas flame, of special importance in high temperature furnaces. This is to turn the process upside down, so to speak, by supplying the *air* rather than the gas *under pressure*, the gas being drawn in to mingle with it in the burner tube. The advantage of this is that since the volume of air needed for combustion is much greater than the volume of gas, not so much pressure will be needed to give the same mixture velocity in the burner tube, as the air can be admitted through a wider orifice, and it is, therefore, possible to use an ordinary revolving fan to provide the required air pressure. (A fan is much less expensive to purchase and operate than a gas compressor.) A disadvantage is, however, that two supply pipelines are required, one for air under pressure, the other for gas, whereas only the gas has to be piped in the other system. In this air-blast method, the gas supply is regulated by means of a cock or, alternatively, the pressure at which it travels from the gas main can be reduced down to that of the ordinary air of the atmosphere. In this latter instance the ratio of gas to air remains constant over a wide range of air pressures or velocities. The low pressure or two-pipe system is applied to installations where air under pressures from 6-in. water and upwards is available and gas at normal distribution pressures. It is used with both single and two-stage proportioning inspirators. The low pressure single-stage inspirator is for installations where wide range of temperature control with a single set of burners is desired, or where the available air pressure is relatively low. It can be satisfactorily operated with air pressures from 6-in. water and upwards, and with gas pressures between 1 in. and 5 in. water. With this inspirator, air under pressure passing at high velocity through a scientifically designed throat carries with it the correct proportion of gas, supplied from the main at constant pressure through a governor.

The inspirator may be adjusted for various ratios of air to gas by screwing in or out the gas nozzle.

The low pressure two-stage inspirator can be used on gas pressures from 2 in. to 10 in. of water, with air at pressures from ½ lb. per sq. in. upwards.

The principle of operation is as follows. Air under pressure is discharged from a primary nozzle and passes into a primary throat, carrying atmospheric air into the secondary throat, from which a correct mixture is supplied to a single burner or more. The proportion of air to gas in the mixture is regulable by an adjustable shutter.

Once set, it needs no further attention and this proportion will be automatically maintained for all rates of consumption. Because of the two-stage construction employed, this inspirator requires *from the blower* only a small proportion of the air necessary for complete combustion, the amount depending on the pressure provided, This in pirator is also only slightly sensitive to wide variations in gas pressure. Inspirators of both these types are made by British Furnaces, Ltd., Chesterfield, to whom we are indebted for the description given.

The metal nozzle of the burner must be kept cool, and for this reason the mixture is sometimes ignited in a *tunnel burner* made of refractory material. The metal nozzle is set back in the wall of the furnace so as to expose as little of it as possible to the high temperature of the furnace, and what heat is absorbed is conducted back by the metal and radiated by cooling fans on the outside of the furnace so that the tip of the nozzle is not burned away too quickly. The refractory material of which the tunnel is made is even better able than the wall to withstand the high temperature of the localized heat.

Another method is to direct the combustible mixture on to a bed of broken refractory material or on to a furnace arch.

This procedure is adopted to avoid any danger that flame will impinge on the metal being heated. The heat of the flame is imparted to the broken refractory or the furnace arch, then radiated back to the metal. Combustion may be completed on the very hot surfaces produced.

A quite different burner system occasionally employed is that known as the *mixture gas system.* Here, instead of gas alone being fed under pressure to the burner, the air and gas, usually in equal proportions, are first mixed and then supplied under pressure. The correct volume of air required for combustion not being present, this mixture will not burn until more air is available, so that there is no fear of ignition in the supply pipe.

Recuperation and *regeneration* are often used in heat-treatment furnaces. This means that the gas and air are passed, independently, through specially constructed chambers called *checkers.* Simultaneously, the hot waste gases or combustion products are passed through another pair of regenerative chambers (sometimes termed *recuperators*) on their way to the flues. In so doing they give up most of their heat to the brickwork in these chambers. At regular intervals the directions of the gas, air, and waste gases are reversed, so that the ingoing gas and secondary air are always maintained at high temperatures before they mix and burn in the actual furnace chamber.

The advantage of this method in heat-treatment furnaces is that the temperature of the flame is increased and the loss of useful heat by way of the flues minimized. The increases in gas and primary air temperatures thus obtained are, of course, only relatively moderate.

It might be thought that still higher flame temperatures could be obtained by raising the gas and the primary air to high temperatures by pre-heating them before they entered the furnace. This, however, is impracticable, because not only is there the danger of premature ignition, but also the gas may "crack" (decompose), clogging up the system with carbon. Gas-air proportioning would then become difficult.

In Great Britain, the simplest and most usual form of gas-furnace for heat-treatment at temperatures between 800 and 1000° C. is the natural draught recuperative oven type. In this, each side of the furnace carries a row of aerated burners of the "Bunsen" type. These may be lighted in various ways, e.g. up one side, across the underside of the furnace arch and down the other side of the furnace into flue openings or *ports* leading to the recuperators; or alternatively below the hearth first, then under the roof arch. Of course, only the secondary air is preheated, but frequently, when the furnace is hot, the primary air is reduced in quantity or even cut off altogether. Then all the air in the furnace, being secondary only, is preheated.

The air-under-pressure system is only suitable for use with highly preheated air if the two currents of gas and air are kept apart until they come together in the furnace chamber or wherever combustion takes place.

We have already stressed the need for uniform heating. Where the furnace is of large size, this may necessitate long and brilliant flames so that the heat is carried sufficiently far forward to reach all parts of the work to be treated. This is attained by careful control of the secondary air, which can be admitted at various points along the length of the flame.

The *diffusion flame system* employs a burner having no supply of primary air. It is, in fact, an ordinary luminous burner so arranged that the gas and secondary air are blown in parallel streams into the furnaces. Every precaution is taken to ensure that the evenness and parallelism of these two streams are maintained, and that no eddy currents disturb them. This achieved, combustion will only take place slowly at the surfaces where the adjoining layers of gas and air diffuse into one another.

It is sometimes essential to protect the steel from the furnace gases, and in these instances (omitting for the present all considerations of atmosphere control) a *muffle* type of furnace may be employed. This comprises a chamber composed of refractory material located inside the furnace in such a manner that the flames lap round it without, however, being able to enter. (See Fig. 29.) This type of furnace is naturally more expensive to operate, because the heat has to be great enough to penetrate the muffle walls. The method of heating adopted for muffle furnaces is the same as that for the natural draught recuperative oven type.

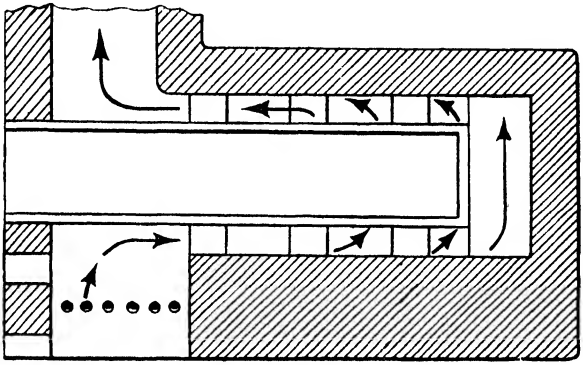


Fig. 29. Muffle Furnace

Both forms of furnace are simple and trustworthy, as well as being highly efficient. When heat-treatment involves temperatures beyond the range 800–1000° C., however, as in the hardening of high-speed steels, which calls for continuous temperatures as high as 1350° C., they do not get hot quickly enough, or, to put it more scientifically, the amount of heat required to raise each unit of furnace volume to these higher temperatures is too great, and cannot be achieved with this type of system. Consequently, an air blast system has to be employed. In many furnaces for hardening high-speed steel, two chambers are used, of which one, heated by the waste gases, preheats the steel, which is then transferred to the second, a small high-temperature muffle furnace heated by the original air-gas supply.

In the use of gas furnaces, much of the economy depends on avoidance of heat losses by way of the flues, and by *radiation* and *convection* from the furnace structure itself. Radiation, or the passage of heat rays into the outer air structure, is so familiar in everyday life as to need no description. Convection, however, may be less familiar. It is the transportation of heat from one part of a fluid to another by the movement of the fluid from the hotter portion to the colder. This movement is based on the law that heat causes expansion, and therefore a decrease in the density of the heated substance, so that the heated portion of a fluid, being less dense than the unheated, will rise, the colder portion taking its place. In this way a *convection current* is created. An excellent example of both radiation and convection is the domestic hot water cistern, which *radiates* heat through its metal shell into an airing cupboard, while at the same time *convection currents* are sending supplies of heated fluid into it from the boiler behind the fire, cold fluid descending into the boiler in replacement. These rising currents carry heat with them, some of which they surrender or lose to the cold water and metal of the cistern with which they come into contact. Similarly, in a heat-treatment furnace, heat that should be usefully employed on a mass of steel can, if design is bad, be lost by its transfer to cold air by way of convection currents.

Heat-loss by the passage of hot waste gases through the flues can be greatly lessened by the methods of recuperation and regeneration already described. The furnace *dampers*, adjustable iron plates fitted into the flues to control the draught and, in this way, the speed with which the fuel burns up, can also be effectively utilized to minimize these losses. By their means the secondary air can be regulated, which has an important influence on atmosphere control, as will be seen. It is often a feature of furnace arrangement that gas and damper controls are linked together either mechanically or by gas pressure at the burners acting on a large diaphragm or dividing plate. As the gas pressure is increased, the diaphragm is moved further away from its original position, so that more air is sucked into the burner; but for the most efficient results, this must be synchronized with the rate at which the waste products of combustion pass into the outside atmosphere. This rate, in turn, is controlled by the damper position. In some furnaces the door and the dampers are interconnected in such a way that as soon as the door is opened the damper shuts, and consequently the draught stops. This prevents any cold air from coming through the door into the furnace.

Radiation and convection heat-loss can be minimized by insulation, the extent of this being mainly governed by the purpose the furnace is meant to fulfil. For example, if a furnace is only used occasionally, every time it is lighted some heat is absorbed by the cold furnace structure, and is thus wasted so far as doing active work on the steel is concerned. In consequence, the more rapidly the furnace structure acquires heat the better, and the less frequently the furnace is used, the greater the advantage of insulation, to keep as much heat in as possible. For this reason it is becoming common practice to use a layer of light insulating bricks outside the normal refractory furnace lining.

These cut down enormously the heat lost by radiation, since they have exceptionally low thermal or heat conductivity, being full of minute air pores which conduct heat to the furnace casing to a considerably less degree than the material of which the brick consists. The ordinary refractory lining of the furnace must, of course, be retained so as to provide adequate mechanical strength.

CHAPTER VII

Types of Gas Furnaces

In this chapter are illustrated and briefly described certain modern gas-fired heat-treating furnaces. It is not claimed that it gives a complete description of every type of furnace. The intention is merely to indicate how some characteristic furnaces are constructed and what they do. The reader should carefully study in this connection the later chapter on atmosphere control. Some

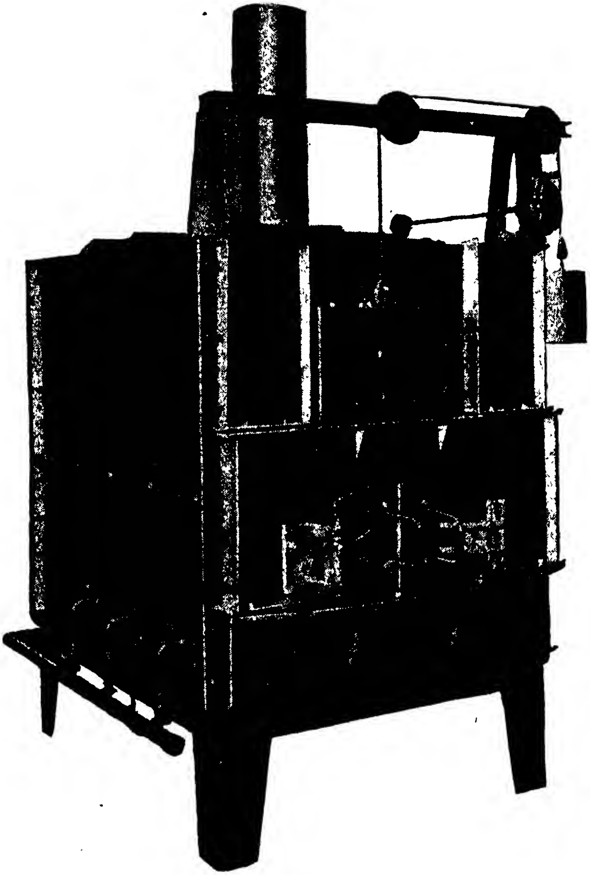


Fig. 30. Typical "Incandescent" Semi-muffle, Gas-fired, Double-deck Furnace

specialized furnaces are also dealt with in later chapters, where the particular heat-treatment operations for which they are designed are described.

Fig. 30 shows a typical semi-muffle, gas-fired, double-deck furnace with the top chamber heated entirely by waste gases. It is made by the Incandescent Heat Co., Ltd., of Birmingham, and is fired by natural draught burners designed for operation on town gas at normal mains pressure. The upper chamber may be used for preheating the load to avoid unduly rapid heating and to prevent distortion. Auxiliary burners are applied so that the temperature may be controlled within very fine limits.

Flue losses are minimized by making the waste gases from the lower chamber partly heat the upper, or—if working conditions admit—the upper chamber can be heated entirely by waste products from the lower.

Both semi-muffle and complete muffle double-deck furnaces can be supplied with each chamber independently fired or with the top chamber heated by waste gases only. Any temperatures between 500° and 1000° C. can be maintained within limits of plus or minus 5° C. Table IX gives the standard sizes in which these furnaces are supplied.

TABLE IX

INTERNAL CHAMBER DIMENSIONS

Working Length in.	Width in.	Height to Crown in.	Length from Back Wall to Inside of Door in.
24	18	12	30
30	18	12	36
30	24	12	36
36	18	12	42
36	24	12	43
36	30	15	43
42	24	15	50
42	30	15	50

They are suitable for all classes of heat-treatment requiring working temperatures up to 1000° C., e.g. heat-treatment of finished machine parts, reheating, tempering, hardening, refining, or where preheating or double-quench work is to be handled.

Fig. 31 shows a typical standard recuperative furnace with chamber dimensions 24 in. long by 18 in. wide by 12 in. high. These furnaces are built up of heavy heat-resisting castings, bolted together to form a rigid unit. The main body of the furnace is mounted on cast iron legs, so as to raise the hearth to a convenient working height.

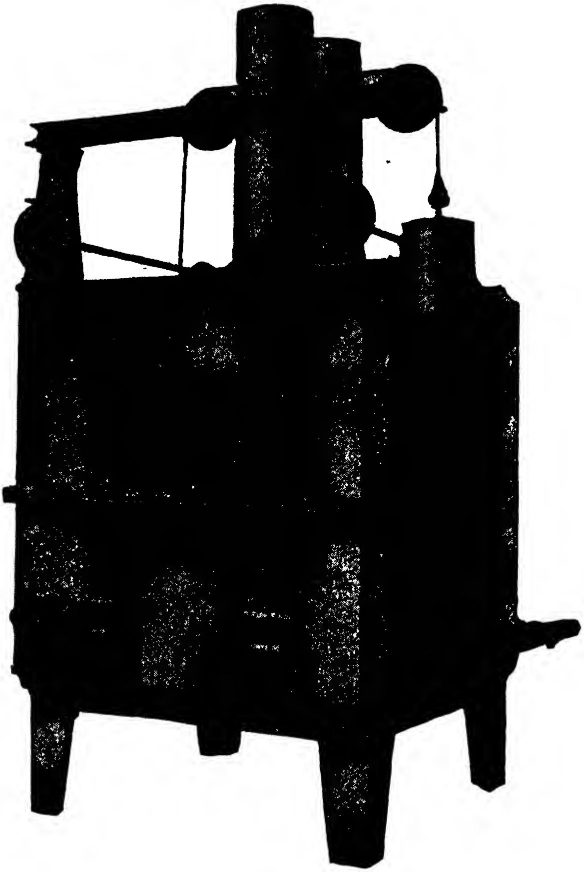


Fig. 31. Typical Standard Recuperative Furnace

The furnace, by the same makers as the previous type, is fired by natural draught burners operating on standard town gas supply, and is designed for both intermittent and continuous operation. Annealing, normalizing, carburizing, reheating, hardening and tempering, and all heat-treatment processes throughout the temperature range of 600° to 1200° C. can be handled. Operating temperatures are quickly reached, and there is absolute temperature control and equalization within 5° C. The waste gases are passed through continuous recuperators, effecting the immediate and full utilization of waste heat. There is no temperature lag due to recuperation. Full recuperation and thorough insulation result in reduction of heat loss due to radiation and waste gases.

Each burner is individually controlled, and fires into a separate combustion chamber beneath the hearth. The gases, thoroughly mixed with highly preheated secondary air, attain a high temperature before being passed to the working chamber. The furnace may be operated with a neutral, completely oxidizing, or completely reducing, atmosphere, terms explained in the chapter on atmosphere control.

Because the waste gases are drawn to the front of the furnace, infiltration of cold air is effectively prevented, the atmosphere remaining unaffected when the door is opened.

Table X shows the standard sizes in which this furnace is supplied.

TABLE X.

INTERNAL CHAMBER DIMENSIONS

Working Length in.	Width in.	Height to Crown in.	Length from Back Wall to Inside of Door in.
24	18	12	30
30	18	12	36
30	24	12	36
36	18	12	42
36	24	12	42
36	30	15	43
42	24	15	49
42	30	15	51
48	24	15	57
48	36	15	57
54	36	18	65

Fig. 32 shows a double-deck tool-hardening furnace made by the Incandescent Heat Co., Ltd. These furnaces are specially designed for the heat-treatment of carbon and high-speed steels, with freedom from blistering or pitting. Neutral or reducing atmospheres are maintained in both upper and lower chambers, ensuring precision heat-treatment with minimum scale. The furnace is fired by two air-blast burners operating on gas at mains pressure and air at 16 in. w.g. The burners are fitted with indexed quadrant controls. In other words, the ordinary valve used to open or close a gas supply in a pipe has fitted to it a quadrant, marked as shown in Fig. 31. As the valve is turned, a pointer or needle fitted to it moves over the quadrant, indicating the degree of the opening of the valve, so that both atmosphere and temperature can be regulated to very close limits. Temperatures up to

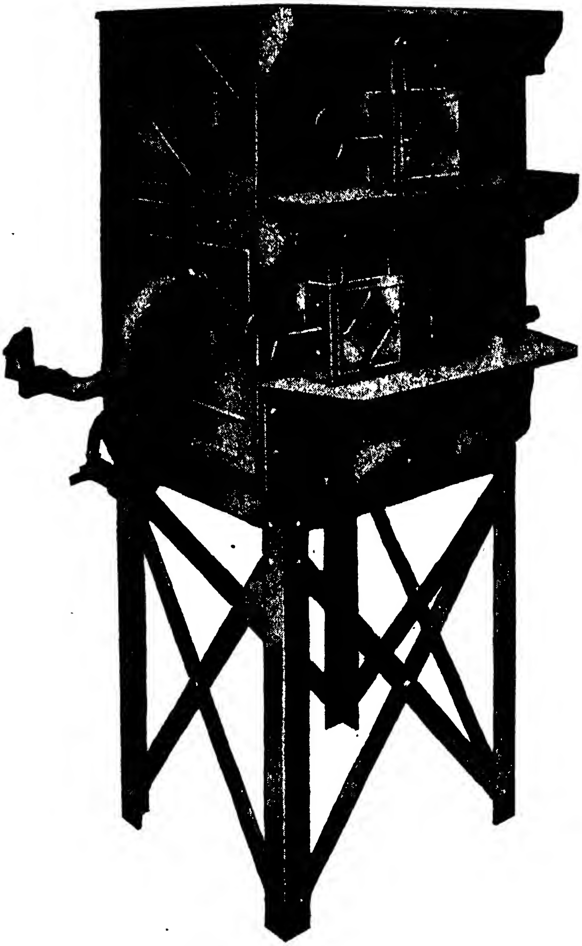


FIG. 32. DOUBLE-DECK TOOL-HARDENING FURNACE

1350° C. are evenly maintained to within 5° C. in the lower chamber. Table XI shows the standard sizes in which this furnace is made.

TABLE XI

CHAMBER DIMENSIONS

Depth in.	Width in.	Height in.	Opening in.
9	9	5	5 × 5
12	12	8	8 × 8
18	12	12	12 × 12
18	15	12	15 × 12

Fig. 33 shows a hardening furnace for high-speed steel, made by the Incandescent Heat Co., Ltd., under licence from the Gas Light and Coke Company. This is operated by single-valve control and is designed to maintain a highly protective atmosphere (see Chapter X) for tools under treatment, so as to eliminate decarburization, blistering, pitting, grain growth, and other hardening difficulties. A temperature of 1350° C. in the hardening chamber is quickly attained. The upper or preheating chamber is maintained at approximately 800° C. by waste heat from the outgoing gases. The combustion system is automatically and effectively controlled by an air-gas ratio proportioning-valve. By the introduction of a controlled supply of *purging gas* (gas unmixed with air at the burners, so as to create a reducing atmosphere in the furnace chamber) directly into the hardening chamber, the furnace atmosphere is maintained in the correct reducing condition essential for successful hardening.

TABLE XII

CHAMBER DIMENSIONS

Depth in.	Width in.	Height in.
10	6	2½
10	6	5
12	7½	5

The burners are specially designed with *cooling fins* (metal fins or projections designed to present a large surface area to the air so as to dissipate the heat more rapidly) and refractory orifices.

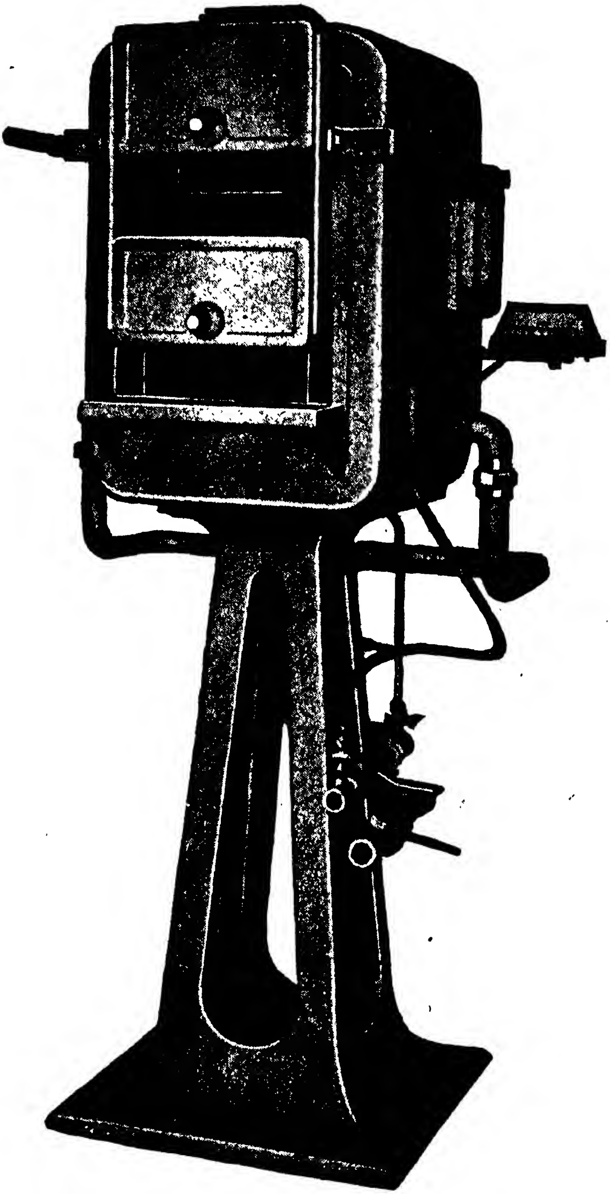


FIG. 33. HARDENING FURNACE FOR HIGH-SPEED STEEL

A pyrometer with a temperature range up to 1400° C. is included. while a visible gas-pressure gauge enables the operator to control the atmosphere within precision limits.

The removable *crown* (the "top" or "roof" of *any* furnace chamber) makes all internal parts accessible and easy to repair.

Fig. 34 shows a normalizing furnace made by British Furnaces, Ltd., Chesterfield. This is designed to deal with about 1000 lb. of ring and gear forgings per hour, the work being loaded on to heat-resisting alloy trays. The gross load passing through the furnace is about 1390 lb. per hour, and the temperature in the hot zone is 982° C. (1800° F.). The trays carrying the work are pushed through the furnace over three rows of heat-resisting alloy rollers set in beams of the same material.

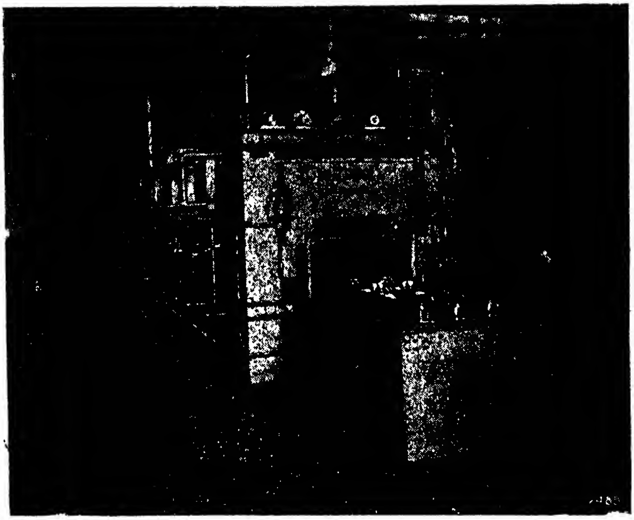


FIG. 34. NORMALIZING FURNACE

The electrically-driven rocker-arm pusher, which pushes the work forward over the rollers, is synchronized with both the charge and discharge doors, and all operations are completely automatic throughout the cycles of charge and discharge. As the pusher has only to operate every 16½ minutes, it is not kept running continuously, but is started at correct intervals by means of a special time clock.

The furnace has several zones covering heating, soaking, fast-cool, and slow-cool, and the temperature is automatically controlled throughout. The internal dimensions are 3 ft. 9 in. wide and 44 ft. long, and the hot zones have 9 in. of high quality insulation throughout in order to minimize heat losses as much as possible. This construction, together with the use of automatic proportioning burner equipment, is claimed to give maximum combustion efficiency and ensure a low fuel consumption.

When a net capacity of 1000 lb. per hr. is employed for operating, corresponding to a gross output of 1390 lb. per hr. and a temperature of 982° C. (1800° F.) in the soaking zone, i.e. the zone in which the steel is *soaked*, or heated until the entire mass is at the same or nearly the same temperature, the gas consumption will be 2700 cu. ft. per hour.

Fig. 35 shows an installation for treating high-speed steel twist-drills and reamers. This, made under licence by British Furnaces, Ltd., using patents held by the Sheffield and District Gas Company, comprises a double-chamber pit-type preheating furnace in the centre, with the single-chamber high-temperature furnace on the left. On the extreme right is the unit for producing the special atmosphere used in the muffles of both furnaces. Town gas is burned in the unit at a fixed rate and under definite conditions to produce combustion products of known composition. These flow through a vertical water-cooled vessel, where they are reduced to a temperature sufficient to lower the water vapour content appreciably.

The cool waste products issuing from the cooler are of such a chemical composition that their scaling and decarburizing properties are greatly reduced. The other gases in the mixture leaving the cooler are carbon dioxide (CO_2) and nitrogen (N_2). Atmospheric nitrogen does not affect steel, but carbon dioxide, in the presence of even a small amount of water vapour, can both form scale and decarburize, though to a less marked degree than either water-vapour or air. To overcome this tendency a small amount of unburned town gas is added to the mixture leaving the cooler, and efficient mixture ensured.

When this mixture of gases passes into the working chamber, it rises in temperature and chemical reactions take place, producing a mixture of new gases, whose composition depends on the furnace temperature when using any one particular proportion of cooled combustion products and unburned gas. This proportion is readily controllable, and allows almost any type of atmosphere to be produced in the furnace.

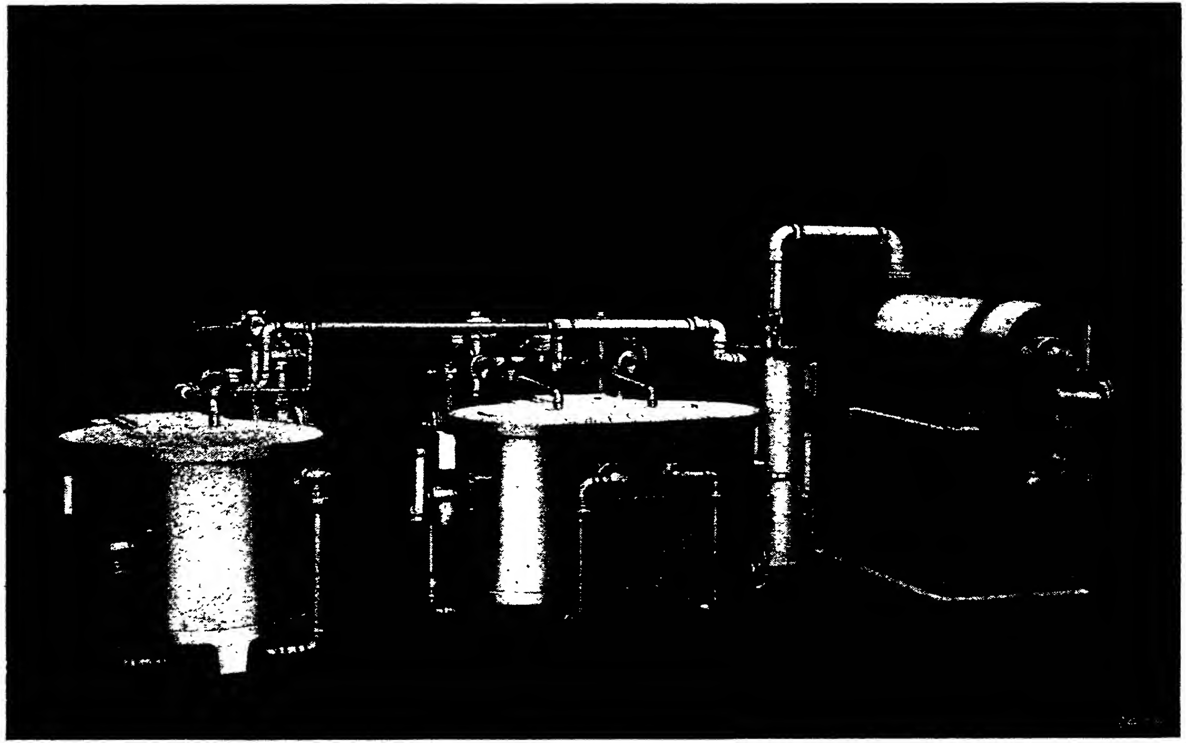


FIG. 35. HARDENING AND TEMPERING OUTFIT WITH ATMOSPHERIC CONTROL FURNACE PREPARATION UNIT IN THE RIGHT BACKGROUND

The secondary hardening treatment of the steel is carried out in gas-fired furnaces of the type shown in Fig. 36. In these, the atmosphere inside the furnace is recirculated over the work by a fan in the furnace base, thus giving absolute uniformity of temperature.

As the furnaces are open-gas-fired, the atmosphere inside them consists of combustion products with little, if any, free oxygen.

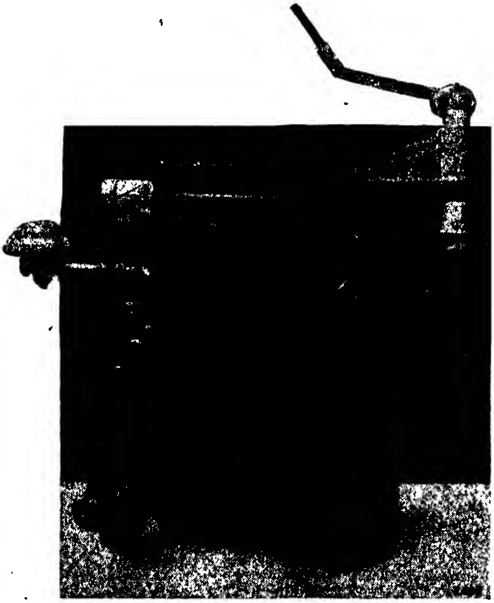


FIG. 36. SECONDARY TREATMENT FURNACE

In consequence, the secondary hardening treatment is carried out in a much more favourable atmosphere than where the circulated medium is air only. The surface condition of the work is therefore much improved. These furnaces are also supplied by British Furnaces, Ltd., Chesterfield.

Fig. 37 shows a gas carburizing furnace, of the type having a double row of burners, with single flow of work, all of which passes through the furnace in the same direction. It is designed to deal with a gross charge of 1200 lb. per hr. with a case depth between 0·045 in. and 0·055 in. at a working temperature of 925° C. (1700° F.).

The trays carrying the carburizing boxes, in which the parts for treatment are contained, are pushed through the furnace over four rows of heat-resisting alloy rollers, as in the normalizing furnace described earlier (page 81). Two electrically driven rocker arm pushers are provided at the charging end, one for each row of boxes, and these pushers are synchronized with the doors, of which there are four. Both doors and pushers are completely automatic, being electrically operated and controlled by a special time clock.

The heating and soaking zones are under full automatic temperature control. The furnace is 5 ft. wide inside and 52 ft. 3 in. long between the doors. It is lined throughout with 9 in. of refractory material, backed with 9 in. of highly efficient insulation.

FIG. 37. CARBURIZING FURNACE, DISCHARGE END

Similar burner equipment to that of the normalizing furnace is provided. When the furnace is operating at a gross capacity of 1200 lb. per hr., with a heating cycle of about 18 hr., the gas consumption will be 2450 cu. ft. per hr. This furnace is made by British Furnaces, Ltd., Chesterfield.

Fig. 38 shows a reheating furnace of continuous conveyor type designed to deal with 500 lb. per hr. of spiral bevel gears and pinions, heated to 925° C. (1700° F.). The heating time is variable, between 40 and 60 minutes. The conveyor belt is totally enclosed within the furnace chamber so that little heat is lost on its return, passing to the charging end. This belt is built up of heat-resisting alloy interlocking links fitted with rollers on the under side. The rollers pass over skid rails, which are in turn supported by cross members evenly spaced along the length of the furnace.

Foot-operated doors provided with *gas screens* (a series of auxiliary burners just inside the door, through which gas alone passes and then only when the doors are raised; by this means a reducing "curtain" or "screen" of flame is maintained which prevents ingress of air into the furnace chamber) are arranged on each side of the furnace at the discharge end, through which the work is removed for quenching. Provision is also made to discharge to the atmosphere any work not removed from the conveyor by the operators. The furnace is efficiently insulated and fitted with automatic proportioning burner equipment. In addition a metallic recuperator is provided to give still greater efficiency.

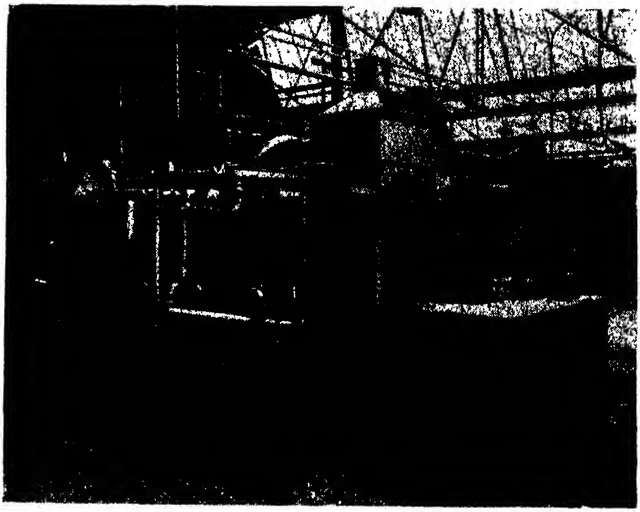


FIG. 38. REHEATING FURNACE

The gas consumption required to deal with 500 lb. of steel per hour heated to 925° C. (1700° F.) is 750 cu. ft. per hr. This furnace is also built by British Furnaces, Ltd., Chesterfield, and is under full automatic temperature control.

Fig. 39 shows a city gas-fired heat-treatment furnace of the semi-muffle type, with a hearth 18 ft. long by 4 ft. wide. The hearth is under-fired (i.e. fired from below it) to ensure equalization

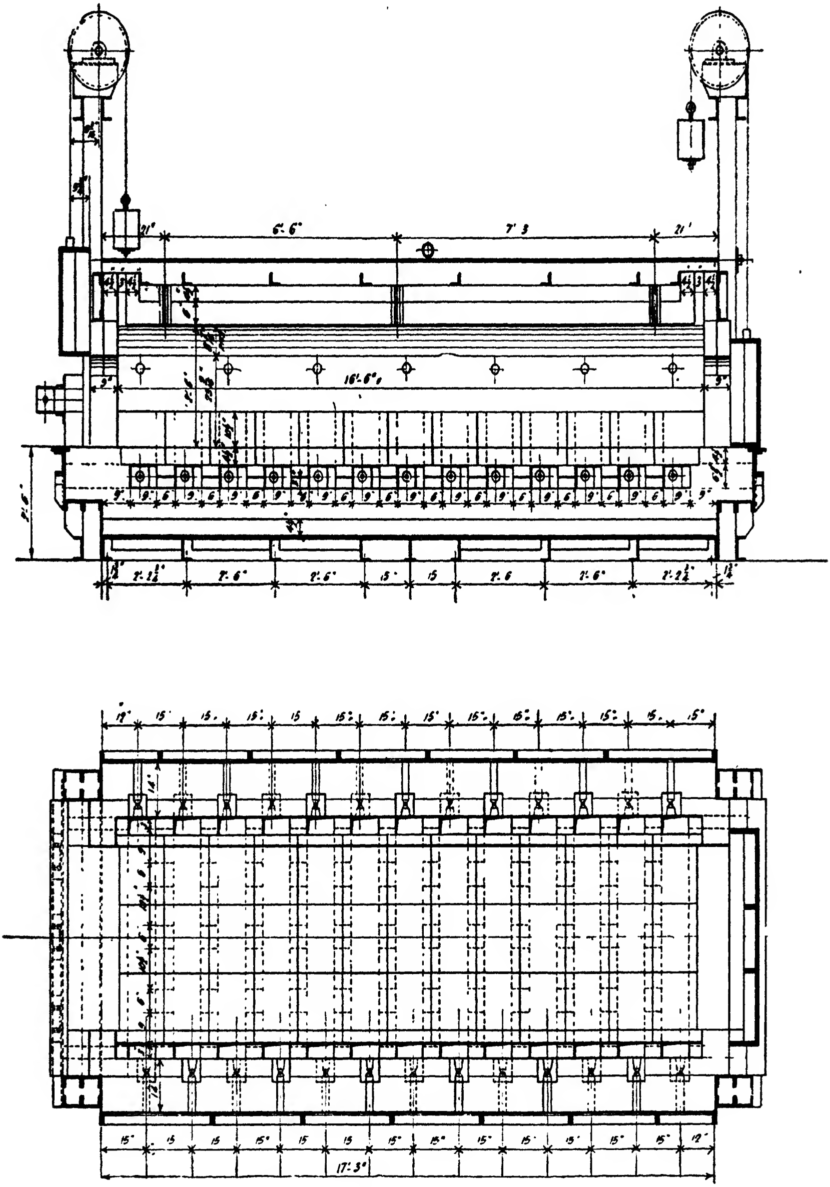


Fig. 39. City Gas-fired Furnace of the Semi-muffle Type for the Thermal Treatment of Bars

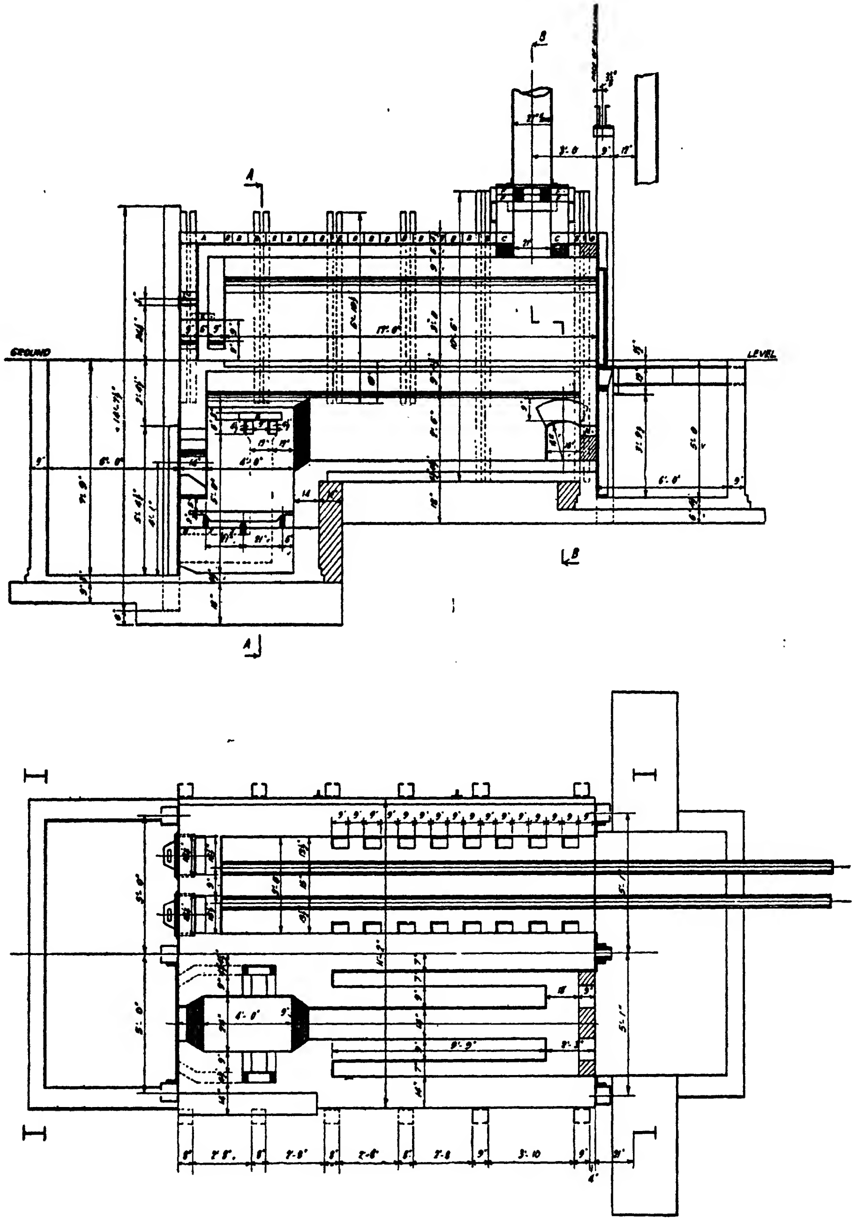


Fig. 40. Coal-fired Twin Chamber Furnace for the General Thermal Treatment of Bars, Forgings, etc.

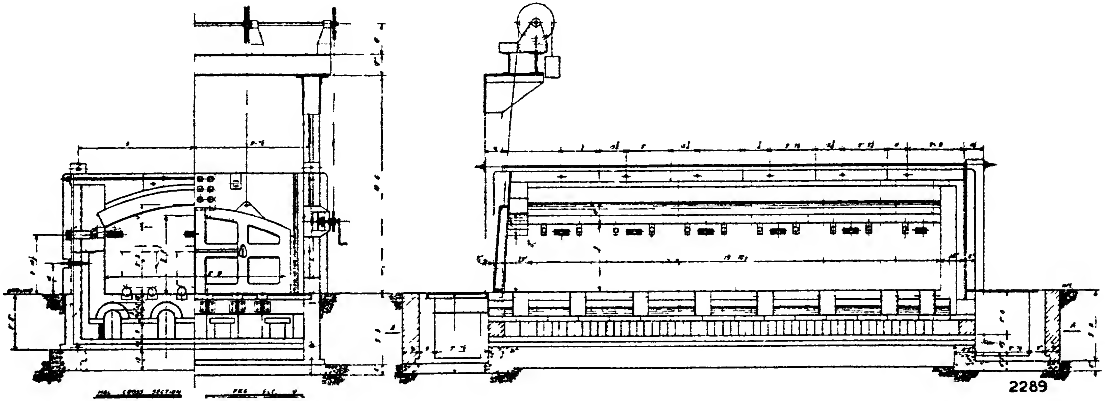


FIG. 41 CITY GAS-FIRED FURNACE OF THE OVER FIRED TYPE FOR THE THERMAL TREATMENT OF BARS, STRIP, AND WIRE IN COFFINS OR POTS

FIG. 42. COAL-FIRED TWIN CHAMBER ANNEALING FURNACE

of heat, while additional burners are arranged in the side walls of the chamber to accelerate the rate of heating up. The furnace is used for the heat-treatment of long bars.

Fig. 41 shows a city gas-fired heat-treatment furnace suitable for the heating of bars, strip, or wire, in coffins or pots. It is of the over-fired type (i.e. fired from above) and the products of combustion flow between the coffins or pots, and through outlet ports arranged in the hearth of the chamber. Many furnaces of this type have been installed and are suitable for operation at temperatures up to 1000° C.

The furnaces shown in Figs. 39, 40, 41, and 42 are all constructed by Messrs. G. P. Wincott, Ltd., of Sheffield.

CHAPTER VIII

Electric Heat-treating Furnaces

THE electric heat-treating furnace is based essentially on the resistance of particular metals to the passage of an electric current, which resistance results in the generation of considerable heat. There are numerous metals offering various degrees of resistance, but not all of these are suitable for commercial furnaces. For example, platinum is a suitable metal, but is too costly for all but the small units used in a laboratory furnace. It was not until highly resistant nickel-chromium and nickel-chromium-iron alloys were discovered that the electric furnace became a commercial possibility in the treatment of steel.

The *resistors* or *resistances*, termed *heating elements*, have usually to be so disposed in the furnace that they will convey their heat directly to the charge by radiation. There are, however, exceptions to this rule. For example, in low temperature furnaces the heat is transmitted to the charge by the enforced circulation of electrically heated air. There are also furnaces in which the element is embedded in a refractory substance, but this method is confined to relatively small furnaces needing only a small amount of heat per unit of wall surface.

The heating elements may be of wire, rod, ribbon, heavy strip, tubes, or in cast form. They have to be given some kind of support, and different means are adopted for different forms. Wire is usually wound into a spiral, and may be carried on shelves, in channels, or (for those applications not calling for high heats) in tunnels, or may be embedded in a refractory material of the type indicated above.

Rod is either straight or bent into the form of a hairpin, in which instance it is carried by refractory supports placed at intervals along its full length. Alternatively, it may be in serpentine or zig-zag form, in which instance it will be held in place by hooks of refractory material.

Strip or ribbon, though sometimes coiled in spirals, is mostly serpentine or zig-zag in form, and is arranged with the edge to the furnace wall, support being afforded by refractory or metal hooks. Strip may also be placed flat to the wall, in which case it provides its own support, being given a fluted shape or one approximating to that of a cycle rim, and supported at the ends. In general, the Continental furnace builders use the wire spiral, the American the strip, ribbon, and cast elements, while the British, having at times employed all these types, are, according to Mr. A. Glynne-Lobley, now using for large furnaces only strip, rod, tube, and cast elements.

The resistances of the modern electric furnace are not by any means short-lived. They do not easily oxidize, and the principal cause of such deterioration as they experience is chemical attack of a corrosive type by any harmful gases given off by the charge, or by some interaction with the refractory materials acting as supports, which takes place as a rule only when harmful gases are also present. Renewal of elements is, in fact, a relatively small item of maintenance cost, and there are many instances of years of uninterrupted life from electric furnace elements.

The great advantage of electric furnaces for heat-treatment is the simplicity with which they can be regulated and their adaptability.

All the electrical energy of the furnace is turned into heat, so that if the electrical input is regulated, the heat is also regulated. As electrical energy is easily, instantaneously, and exactly controllable, this presents no difficulties.

Another important factor is that since no material whatsoever has to be *burned* to provide the heat, the furnace needs no passages by which air can enter, no burning zones or chambers, and no flues to take away waste gases and combustion products. Hence, nothing in the construction need interfere with the arrangement of the heating elements or the most effective design of the furnace chamber. It becomes not only theoretically but also practically possible to distribute the heat in such a way as to give uniform temperature in every part of the furnace chamber. This advantage is of enormous importance in heat-treatment.

Later we shall discuss the value of controlled atmospheres. Here it is sufficient to say that special furnace atmospheres can be employed without its being necessary to take into account the efficiency of combustion for heating.

Into the comparative cost of gas, electric and other types of furnaces, it is not our purpose to enter. These are aspects of heat-treatment economics capable of considerable interpretation, and depending to a great extent on local conditions, types of work done, and statistical records kept. It must, however, be pointed out that, as between electric and other fuels, the true basis of comparison is not the respective costs of a gross unit of heat, but the cost of *actually usable* heat.

Fig. 43 shows a box type furnace made by Birmingham Electric Furnaces, Ltd., Birmingham, and designed for carburizing, hardening, tempering, annealing, and normalizing. The outer casing is constructed of mild steel plates. The lining is of a high quality refractory material, and is directly supported by the outer shell or casing. The insulation is of high grade, heat-insulating brick and powder, of thickness varying with the size and purpose of the furnace, being as much as 18 in. in some instances.

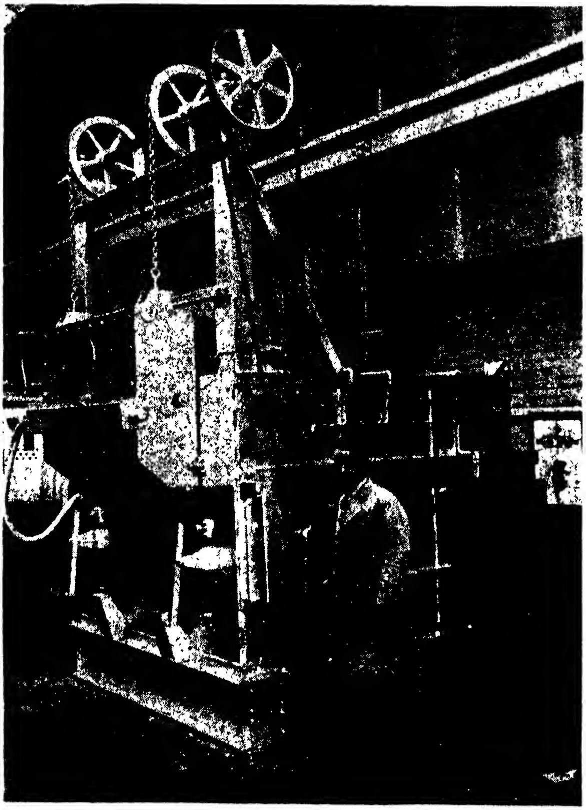


Fig. 43. Box Type Furnace Designed for Carburizing, Hardening, Tempering, Annealing and Normalizing

The heating elements are made of nickel-chromium alloy strip, of exceptionally heavy cross-section. They are placed on the sides, roof, door, and under the hearth or floor of the furnace, being supported by nickel-chromium alloy hooks—a patented feature—which prevents all contact with the refractory material, and so any danger of interaction leading to deterioration. This method also prevents any masking or shielding of the elements by refractory material, thus avoiding *hot spots* (localized zones having higher temperatures than the remainder).

Cast nickel-chromium alloy guards held in place by nickel-chromium rods built into the brickwork protect the side elements from accidental contact with the charge. The elements located under the hearth are completely covered with cast nickel-chromium plates.

The hearth itself can be either grooved to take the arms of a charging machine, as in the illustration, or built in flat for hand operation. Parts liable to wear are covered with heavy cast nickel-chromium plates.

The door is of special patent design and *sockets* (fits closely) into the furnace opening, which cuts down to a minimum the heat losses at this point. When opened, it swings outwards and upwards, the hot face being kept parallel with the furnace front away from the operator. The heating element fitted to the inner face of the door is of great importance in assuring uniform heat distribution. The cast iron frame has a machined face against which the door seats, thus minimizing air leakage and consequent loss of heat.

Fig. 44 shows a furnace for the hardening of high-speed steel made by Birmingham Electric Furnaces, Ltd. This is designed for regular use at temperatures up to 1400° C. and is suitable for all classes of high-speed steel. The casing is of steel plates and sections, with a cast iron front. The space under the furnace accommodates the electrical equipment. The lining is of refractory material well insulated. The door is of vertical sliding type. The hearth is made of a special heat-conducting refractory and has side flanges. The heating elements are rods of non-metallic *silicon carbide* arranged from front to back in both sides of the chamber, an arrangement giving uniform temperature without overheating of any elements. They are supported between special, water-cooled, spring-loaded terminals, and can be replaced without interference with the furnace brickwork. A minimum life of 500 hr. is to be expected, while 900–1000 hr. is often obtained.

In this furnace, a controlled atmosphere is used in the furnace chamber, obtained by the burning of coal-gas and air, the atmosphere generator being mounted on the side of the furnace casing.

The electrical equipment comprises a switch panel for controlling the current and a power transformer so that suitable voltages can be used, in order to compensate for the change in resistance of the silicon-carbide rods as they age with use. Temperature control is fully automatic. The furnace is normally designed for A.C. supply, and although D.C. supply can be accommodated, it is not recommended. Any type of temperature control equipment can be supplied. It is possible for a pneumatically-operated door-mechanism to be supplied. This is worked by a convenient foot-pedal, and leaves the operator's hands free to manipulate the work. A time-switch can be fitted on the control-panel. This will switch on the furnace automatically so that it will be at working temperature when the operator arrives.

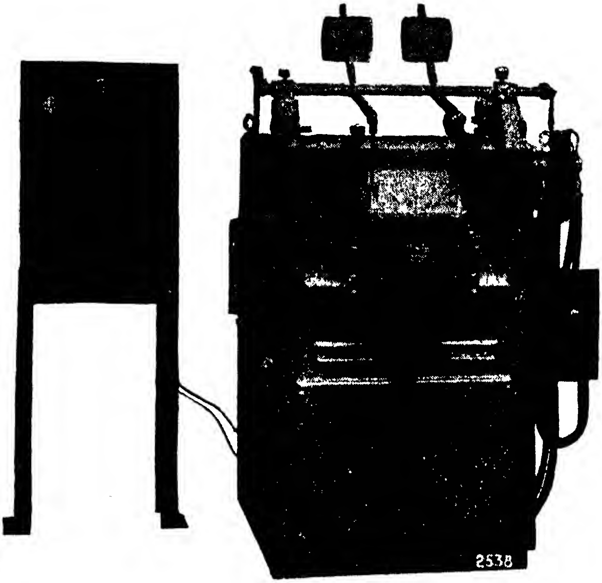


FIG. 44. FURNACE FOR HARDENING HIGH-SPEED STEEL, DESIGNED FOR REGULAR USE AT TEMPERATURES UP TO 1400° C.

Table XIII shows the range in which these furnaces can be supplied.

TABLE XIII

Hearth		Door		Overall					
Length Excluding Vestibule in.	Width between Flanges in.	Width in.	Height in.	Length in.	Width in.	Height in.	Rating kW	Net Weight lb.	Gross Weight lb.
9	4	4½	3	36	32	54	6	940	1200
12	5	6	4	51	51	72	15	2420	2990
12	7	8	6	54	56	75	20	2860	3790
18	9	10	6	63	63	78	28	3960	4980
24	11	12	8	69	66	84	42	4120	5270
30	15	16½	12	93	78	90	60	9480	12000

It might be imagined that as gas is used for producing the controlled atmosphere in the furnace chamber, it could just as well be used for heating the furnace. The reason for using gas and electricity in combination in this instance is that by this means both temperature and atmospheric analysis are independently and exactly controllable.

Fig. 45 shows a vertical forced-air circulation furnace made by Birmingham Electric Furnaces, Ltd. This is designed for carrying out heat-treatment processes such as the tempering and the secondary hardening of high-speed steels. Temperatures up to about 700° C. can be attained rapidly and economically in this type of furnace.

A centrifugal fan, mounted at the bottom of the furnace chamber, creates a powerful circulation of air upwards over the heating element and downwards through the charge. The air absorbs heat from the elements and transfers it rapidly during its downward course to the material in the work-basket or container.

Highly sensitive temperature control is furnished by a *charge progress recorder*, which not only keeps the furnace automatically at any desired temperature, but also shows when the work has reached the set temperature throughout. The charge can then be withdrawn or the soaking period begun, according to the treatment. Precise temperature and time control is thus provided.

The furnace comprises a heat-insulated chamber of cylindrical form with an inner metal cylinder arranged to take a work-basket. The heating elements are mounted in the ring-shaped space between the insulated walls and the cylinder or container. The container is intended to prevent the direct radiation of heat

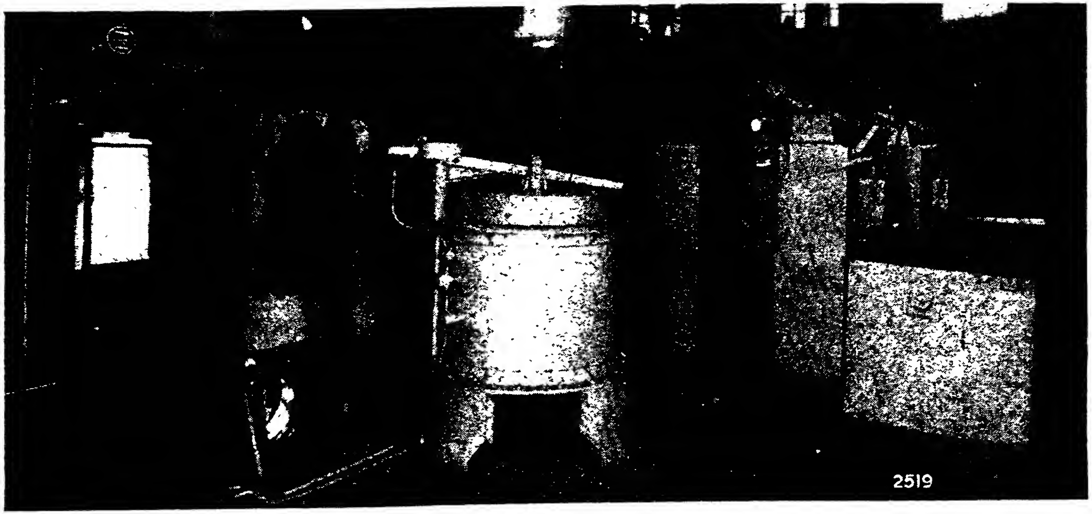


FIG. 45. VERTICAL FORCED-AIR CIRCULATION FURNACE, DESIGNED FOR SECONDARY HARDENING OF HIGH-SPEED STEELS, AND OTHER LOW TEMPERATURE OPERATIONS

on to the charge, and to compel the circulating air to follow a definite path.

Table XIV gives the standard sizes in which this type of furnace is supplied.

TABLE XIV

Work-basket		Overall Dimensions			Rating
Diameter in.	Depth in.	Diameter in.	Height in.	Diameter with Swing Lid in.	kW.
10	10	34	59	44	4
16	12	46	65	65	10
20	18	54	75	78	20
26	24	67	93	97	40
32	32	80	109	116	60

Fig. 46 shows a semi-continuous nitriding furnace, also made by Birmingham Electric Furnaces, Ltd., the essential feature of which is the permanent location of two containers, provided with covers that can be lifted off, on stationary hearths. Temperatures for nitriding are generally about 500°–600° C. The heating chamber is mounted on track wheels so that it can be placed at will over either container by means of a crank-handle driving the wheels through roller-chains. Circulating fans, electrically-driven, are fitted in each container, and give highly uniform temperature distribution, as well as intimate contact of the nitriding gas with all parts of the charge. This allows the containers to be loaded to full capacity without risk of uneven treatment.

The simple transfer of the furnace from one hearth to the other, which can be carried out by an unskilled operator, makes it unnecessary to handle hot containers.

The supply of nitriding gas is fully controlled by conveniently placed hand-operated valves, so that it is not necessary to disconnect the gas pipes, and as there are no flexible gas-connections, there is no danger that the work will be spoiled by the infiltration of air. The containers themselves are rendered gas-tight by means of a special, dense, fine, dry powder with which they are sealed and made gas-tight. This needs no particular skill for its use.

As the nitriding gas is controlled by valves, the spent or waste gas can be diverted into the second container to prevent air from

Fig. 46. Semi-continuous Duplex Nitriding Furnace

getting in while the nitrided charge in that container is cooling down, and also to cleanse or purge it after it has been recharged, thus making it unnecessary to waste fresh gas on these functions.

As the furnace is movable in the manner indicated, the heat stored up in the furnace lining can be saved, since the chamber is not cooled off before it is unloaded, and no power and time are wasted in reheating it.

The heating elements do not come into contact with the nitriding gas and cannot, therefore, be injured by it.

Fig. 47 shows a "Heavy-Hairpin" type of electric heat-treatment furnace made by Messrs. Wild-Barfield Electric Furnaces, Ltd., Watford, used for carburizing, reheating, hardening, and general heat-treatment up to 1000–1050° C. The casing is of heavy steel plate with angle tee and channel riveted to form a rigid structure. The thrust or outward pressure of the arched roof is taken through hard insulating bricks to channels along the side of the case. The furnace chamber is composed of specially moulded element bricks. Those bricks in the hearth are usually of material most readily conducting heat, and are of bridge fin type. They are also highly resistant to the chemical and erosive action of any slag that may form. The side and roof bricks also have fins, through which pass the elements, carefully safeguarded against over-heating at these fins. When elements are fitted in the side walls, a curb is in most instances built in to prevent damage to the brickwork when loading or discharging.

The full hearth width is used. Directly behind the element-bricks a high temperature insulating material is used, backed by low temperature material with greater insulating properties. Elements are also fitted in panel form in the furnace door, the panel being insulated and the door frame held to ensure a tight joint between it and the front plate.

The patented elements themselves are in the form of a hairpin, and are of 80/20 nickel-chromium alloy, usually of heavy section drawn rod. Each end of the hairpin is thickened where it passes through the insulation. As the thickened end is lower in resistance than a similar length of element portion, there is no risk of over-heating. The thickened ends are threaded (provided with a screw thread) and copper-plated, and a thoroughly sound joint ensured between element and connector.

Another and later type of element for these furnaces is the

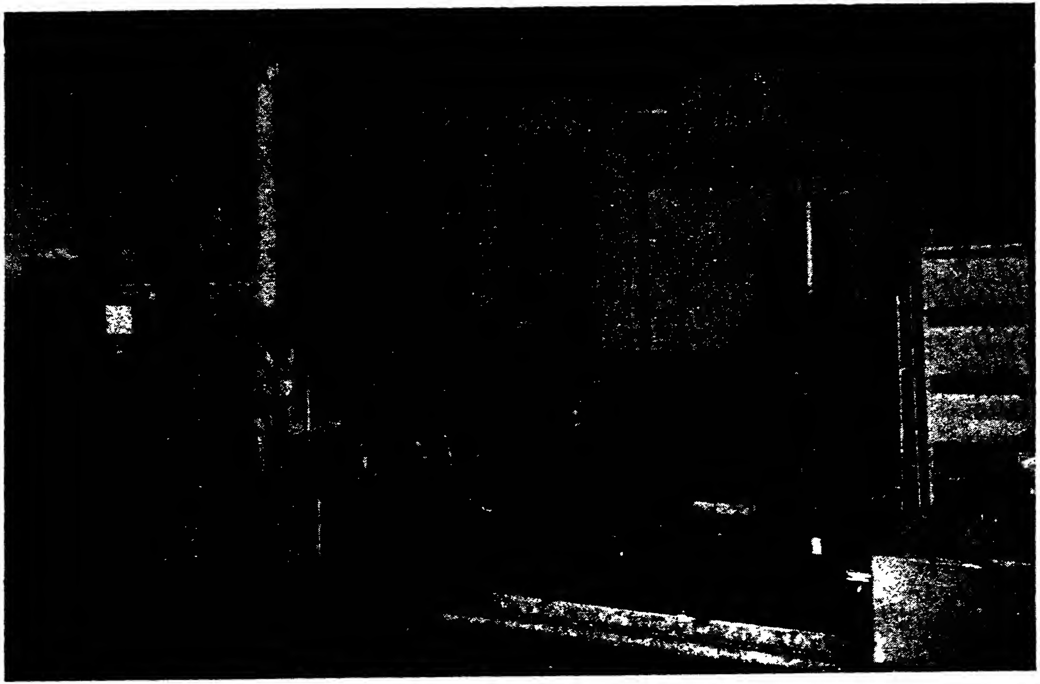


Fig. 47. "Heavy-hairpin" Type of Electric Furnace

"Tubular-Hairpin." When any furnace is operated at temperatures between 1100 and 1200° C., a core effect occurs in the elements, i.e. the interior is hotter than the exterior, as a result of phenomena that need not concern us here. Temperatures of 1100 to 1200° C. are not, of course, used for nitriding. By using an element in the form of a tube, this effect is eliminated without any loss of strength or interference with the ease of replacement.

These tubular elements make it possible to use a higher working temperature, without shortening the element life and, in consequence the scope of these furnaces is widened. They are used for production carburizing, hardening, etc., and for general ferrous heat-treatments up to 1150° C.

Table XV shows the principal dimensions of the standard range of "Heavy-Hairpin" and "Tubular-Hairpin" furnaces.

TABLE XV

Chamber	Door Opening	Overall Dimensions	Rating kW
2 ft. 0 in.	1 ft. 0 in. × 10 in.	4 ft. 7 in. × 3 ft. 3 in. × 5 ft. 9 in.	14
2 ft. 8 in.	1 ft. 4 in. × 10 in.	5 ft. 3 in. × 3 ft. 7 in. × 5 ft. 11 in.	21
3 ft. 4 in.	1 ft. 8 in. × 14 in.	6 ft. 3 in. × 4 ft. 0 in. × 6 ft. 10 in.	35
4 ft. 0 in.	2 ft. 0 in. × 14 in.	6 ft. 11 in. × 4 ft. 7 in. × 7 ft. 1 in.	46
4 ft. 0 in.	2 ft. 4 in. × 14 in.	6 ft. 11 in. × 4 ft. 11 in. × 7 ft. 3 in.	52
4 ft. 8 in.	3 ft. 0 in. × 18 in.	7 ft. 9 in. × 5 ft. 9 in. × 8 ft. 2 in.	80

Fig. 48 shows a Wild-Barfield high-speed steel hardening furnace for tool-room purposes. In this the preheating and actual hardening units are mounted on a common stand with the requisite controlling components arranged below. Thus, these furnaces are suitable for small hardening shops not called upon to treat large tools. Larger shops can use them for odd jobs, when it is uneconomical to start up a larger furnace, or if the larger furnaces are fully employed. Automatic control of temperature is feasible, but is not usually provided, control being by hand.

The furnace preheating chamber is built of moulded refractory material and wound with 80/20 nickel-chromium alloy wire, surrounded by a thick insulating layer and fitted in a substantial sheet steel case. Entry for town gas is provided. A cut-out, fusing at 960° C., prevents the furnace winding from damage due to overheating. The high temperature chamber has a case of sheet steel, lagged (covered on roof, wall and sides) with insulating bricks, a hard refractory inner chamber, and a removable hearth tray. Recrystallized carborundum heating elements with low resistance ends which do not require water cooling are fitted in the roof. Atmosphere control is provided by what is termed the *counterscale curtain.* In this the gas and air are introduced through a mixing chamber to the combustion chamber in the furnace vestibule. The burnt gases are forced up through a slot extending across the door aperture and forming a screen or curtain that prevents infiltration of air. By filling the chamber they also keep decarburizing or oxidizing agents away from the work. To stop air from getting in when the door is open, a larger quantity of the mixture is admitted, i.e. the chamber is "flooded" and this effectively keeps out the air. Table XVI shows the principal dimensions of these furnaces.

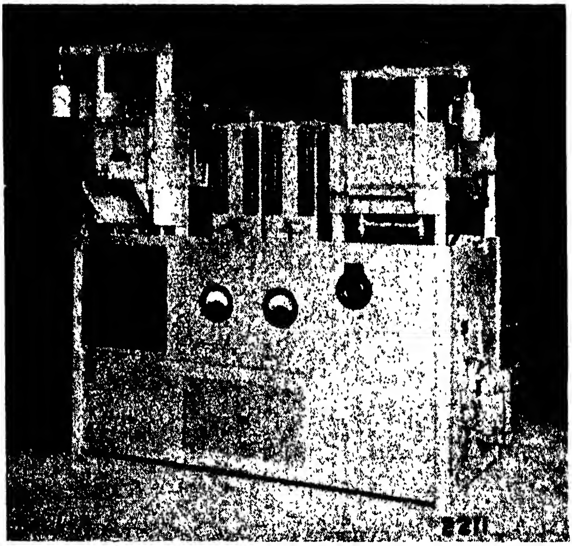


FIG. 48. HIGH-SPEED STEEL ELECTRIC HARDENING FURNACE FOR TOOL ROOM

TABLE XVI

Largest Tool lb.	Pre-heating Chamber Length in.	High Temperature Chamber Length in.	Door Opening				Rating kW
			Width		Height		
			Pre-heating in.	High Temp. in.	Pre-heating in.	High Temp. in.	
5	15	8	6	4	3½	2	5·1
8	15	12	6	4	3½	4	6·6
10	19	16	7½	4	5	4	9·6

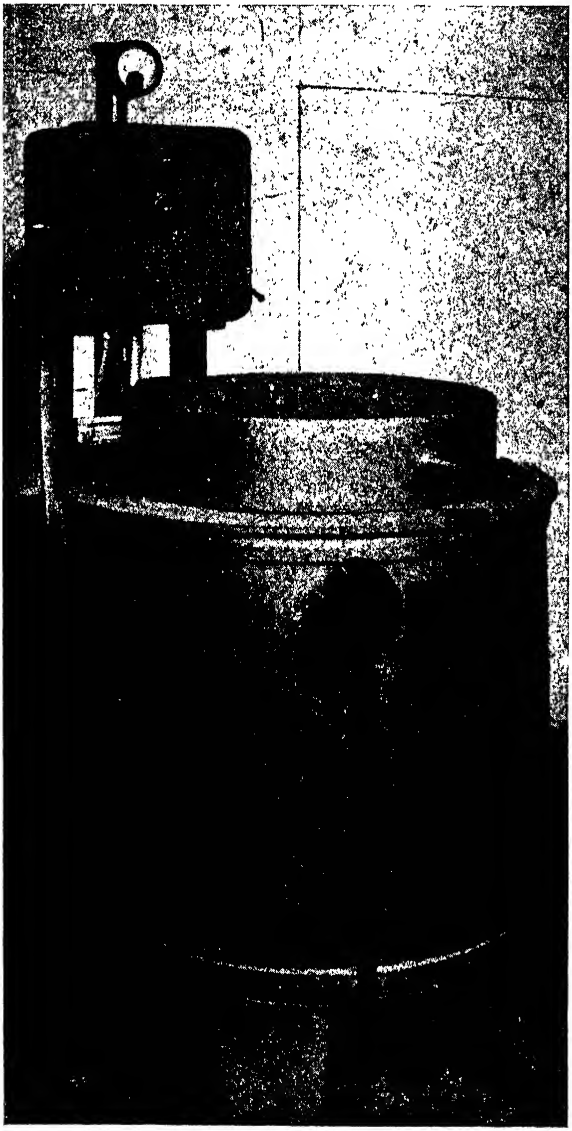


FIG. 49. TOOL-ROOM MODEL FURNACE, WITH FORCED-AIR CIRCULATION, FOR SECONDARY HARDENING OF HIGH-SPEED STEEL

Fig. 49 shows a larger size capable of handling most tools in general use.

Vertical furnaces can be made if required.

Fig. 50 shows a still larger Wild-Barfield high temperature furnace designed for producing high-speed steel tools. These equipments comprise two separately controlled furnaces, one for preheating and the other for actual hardening.

The arrangement and construction of these equipments thus differ considerably from those previously described. They are furnished with automatic temperature control and the "counterscale-curtain" method of controlling atmosphere. Besides being used for hardening high-speed steel, they can be used for various experimental purposes requiring temperatures of 1350° C. and up to 1400° C. for short periods.

Table XVII shows the standard measurements of the high temperature furnace.

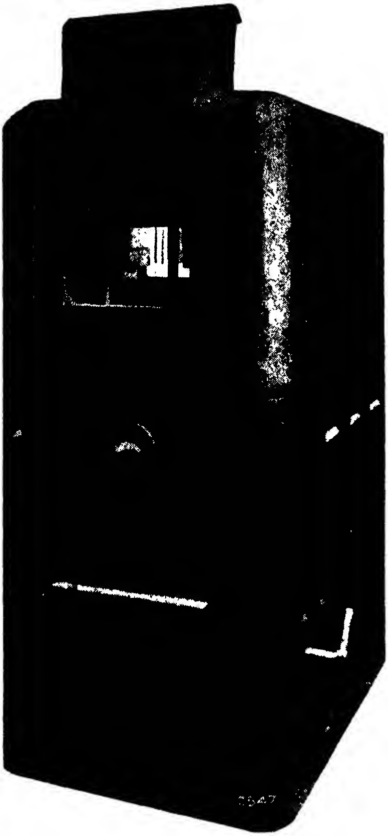


Fig. 50. Larger Size of Electric Furnace for Tools

TABLE XVII

Largest Tool lb.	Chamber Length in.	Door Opening		Floor Space in.	Rating kW
		Width in.	Height in.		
18	18	6	6	35 × 28	18
25	24	12	10	40 × 40	30
35	30	16	12	46 × 45	40

Fig. 51 shows the "Hairpin-Minor" preheating furnace for these larger high-speed steel-hardening furnaces, in which the

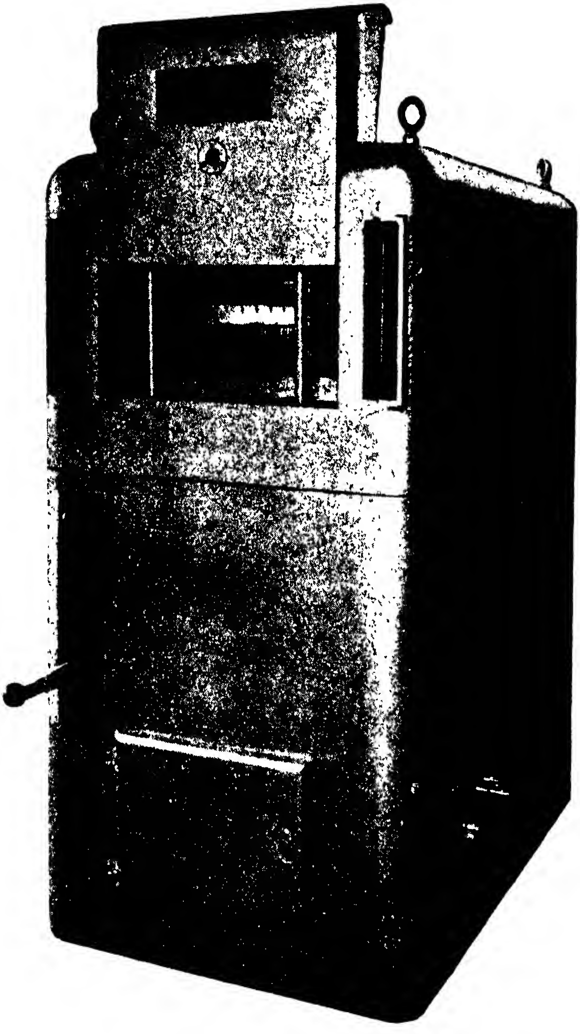


FIG. 51. "HAIRPIN-MINOR" PREHEATING FURNACE

wound-muffle construction is abandoned in favour of a chamber constructed of special refractory bricks in which the heating elements lie. These elements are of heavy section nickel-chromium alloy and have a sinuous or serpentine form. A wall-mounting controller automatically controls temperature. These furnaces are not only preheaters; they can be used for general hardening, annealing, carburizing, etc.; secondary hardening of small tools can also be carried out if suitable tappings are provided on the transformer to reduce the input of electric current at the lower temperatures. Large tools, however, should not be given secondary hardening in these furnaces.

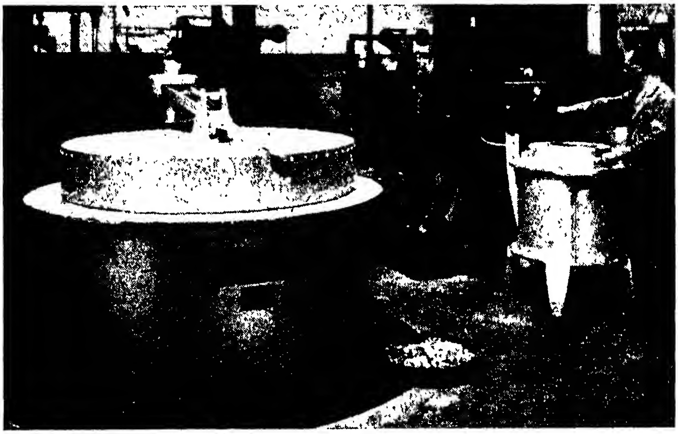


FIG. 52. TWO VERTICAL FORCED-AIR CIRCULATION EQUIPMENTS

Table XVIII gives their standard measurements.

TABLE XVIII

Chamber Length in.	Door Opening		Floor Space Occupied in.	Rating kW
	Width in.	Height in.		
18	9	5½	31 × 44	7·5
24	12	6½	35 × 50	12·0
30	15	8½	39 × 56	20·0

Fig. 52 shows the Wild-Barfield Standard forced-air circulation furnace for the secondary hardening of high-speed steels and general tempering. A carefully designed cylindrical brick-lined chamber, with an inner concentric metal cylinder, holds inside it a work-basket. The inner cylinder sits upon a throat mounted above the fan, and the base of the work-basket is perforated. The heating elements are mounted in the ring-shaped space between the insulated wall and the container. The latter prevents direct radiation of heat on to the charge, and confines the circulating air to a direct path. At the bottom of the chamber is a centrifugal fan, which causes a powerful air current to be driven upwards over the heating elements and downwards through the charge. The air absorbs heat from the elements and delivers it to the material in the work-basket as it travels downwards. The air circulation is thus continuous, no fresh air being drawn into and no hot air expelled from the chamber. Thus, all the heat is conserved and imparted to the charge as quickly as it can be absorbed.

The furnace has a circular lid easily lifted and swung to one side by means of a lever. The elements are of heavy section nickel-chromium wire supported on special grooved refractory *formers* (i.e. having the same internal shape as the external shape of the wire). A cut-out shuts off the current as soon as a certain temperature is exceeded, thus protecting the heating elements, and a door-switch isolates the elements and stops the fan when the door is open. A combined automatic temperature-controller and charge progress recorder is provided. These furnaces operate on normal A.C. or D.C. supplies, and are made in sizes similar to those listed in Table XIV.

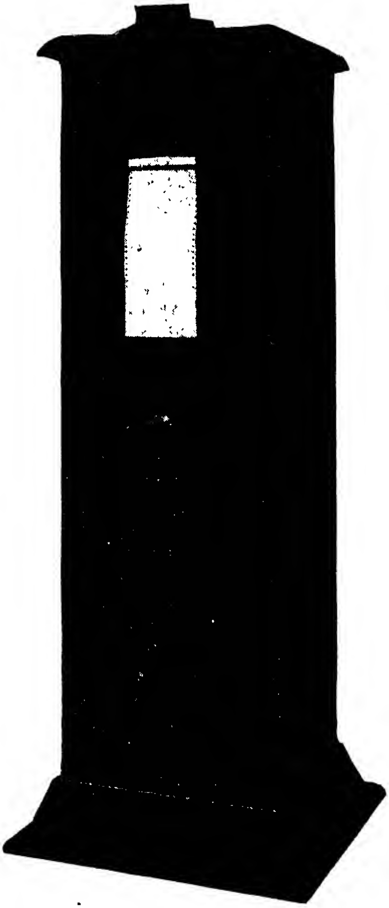


FIG. 53. CHARGE PROGRESS RECORDER

Fig. 53 shows the Wild-Barfield charge progress recorder, which shows when the charge itself, as distinct from the furnace, has reached the desired temperature, and in addition to maintaining the furnace automatically at any desired temperature,

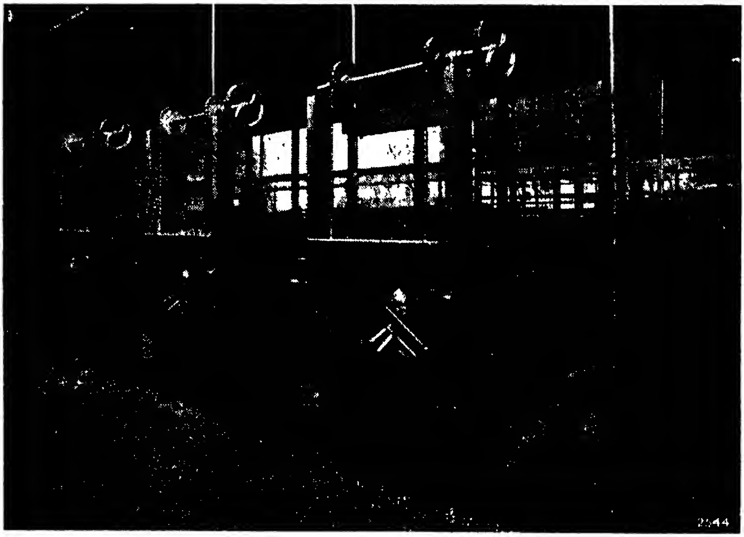


FIG. 54. BATTERY OF NITRIDING FURNACES

FIG. 55. BATTERY OF CARBURIZING FURNACES

records it, together with the progress of the charge, on a single chart. When the two record lines, which are black and red respectively, coincide, the work is at the set temperature throughout and may be withdrawn or left to soak as required. Use of this apparatus prevents lost output through leaving work in the furnace longer than necessary, while the permanent record proves correct heat-treatment, indicates whether the plant has been operated at full capacity, and aids in the location of hold-ups in production.

Fig. 56. Two Tool-room High-speed Steel Hardening Equipments

Fig. 54 shows a battery of Wild-Barfield nitriding furnaces installed for the treatment of engine components, etc. The furnaces shown are generally of standard construction, having refractory-lined chambers with coil heating elements and a specially designed hearth to take the heavy nitriding container.

Fig. 55 shows a battery of carburizing equipments with 2-zone control. Fig. 56 shows two tool-room high-speed steel hardening equipments. In the two vertical forced-air circulation equipments, shown in Fig. 52, the larger has a work-basket 32 in. diameter × 40 in. deep. This type of furnace is used for general low temperature treatments, the smaller being the Wild-Barfield standard tool-room tempering equipment, widely used in conjunction with the standard tool-room high-speed steel hardening equipment.

CHAPTER IX

Petroleum and Fuel Oil Furnaces

PETROLEUM and fuel oil furnaces are chiefly used for heat-treatment in the United States, where supplies of these fuels are cheap and plentiful. There are, however, quite a number of oil-fired furnaces in use in this country for other purposes.

Petroleum fuels are of two main types, termed respectively *propane* and *butane.*

Propane is a colourless gas with a complex hydrocarbon composition represented by the chemical formula $CH_3CH_2CH_3$, showing it to be composed of atoms of carbon and hydrogen. It is derived from crude petroleum. In the commercial form it is impure, and contains not only propane but also *propylene* and minute quantities of *ethane,* butanes, and *butylenes.* Propylene is another colourless gas obtained as a result of chemical reactions or by electrolysis. It is described as an unsaturated gas and has the composition ($CH_2CH : CH_3$). Ethane is another colourless gas (CH_3CH_3).

Butane is also a hydrocarbon, or compound of hydrogen and carbon, and closely resembles paraffin. There are two butanes, but the one with which we are concerned is that known as "normal" butane, a gas found in petroleum and having the formula $CH_3CH_2CH_2CH_3$. Butylenes are olefinic or oil-forming hydrocarbons and closely akin to ethylene in their properties. They are constituents, with butane, of commercial butane, which also includes a little propane and propylene.

Neither of these gases burns very quickly and, in consequence, it is possible to use a lower speed of air-gas mixture through burner ports (openings) or nozzles without risk of backfiring. Furthermore, it is possible to employ certain forms of burner equipment with a lower manifold pressure. (A *manifold* is a series of pipes with branches for conveying the air-gas mixture under pressure from the source and for carrying the waste gases to the exterior of the furnace.) This lower pressure has the advantage that it provides a wider range of flame manipulation between full-on and nearly off.

The relative efficiencies of the different liquid fuels are directly proportionate to the available heat of the gas, assuming identical conditions of furnace design and operation. This brings us to the point: What is the available heat of a fuel? It can be taken as the gross B.T.U. value minus the amount of heat contained in the combustion products at the specific temperature concerned. The *B.T.U.* value is the value expressed in British Thermal Units. (A unit of this type corresponds to the amount of heat necessary to raise the temperature of 1 lb. of water by one degree Fahrenheit.)

Propane and butane both have a high available heat, and have the additional good feature that they do not contain any ingredients or constituents that cannot be burned, e.g. water, inert gases such as nitrogen, carbon dioxide, etc.

Fuel oil is a general term including a considerable range of products obtained by distilling petroleum or blends of these with other oils of petroleum type. The fuel oils used for heating industrial furnaces are known as "heavy" fuels. The property they must possess is a low enough viscosity, so that when heat is applied to them and they are *atomized*, i.e. brought to a fine spray, by being passed through a burner of suitable form, they will burn completely without waste or residues.

It should be noted here that *viscosity*, or "stickiness," is the power a substance possesses of resisting a change in the arrangement of its particles, so that low viscosity implies a lower resistance to this change, i.e. to "flow." Unless the fuel oil can be economically heated so as to flow and become atomized at the burners, it is unsuitable for industrial heating. Too low a viscosity is not so important as too high, because the more fluid fuels can be used with success so long as care is taken to prevent wastage by leaking at joints and seams.

It is essential in using fuel oil to possess some type of storage equipment, usually a tank or series of tanks placed at a fair height above the furnaces they are to supply. A common arrangement is to divide the total tankage into four sections, one portion in use, one full and ready for use, one cleaned and empty in readiness for its supply of oil, and the fourth in process of being cleaned. Inside the tanks are steam heating coils, i.e. symmetrically-coiled piping filled with saturated steam at any available pressure.* The purpose of this is to keep the oil warm, a

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* *Saturated steam* is steam at that stage in which no further rise in temperature occurs until all the water is converted into steam of a specific volume (expressed as v/cub. ft.).

temperature of approximately 27° C. being regarded as suitable for normal conditions. The tanks are also provided with draining pipes to enable sediment and water to be easily removed when necessary. If the ordinary pressure of the supply is not sufficient in itself, it may be necessary to pump the fuel oil into the tanks by means of a screw pump, motor-driven through gearing.

The combustion equipment comprises a pump for propelling the fuel into the burners, some form of preheater to warm the oil to the correct low viscosity in readiness for atomization, a means of registering the air supply, burners or, as they are more usually termed, *atomizers*, and fans or some other type of apparatus for producing an air current.

The atomizers are of four main classes, which one is chosen depending entirely on the circumstances. The first type is the mechanical pressure atomizer, in which the oil is supplied under a mechanically-produced high pressure, preheated by exhaust steam, and finally driven, when fluid enough, through small holes or passages in a plate or nozzle, thus producing a spray of pure drops. There is a possibility that the small orifices in the plate or nozzle may become obstructed by sediment.

The second class includes the centrifugal atomizers. Here, a cup containing the oil revolves at a great speed, and is impinged upon by an air-blast which goes round its outer edge. Centrifugal force drives the oil outwards from the cup, and the air-blast scatters it into a mist of finely divided droplets. A means of registering the air introduced is necessary, and the wear on the rotating parts, combined with the room they require in the furnace, is apt to make this type of atomizer expensive.

The third type is the steam atomizer. Instead of the oil being whirled centrifugally from a revolving cup, it is allowed to dribble from a hole. A jet of steam by its impact then disperses the oil into minute droplets. This dispersal may occur either externally to the metal parts of the burner itself or internally, in which instance the steam encompasses and carries away the droplets, driving them eventually through an opening of a form suitable to the type of flame desired.

The fourth type is the air atomizer, and as this is identical with the previous type, except that air is substituted for steam, there is no need to describe it in detail.

Admixture with air is, of course, as in an internal combustion engine, essential for burning, and this admixture must be thorough.

It is achieved by means of an air register through which the air is introduced, though it may, alternatively, be taken in through openings in the furnace either by natural or *forced*—i.e. mechanically caused—draught. Where this latter method is adopted for heat-treating furnaces, the air is generally provided by way of the atomizer, no air register being employed.

The fuel oil flame should not strike straight on to the steel being treated nor on to the brickwork of the furnace, and the usual practice is to interpose a "baffle" wall to take the flame.

CHAPTER X

Atmosphere Control

THE science of furnace atmosphere control is in its infancy, and so much has been discovered that considerable time will be required to digest the implications of the innumerable data available. In consequence, it cannot be claimed that this chapter expresses finality. It must be regarded as a preliminary and temporary summing up of what has so far been established.

As soon as steel is raised in temperature in a confined space, as in a heat-treating furnace, its surface is acted upon by the atmosphere it encounters there. This atmosphere is gaseous and contains, if uncontrolled, a good deal of oxygen, free or combined. This oxygen, under the influence of a raised temperature, may combine with metallic elements in the steel's surface and form a crust or "scale" of oxide. This condition is known as *oxidation.* In many instances it is prejudicial to the finished appearance of the steel, and may also, if too severe, weaken the steel considerably, impair its surface, and, by aiding corrosion as a result of the superficial depressions and blemishes it causes, lead to a speedier corrosion-fatigue failure in service.

Alternatively, there may be elements in the atmosphere with a strong affinity for carbon, which they extract from the surface layers of the steel. This condition is known as *decarburization.* Carbon is, of course, the basis of steel's hardness, and the absorption of carbon from the surface means that the uppermost layers of the steel will be soft. This is the cause of what is commonly termed "soft skin."

Finally, in special circumstances, there may be a reverse process. An excess of carbon in the furnace atmosphere may lead to the absorption of this element by the surface layers of the steel, thus producing a condition known as *carburization*, characterized by an extremely hard skin or *case* about a softer *core* or interior. This condition is often deliberately brought about because of its advantages in many fields of steel application, as the reader will find when he comes to the chapter on case carburizing. At the same time, if this particular effect is undesired, its occurrence can be as troublesome and annoying as the other conditions described.

Decarburization is a disadvantage because it turns soft what should be hard. Parts, or tools, required for a given set of dimensions will be useless until the soft skin is removed, and will then be found below size. If this skin is not removed, usually by expensive grinding or machining, trouble will be experienced owing to the absence of the necessary high degree of hardness.

Steel users have therefore been led to experiment more and more in an attempt to avoid these difficulties and to preserve the original surface condition of the steel. They have studied minutely the atmosphere inside different types of furnaces, its constituents, and the chemical effects of these on steel. A most impressive research has been carried out also by the Sheffield and District Gas Company.

It is known that the atmospheres produced by fuel combustion in a furnace contain the following gases, the relative proportions of which vary in accordance with the degree of mixing and the relative quantities of fuel and air admitted into the burners—

(1) Carbon dioxide (CO_2).
(2) Water vapour (H_2O).
(3) Nitrogen (N_2).
(4) Oxygen (O_2).
(5) Hydrogen (H_2).
(6) Unburned hydrocarbons from the fuel.
(7) Carbon monoxide (CO).
(8) Sulphur dioxide (SO_2).

Of these the most active is free (i.e. uncombined with any other element) oxygen. As soon as the furnace temperature rises above 200° C., the free oxygen interacts chemically with the surface of the steel to form oxides and scale. Hence it was realized that if as much free oxygen as possible could be excluded from the atmosphere in the furnace chamber, there would be a marked reduction in the extent of this oxidationand scaling. Of these constituents, Nos. 1, 2, 4, and 8 cause oxidation and scaling, accompanied by decarburization.

Nos. 5, 6, and 7 are reducing gases, i.e. they tend to prevent oxidation and scaling, although 5 can bring about decarburization. Nos. 6 and 7 may actually carburize the steel's surface. It will thus be seen that oxidation is almost invariably accompanied by decarburization, but the latter may occur without the formation of scale.

This sounds quite easy, until it is remembered that combustion demands the presence of oxygen when the fuel employed is solid, e.g. coal, wood, or coke. Not only must there be oxygen in the furnace atmosphere at the outset, but also new supplies of air must be continually admitted so as to maintain efficient combustion. Otherwise the original oxygen will be exhausted, combustion will cease, temperature will fall, and proper heat-treatment come to an end. Even when the fuel is liquid, as with fuel oil, some free oxygen has to be present in the atmosphere to support combustion, even though the additional air required is not nearly so great as for solid fuel. Furthermore, if much sulphur is present in the fuel, scaling will be enhanced.

With town-gas-fired furnaces, however, a closer measure of atmosphere control becomes possible, because if the burners are correctly designed, the air for combustion is mixed with the gas before it enters the furnace chamber, and is ignited at once, so that only a flame enters the chamber. The combustion obtained demands neither free oxygen in the furnace atmosphere nor additional supplies of gas for its continuance. From the point of view of controlled atmosphere, the oven type of town-gas-fired furnace is, therefore, the most efficient.

This is because all other types of furnaces, such as muffles and electric furnaces, demand an atmosphere of air, unless special equipment is employed for the production of synthetic atmospheres.

Thus far this chapter has dealt only with furnaces in which the temperature is higher, but not much higher, than 200° C. As we have seen in earlier chapters, however, not only do heat-treatment furnace temperatures rise to as high as 1350° C., but the period during which steel is maintained at the higher temperatures may be greatly prolonged. It will be obvious that if there is anything in the furnace atmosphere capable of injuriously affecting the surface of the steel, its effect will be greater the longer it is allowed to go on attacking. Moreover, it should be noted that the higher the temperature, the greater the disintegration of the constituents of the furnace atmosphere, and the greater likelihood not only of the liberation of elements capable of combining harmfully with elements in the steel, but also of the steel itself being much more receptivo to these elements.

Hence, where high temperatures and prolonged heating periods are necessary, special precautions against oxidation and scaling become essential. When solid fuels are employed, it may even be necessary to pack the steel in metal boxes and surround it with cast iron borings (containing "free" carbon in the form of graphite) inside the boxes, so powerful is the action of even small amounts of free oxygen. With town-gas-fired furnaces, the only atmosphere is that of the products of combustion, and these contain no free oxygen, so that packing of the steel is needless.

At the same time, although a furnace atmosphere without free oxygen can be obtained, there are other important factors to be considered. In the first place, as soon as temperatures over 1000° C. are reached, carbon dioxide and water vapour, both present in the combustion products and the furnace chamber, react with the iron of the steel, to form iron oxide. Both these produce the flakiness of the surface known as *scaling*. Hydrogen, water vapour, and carbon dioxide also combine with the carbon to remove it from the surface layers. These result in a soft skin, i.e. a decarburized surface. Free oxygen does not necessarily, although it does almost invariably, decarburize the steel, but will produce scaling or oxidation. To prevent all possibility of both oxidation and decarburization at these high temperatures and long soaking periods, it becomes necessary, as when high-speed steels are hardened, to use special equipment to produce a synthetic muffle atmosphere, i.e. the atmosphere in a furnace of muffle type in which the charge is heated out of contact with the fuel or combustion products.

For example, in one modern furnace for the heat-treatment of high-speed steels, the gas and air, mixed in proper proportions, are burned in a brick-lined combustion chamber, and the combustion products are cooled in cooling towers, which has the effect of eliminating, by condensation, the water vapour and sulphur dioxide (SO_2) they contain, thus getting rid of two important scaling agents.

Then they are mixed with unburned town gas. This mixture is used to purge the muffle or charge-heating chamber of the furnace of any free oxygen, or oxygen-containing compounds the waste gases may contain, and is so proportioned that its individual gases react to form a perfectly balanced atmosphere. The exact proportions of the waste gases and the unburned town gas needed for this purpose can be calculated from chemical principles, into which we need not go here, and this is left to those whose business it is to supply furnace burners and equipment which will ensure that a correct atmosphere is produced in the actual heating chamber. Under these conditions not more than 1/10,000th of an inch of scale is formed on the steel, and there is no decarburization.

Another method of producing a balanced furnace atmosphere is known as *pyrogenic decomposition.* This involves passing town gas through a heat-resisting steel tube stuffed with mild steel turnings (i.e. the waste material produced when steel is machined in a lathe or other machine tool). The gas decomposes and, in addition, any oxygen in it is removed by the iron of the steel to form oxide of iron before the gas reaches the combustion chamber. The extent to which the oxygen (and sulphur) is removed is governed by the speed with which the gas is made to pass through the tube. If this is regulated to give the correct proportion of hydrogen-methane (the gases produced by the aforesaid decomposition) steel of almost any carbon percentage can be treated without scale, carburization, or decarburization. This method is, however, applicable only to temperatures below 1000° C., because above this temperature methane breaks down into its elements, carbon and hydrogen.

In another system, the cooled combustion products are passed over hydrated iron oxide such as *bog iron ore* ($Fe_2O_33H_2O$). This removes the sulphuretted hydrogen (or hydrogen sulphide), H_2S. The dried and purified gases, comprising for the most part nitrogen, hydrogen, carbon monoxide, and carbon dioxide, are then either introduced directly into the furnace or, if it is required that there should be an absolute minimum of water, are passed through chemical drying machines or through a refrigerator, which, by severely chilling the gases, condenses out any remaining moisture.

With electric furnaces a special atmosphere is provided for temperatures over 1200° C. These furnaces, at temperatures below this figure, often have an atmosphere of air. This would cause considerable scale at the higher heats, so that for these high temperatures it becomes necessary to *neutralize* the furnace atmosphere, i.e. to make it completely non-scaling, non-carburizing, and non-decarburizing.

In this country, town gas and anhydrous (water-free) ammonia are the main sources of these neutral electric furnace atmospheres, but butane (see p. 110) has also been employed because it is relatively sulphur-free as compared with town gas. Its use to-day is rare because better methods of production have minimized the sulphur content in town-gas furnace atmospheres.

Ammonia is available for the production of electric heat-treating furnace atmospheres in large cylinders. It is first *cracked* (broken up into its separate constituents, namely, 75 per cent hydrogen, 25 per cent nitrogen). Ammonia is a simple substance, and when cracked contains no impurities at all, being free from both sulphur and water vapour. Hence one would imagine it ideal as an atmosphere for the heating of metals, which could neither oxidize nor carburize in its presence. So the early steel treaters thought, but they had overlooked two vital matters. Cracked ammonia is costly, and what is more, is likely to explode dangerously when heated. This made its use injudicious, but an alternative was found.

This comprised burning cracked ammonia in the presence of air and eliminating, by condensation in cooling towers, the resultant water vapour. In this way a furnace atmosphere was produced containing 90 or more per cent of nitrogen, the balance being hydrogen. The curious feature is that the modified proportions of nitrogen and hydrogen make this gas not only non-explosive and non-poisonous, but also twice as cheap as ordinary cracked ammonia. Even so, it was much dearer than a town-gas atmosphere and was, in consequence, only economical when no other type of furnace atmosphere would do what was required.

Of recent date, however, a way has been discovered of producing burnt ammonia at a cost no greater than that of a town-gas atmosphere.

In this system, the ammonia-burning apparatus or *gas generator* and the furnace form a closed circuit in which the gases, after being passed through the furnace, are returned to the burner purified by the extraction of the water vapour and the addition of more "unburnt" ammonia vapour and their analysis adjusted to the correct proportions, after which they are returned to the furnace for further use. As a rule only about 10 per cent of unburnt ammonia is needed to restore each batch of used gas, so that the cost is materially reduced. Furnace systems of this type are widely used in bright annealing.

A quite different method of producing a controlled electric furnace atmosphere is to use charcoal as the raw material. This gives an atmosphere practically free from sulphur, containing 30 to 35 per cent of carbon monoxide, a small percentage of carbon dioxide, and a balance of nitrogen. This atmosphere is more expensive than the regenerated burnt-ammonia atmosphere described above, but is excellent as a means of completely preventing decarburization in certain steel parts, particularly for aircraft and automobiles, where it is essential that this defect should be avoided.

CHAPTER XI

Heat-treatment Furnace Refractories

THE performance of a heat-treatment furnace may be considerably affected by the character and condition of the refractory or heat-resisting materials with which it is lined. There are wide differences in these; some contain fewer impurities than others, come from different sources, are bonded in different ways, and made by different methods. Care must, therefore, be exercised in the choice of refractories by a furnace builder, and for this reason in the present chapter we give certain details that will help a furnace-user to choose and use his furnaces more efficiently.

Most heat-treatment furnaces operate at a relatively low temperature, but this does not mean that the refractories used can be of low grade. There are serious drawbacks to the use of low-grade refractories. When ferrous metals are being heat-treated, the furnaces are usually designed to work on an increased gas-air ratio, thus giving a reducing (oxygen-removing) atmosphere high in carbon monoxide and hydrocarbons. This causes the presence of an excess of carbon monoxide, because there is not sufficient oxygen present to burn all the carbon in the fuel to the dioxide, CO_2. Should the refractories contain any free iron oxide in their composition, such products are liable to disintegrate if held at temperatures between 400° C. and 600° C. in the presence of carbon monoxide. The critical temperature range for this type of disintegration of firebricks possessing free iron oxide in the presence of methane is considerably higher, namely, 800° C. to 900° C. Even so, failure of this type in heat-treatment furnaces is extremely rare.

Firebricks for heat-treatment furnaces must therefore be well burned, i.e. baked in advance of use; of the highest quality; and with as little free iron oxide in their composition as possible Most firebricks contain a small percentage of ferric oxide, but if they are hard-burned, the iron oxide will combine with the silica in the clay, making it less susceptible to carbon monoxide attack.

CARBURIZING FURNACES

The object of all carburizing compounds is to produce carbon monoxide gas. Carburizing furnaces are most efficient when gas-fired, because no ash or slag is produced, so that a setting or lining composed almost entirely of heat-insulating materials can be used. A setting of this kind is most effective because it ensures (*a*) a quicker and completely controlled thermal cycle or recurrent period of heating; (*b*) less storage of heat in the brickwork; (*c*) lower loss of heat through the furnace walls; (*d*) uniform temperature throughout the furnace; (*e*) a saving in fuel; (*f*) greatly reduced weight of brickwork.

Fig. 57 shows a section through a gas-fired carburizing furnace built of super-quality hot-face refractory insulating bricks, with a hearth of *vitrified* (converted into a glass-like form) firebricks, set on a base of super-quality insulating concrete, the whole being encased in an outer shell of low temperature insulating bricks, similar to diatomite, an extremely porous substance, being the silica skeleton of minute organisms (diatoms). *Diatomite* is an excellent heat-insulator, but is not suitable if exposed to temperatures above 950–1000° C. Pre-calcined diatomite is serviceable at slightly higher temperatures. Incidentally, the super-quality insulating concrete above-mentioned must not be confused with insulating concretes of the diatomite type containing low temperature aggregates. Many advantages are claimed for the type of furnace construction outlined. The super-quality hot-face refractory insulating bricks are made from English *kaolin* (a pure clay having the formula $Al_2O_3 . 2SiO_2 . 2H_2O$, being a hydrated silicate of alumina; in other words, a compound of aluminium oxide, silica, and water). The porosity of these bricks is controlled and artificially induced. They are unusually pure and will withstand flame temperatures up to 1350° C., but cannot be used if there is any likelihood of their being subjected to severe abrasion or excessive slag attack. The purity of the materials from which the bricks are made and, in particular, their freedom from iron oxide, render them insusceptible to attack as a result of exposure to carbon monoxide.

The vitrified hearth bricks are relatively impure, but the vitrifaction given to them in course of manufacture is so high that they become almost impermeable, while their great hardness enables them to withstand the continual abrasion caused by the insertion and withdrawal of the carburizing boxes.

The insulating concrete base below the hearth gives good hearth insulation in a material that, while of insulating character, is also mechanically strong enough to withstand the weight of the structure and any loads placed on the hearth. Ordinary insulating bricks are too friable (easily crumbled) to be used below the hearth, because they will not withstand the loads imposed upon them.

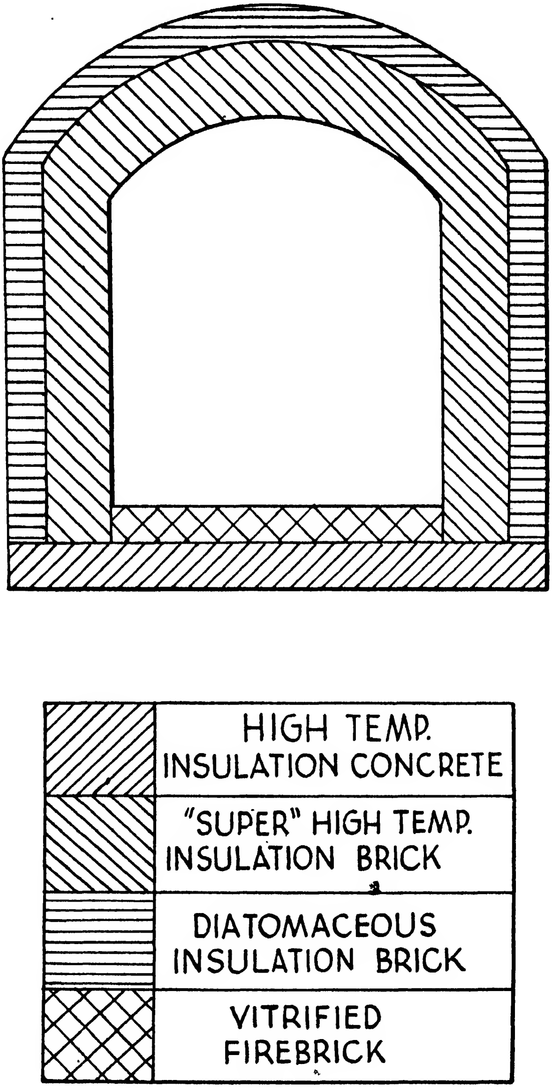

Fig. 57

COAL-FIRED HEAT-TREATMENT FURNACES

In these, the temperature of heat-treatment may be fairly low, but a temperature of not less than 1250° C. in the combustion chamber is necessary in order to ensure good combustion and consequent economical use of fuel. Combustion chambers are therefore built of firebricks containing 37/42 per cent alumina. Moreover, where furnaces are constructed on recuperative principles (see Chapter VI, "Furnaces"), walls with hot gases passing on both sides should also be built in firebricks of the same high quality.

Other walls not subjected to hot gases on both sides should be built similarly, since although these bricks appear to have unnecessarily high refractoriness in comparison with the temperatures they may have to withstand, their use is advisable because of their resistance to carbon monoxide attack as a result of the hard burning received during their manufacture. Furthermore, if the furnace is efficiently insulated, the mean temperature of the firebricks becomes surprisingly high, and the use of good materials provides a margin of safety if misjudgment by the operator, or some operational defect, causes high temperatures to be attained.

Furnaces of this type can be advantageously insulated as follows: (*a*) *Hearth* of vitrified firebricks set on a base of super-quality insulating concrete; (*b*) *front, rear, and side walls* of 37 to 42 per cent alumina firebricks insulated with low temperature insulating bricks; (*c*) *roofs*. The roof over the treatment chamber should be insulated with low temperature insulating bricks, but not the roof over the combustion chamber. Experience has shown that it does not always pay to insulate the whole of the furnace roof, including that of the combustion chamber, because the shortened life of the firebricks more than offsets the advantages of insulation. It may seem absurd to insulate three-quarters of the roof while leaving the remaining quarter uninsulated, but actually this procedure is perfectly rational. Heat is lost to the atmosphere by the conductivity of the brickwork. The heat is not actually under pressure, and that one part of the roof is not insulated does not mean that the heat losses through that section would be comparable with the heat losses that would be sustained if the entire roof were not insulated.

It should be noted that the recommendation of vitrified firebricks in the hearth is based on the assumption that the hearth temperature will not exceed 1000° C. If this temperature is likely to be exceeded, bricks with a higher alumina content must be employed. If the process involved is likely to induce excessive scaling or slagging of any type, the top course of the hearth should be built of chrome-magnesite bricks or other basic or chrome-plastic materials. These are less affected by slag at such temperatures, and also obviate the possibility that particles of refractory material will be "picked up" from the hearth. This is always a danger when ferrous metals are in contact with firebricks.

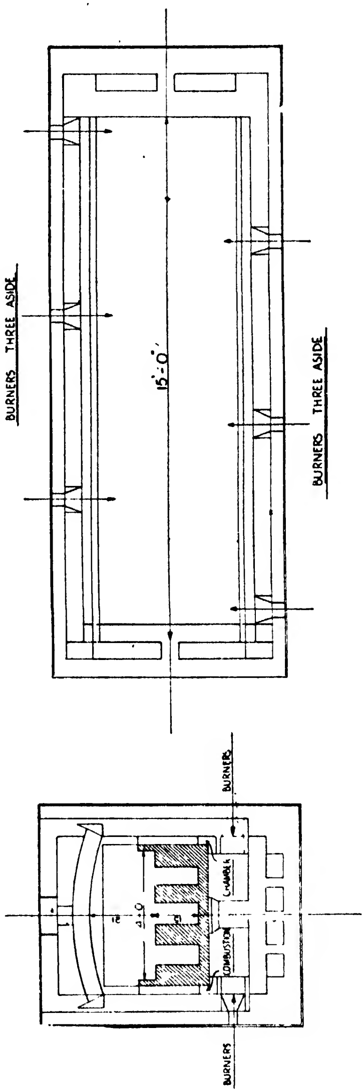

Fig. 58

Heat-treatment Furnaces Mechanically Charged

Much of what has been written concerning coal-fired furnaces is applicable to the above also, but a number of additional features are introduced. The blocks grooved to accommodate the prongs of the charging machine can be a source of weakness. Fig. 58 details the general sources of weakness in this type of furnace due to errors in construction and brick design. For example, (*a*) the corner bricks or checks should be radiused as much as possible, because brick shapes possessing sharp right angles are difficult to dry and fire without cracking. Such faults become more pronounced when the bricks are put into service;

(*b*) increased heating efficiency is obtained by the introduction of "radiation holes" in the supporting brick structure. Such holes should not be introduced near the surface, as they also lead to structural weaknesses, induce drying and burning cracks, which become more pronounced when the bricks are put into service; (*c*) radiation holes in the blocks should not be too near to any surface of the block; especially in side blocks care should be taken to see that the radiation holes do not create a zone of weakness with the checks in the block.

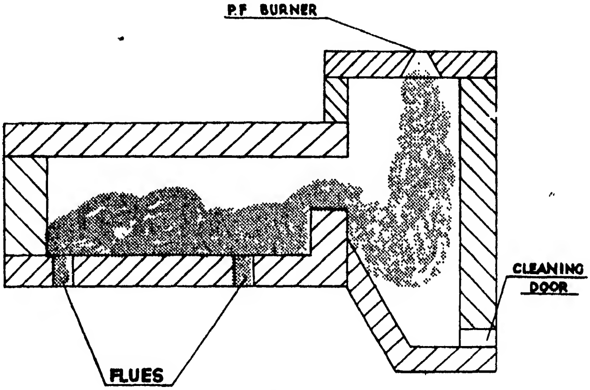

FIG. 59

OIL-FIRED HEAT-TREATMENT FURNACES

All the remarks on coal-fired furnace refractories apply here also. Burner throat-bricks should be made in 42 per cent alumina firebricks highly *grogged*, i.e. containing a fair proportion of pre-fired firebrick ground to a particle size sufficiently fine to be used in the brick batch. Such additions prevent over-shrinkage of the brick during both firing and later use. This type of brick offers a higher resistance to spalling than the type in which little or no grog is used.

PULVERIZED FUEL-FIRED HEAT-TREATMENT FURNACES

Here, again, the notes on refractory materials for coal-fired furnaces generally apply, but the position of the burners is important. Burners whose flames blast over the stock hearth deposit slag and ash on to the stock with consequent loss and cleaning difficulties. An arrangement that materially assists in overcoming this difficulty is shown in Fig. 59. This ensures that ash in suspension is deposited in the grit hopper, and that gases free from grit pass over the materials being treated.

INSULATED FURNACES

When designing insulated furnaces, the following points must be borne in mind: (*a*) Hot face insulation, i.e. the heat insulation of the inner surface of the bricks or lining of the combustion chamber, is obtained by the use of highly porous, low thermal conductivity bricks prepared from clay-combustible mixtures containing, before firing, a certain proportion of combustible matter, e.g. coke dust, coal dust, or sawdust. These can be used at relatively high temperatures without any protecting brick in front, but should not be used if the lining is subject to slag attack or mechanical abuse; (*b*) insulation should not be used if it will bring the mean temperature of the brickwork lining above the *refractoriness-under-load value* of the firebrick. At this temperature the refractory begins to collapse when subjected to a definite pressure. The refractoriness-under-load value of a firebrick indicates its mechanical strength or load-bearing capacity at high temperatures. The mean temperature of the brickwork should not reach this value, as it would result in the attainment by the hot face of the brick of a much higher temperature, leading to possible disruption and collapse under the working load. In calculating this temperature, a reasonable margin of safety must be allowed; (*c*) if low temperature insulating materials are used outside the firebrick lining, care must be taken to ensure that the junction temperature is not above the safe working temperature of the insulating material.

In calculating the above factors, the following table of maximum safe temperatures will act as a guide—

(*a*) Super-quality hot-face insulating bricks—either hot-face or junction temperature 1350° C.

(*b*) Super-quality insulating concrete—either hot-face or junction temperature 1250° C.

(*c*) Standard quality hot-face fireclay insulating bricks—hot-face or junction temperature 1150° C.

(*d*) Low temperature diatomaceous insulating bricks—junction temperature 800° C. These bricks should not be subjected to direct gas or flame impingement.

To enable temperature gradients and junction temperatures to be estimated through any combination of refractory and insulating materials, a chart (Fig. 60) is reproduced on which all such materials are given factor values. This allows rapid approximations to be made. Application for copyright protection of this chart has been made under the joint names of General Refractories, Ltd., and Mr. T. S. Pearson, by whose kind permission it is reproduced here.

JOINTING MATERIALS

In general, firebricks exposed to high temperatures should be jointed with fireclays similar to those from which the bricks are manufactured, but in many heat-treatment furnaces, parts of the walls never reach a temperature high enough to develop a ceramic or heat-fusion bond between the brick-joints.

In such instances the joint remains weak and friable, even after long service, thereby detracting from the strength of the structure. Fireclay will not sinter (i.e. its impurities do not fuse) at temperatures below 1250° C., and even if that temperature is developed on the hot-face, the ceramic bond will only develop to the depth of the joint to which that temperature permeates.

In considering the jointing material to be used, it is therefore advisable to take the temperature as the mean temperature of the brickwork. If the mean temperature is above 1250° C., the appropriate fireclay can be used with satisfactory results, but at lower temperatures high-temperature air-setting refractory cement is a much more suitable medium. This sets with rock-like hardness at atmospheric temperatures, and its refractoriness is only slightly below that of the best fireclays. The use of an air-setting cement for sprung roofs (roofs possessing "sprung" or supported arches, instead of suspended roofs) is not recommended, because sprung roofs must rise as they expand under heat, and an air-setting jointing material would prevent the movement of the bricks necessary to accommodate this rise. Insulating bricks of all types should be jointed with a cement made from the same materials as the bricks, suitably bonded.

ELECTRICALLY-HEATED HEAT-TREATMENT FURNACES

For special purposes, e.g. bright annealing of stainless steel, electric furnaces are often preferred, because they combine cleanliness with efficient temperature control. The refractories used for these furnaces are essentially similar to those employed for coal or gas-fired furnaces, but the use of more expensive

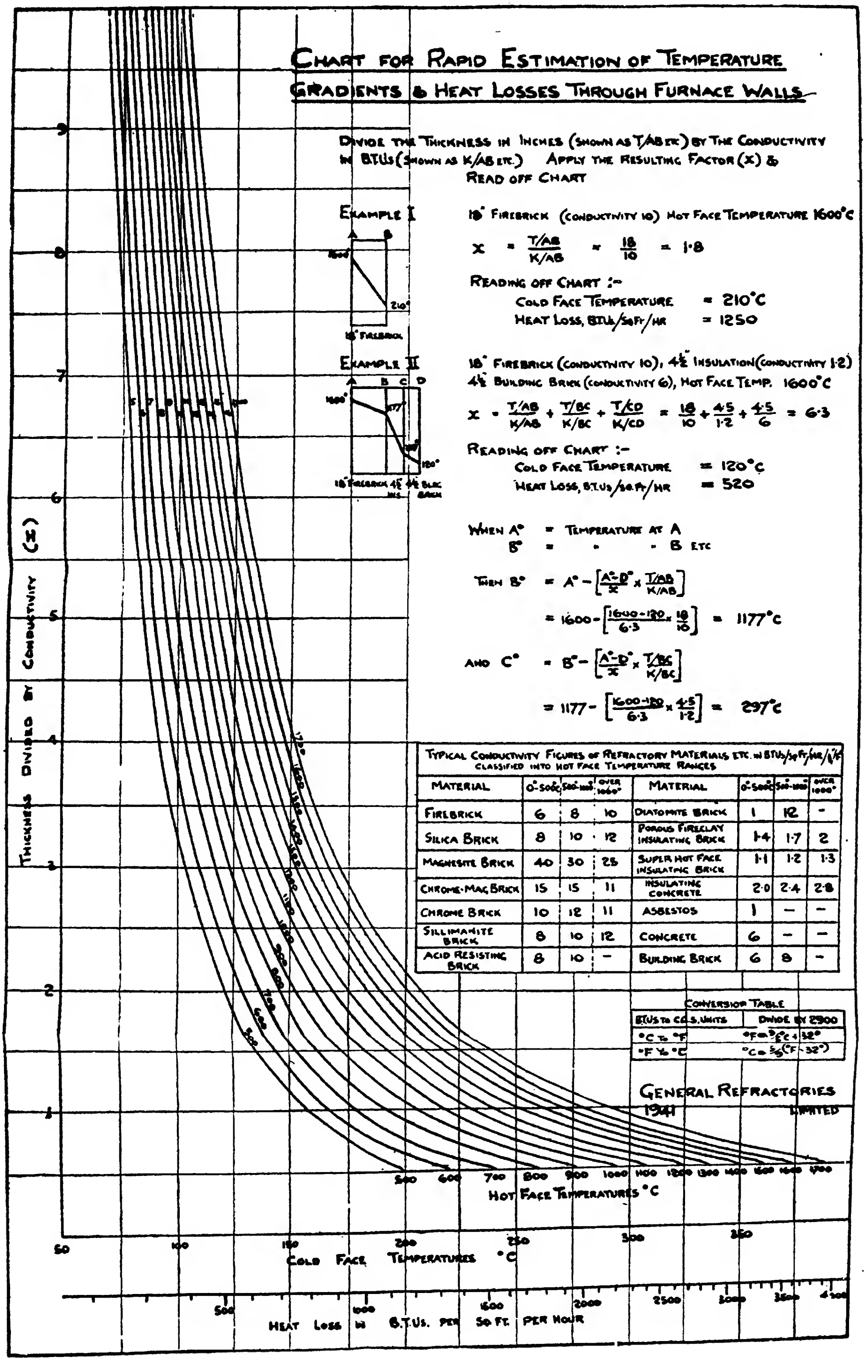

CHART FOR RAPID ESTIMATION OF TEMPERATURE GRADIENTS & HEAT LOSSES THROUGH FURNACE WALLS

DIVIDE THE THICKNESS IN INCHES (SHOWN AS T/AB ETC.) BY THE CONDUCTIVITY IN BTUs (SHOWN AS K/AB ETC.) APPLY THE RESULTING FACTOR (X) & READ OFF CHART

EXAMPLE I

18" FIREBRICK (CONDUCTIVITY 10) HOT FACE TEMPERATURE 1600°C

$$x = \frac{T/AB}{K/AB} = \frac{18}{10} = 1{\cdot}8$$

READING OFF CHART :-

COLD FACE TEMPERATURE = 210°C

HEAT LOSS, BTUs/SQ.FT/HR = 1250

EXAMPLE II

18" FIREBRICK (CONDUCTIVITY 10), 4½" INSULATION (CONDUCTIVITY 1·2) 4½" BUILDING BRICK (CONDUCTIVITY 6), HOT FACE TEMP. 1600°C

$$x = \frac{T/AB}{K/AB} + \frac{T/BC}{K/BC} + \frac{T/CD}{K/CD} = \frac{18}{10} + \frac{4{\cdot}5}{1{\cdot}2} + \frac{4{\cdot}5}{6} = 6{\cdot}3$$

READING OFF CHART :-

COLD FACE TEMPERATURE = 120°C

HEAT LOSS, B.T.Us/SQ.FT/HR = 520

WHEN A° = TEMPERATURE AT A

B° = " " B ETC

$$\text{THEN } B^\circ = A^\circ - \left[\frac{A^\circ - D^\circ}{x} \times \frac{T/AB}{K/AB}\right]$$

$$= 1600 - \left[\frac{1600-120}{6{\cdot}3} \times \frac{18}{10}\right] = 1177^\circ C$$

$$\text{AND } C^\circ = B^\circ - \left[\frac{A^\circ - D^\circ}{x} \times \frac{T/BC}{K/BC}\right]$$

$$= 1177 - \left[\frac{1600-120}{6{\cdot}3} \times \frac{4{\cdot}5}{1{\cdot}2}\right] = 297^\circ C$$

TYPICAL CONDUCTIVITY FIGURES OF REFRACTORY MATERIALS ETC. IN BTUs/SQ FT/HR/1"/F CLASSIFIED INTO HOT FACE TEMPERATURE RANGES

MATERIAL	0°–500°C	500°–1000°	OVER 1000°	MATERIAL	0°–500°C	500°–1000°	OVER 1000°
FIREBRICK	6	8	10	DIATOMITE BRICK	1	12	-
SILICA BRICK	8	10	12	POROUS FIRECLAY INSULATING BRICK	1·4	1·7	2
MAGNESITE BRICK	40	30	25	SUPER HOT FACE INSULATING BRICK	1·1	1·2	1·3
CHROME-MAG BRICK	15	15	11	INSULATING CONCRETE	2·0	2·4	2·8
CHROME BRICK	10	12	11	ASBESTOS	1	—	—
SILLIMANITE BRICK	8	10	12	CONCRETE	6	—	—
ACID RESISTING BRICK	8	10	—	BUILDING BRICK	6	8	—

CONVERSION TABLE

BTUs TO C.G.S. UNITS	DIVIDE BY 2900
°C TO °F	$°F = \frac{9}{5}°C + 32°$
°F TO °C	$°C = \frac{5}{9}(°F - 32°)$

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1941

FIG. 60

bricks, such as *sillimanite,* is often considered desirable in order to avoid contamination of the steel by the refractory.

In general, the heating is accomplished by means of wire coil or hairpin elements inserted in grooves in the refractory. They may be exposed to the working conditions of the furnace, or may be set behind brickwork, or in a suitable cement. In both instances the quality of the refractory is of the utmost importance, since local impurities, in particular iron oxide or alkalis, will result in reaction with, and rapid deterioration of, the heating element. Sillimanite has been found particularly useful in minimizing such reactions.

Silit rods, which consist essentially of silicon carbide, can be used at temperatures as high as 1400° C., i.e. 150° C. higher than most heat-resisting steel elements, but their use is largely confined to small furnaces.

More recently, high temperature hot-face insulation bricks have been used very successfully in the construction of such electric furnaces.

CHAPTER XII

Liquid Heating Baths

THERE is a class of heat-treatment in which the steel is raised to the desired temperature not by enclosure in a chamber heated by combustion processes, but by immersion in a previously heated liquid. These liquids are of two types, molten metals and molten salts. Of the metals, only lead has any commercial applicability to the heat-treatment of steel. The salts are numerous, and are dealt with later in the chapter. Oils are used only in quenching and tempering, and are dealt with in later chapters devoted to these subjects.

LEAD BATHS

Lead is not so commonly used for heat-treating as at one time, because automatic furnaces of the types described earlier have largely replaced it on account of their greater economy and efficiency, and their cleaner and healthier operating conditions. Its chief field of use to-day is for local hardening and tempering, where only a portion of the tool or part is required fully hard. In this direction it is a most useful auxiliary, and instances are known in which alternate hardened and unhardened parts have been produced in one and the same bar by clever manipulation of the lead bath. As a means of heating for local hardening it has advantages over the salts, as we shall see. Another good point about lead baths is that they do not cause oxidation and scaling of the steel. A typical employment of lead is for hardening the teeth of files. It can also be used as a tempering medium.

With its low melting point, 327° C. (621° F.), it is soon raised to temperature, and can be effectively employed for temperatures up to 1285° C., i.e. for most hardening and tempering operations. If impure or oxidized, however, it forms a coating or scum on the surface of the steel being treated. Files are usually given a protective coating to preserve the teeth and prevent clogging of the spaces between them. They are dipped in a mixture of charcoal and flour, or a salt, or even caustic soda. Even so, it will be necessary to sand blast, or pick out by hand, lead particles from the grooves by various means after the hardening treatment, but this is not difficult, and the teeth are not adversely affected by the bath, even if a little adhesion of this kind has occurred.

Another advantage of lead is that it neither contains nor picks up moisture, so that no scaling or oxidation of the steel from this cause is possible, nor is there any danger of explosions resulting from the sudden formation of steam as new lead is added to replenish the bath. Additional good points are the speed with which it can be heated, the absence of chemical attack on the steel, and, with the exception of a readiness to oxidize, its general stability.

On the other hand, certain disadvantages exist. Steel is lighter than lead, and a curious sight for the novice is to see steel files floating on the surface of a lead bath. It will be obvious, therefore, that to keep the steel being treated in the correct, immersed, hardening position, it is necessary to provide various types of fixtures. This is an additional cost, though not one of major importance.

Secondly, the ready oxidation of the metal is an adverse factor, since it not only wastes an expensive bath material, but also renders essential a cleaning process for the parts or tools hardened in it. This oxidation begins as soon as the lead is melted, and unless some step is taken to minimize or prevent it, harm will be done. The usual procedure is to cover the surface of the lead in the bath with a layer of suitable material, as described below, which keeps the air away from it, or, rather, consumes the oxygen and thus prevents oxidation of the lead. Even so, although the hardening or treating temperatures are low, oxidation may still occur, and a supplementary cleaning process will then be indispensable. When the heat-treatment temperature rises above 455° C., however, the protection afforded by the covering is usually sufficient, and little oxidation takes place. Incidentally, it should be noted that the oxide formed is not very soluble in lead, so that it does not permeate the entire mass of molten metal, but remains mainly on the surface.

The speed with which the metal conducts heat, besides enabling the bath to be rapidly heated up with a consequent beneficial effect on output, also assists in the maintenance of an even temperature throughout the molten metal, thereby increasing its efficiency as a heating medium.

Whenever a liquid lead bath is used and cold metal parts are placed in it for treatment, there is a tendency for layers of solid lead to form on the parts. This is because lead has a low *latent heat of fusion*. This means that as only a low degree of heat is absorbed in converting the solid lead into liquid, the chilling effect of the cold steel placed in the bath is sufficient to resolidify the lead at the surfaces of contact. It will be obvious that these cold layers must be completely remelted before the steel can be heated to a higher temperature than the actual melting point of the lead. This is true of salt baths also, but because lead has a higher heat conductivity, these layers melt more rapidly than corresponding salt layers. It is thus possible to use lead at temperatures nearer to the melting point than can be done with salts, a fact of importance when heating costs are considered.

This formation of solidified layers on a cold charge is not always a bad thing where the complex form or design of the parts makes warping or distortion likely, because the chilling effect of the solidified layers causes slower heating, and consequently less sudden stresses of the steel.

Where, however, these layers are economically disadvantageous, they can be prevented by preheating the steel in advance of its immersion in the bath to the melting temperature of lead, or slightly above it. No layers will then be formed, since there will be no chilling effect.

The temperature range within which lead can be effectively used depends on the melting point so far as the lower part of the range is concerned, and for the upper part on the ability of the container or pot to withstand the requisite temperatures, and the efficacy of the bath surface covering in preventing lead oxidation. (See p. 134.) The type of pot used is a factor of importance.

The lead used in these baths is ordinary commercial pig lead (lead in short blocks or "pigs"). Points to be observed in buying lead for this work are absence of tin from the analysis, since tin makes the lead adhesive to, and may even embrittle, the steel; and too great a sulphur content, because sulphur may then be absorbed by the outer layers of the steel, which is undesirable.

The pot is usually heated by either gas or oil, but many, particularly in tool rooms, are now electrically heated, the heating elements being wrapped about the pot, because of the greater length of service obtained from pots so heated, and because the method is cleaner.

The pot when fuel-fired is supported on a refractory base.

This at the same time constitutes the heating chamber, and is provided with burners and outlets or ports for the waste gases. Three types of metal are mainly used for lead pots, namely, cast iron, pressed steel, and special heat-resisting alloys. Cast iron is only used when the temperatures are not likely to exceed 700° C., because its life is too short at high heats, so that it is not suitable for lead baths designed for hardening high-speed steels, etc., unless the pot is extremely small and only a low production is required. The cause of its short life at these high temperatures is oxidation and scaling. Cast unalloyed steel, like cast iron, is quite suitable for temperatures below 700° C. Where higher temperatures are involved, its employment is possible, but may not always be economical, since under severe temperature conditions its life may be too short as a result of scaling, etc. The casting must above all be sound and free from blowholes or cracks.

Pressed steel has the advantages of light weight and absence of blowholes. It can be used successfully at any of the lead-bath heat-treatment temperatures, but has the disadvantage that since it is formed by dies, which are expensive, it cannot be used in a wide variety of forms, but must be restricted to simple standard shapes and dimensions.

The special heat-resisting alloys, though higher in first cost than any of the previously mentioned pot materials, have advantages in length of service life that outweigh this wherever high temperature conditions (over 700° C.) are encountered, though not at the lower temperatures. There are numerous compositions, all falling roughly into two groups: the iron-chromium alloys (usually containing 25 per cent of chromium) and the nickel-chromium-iron alloys (usually containing either 65 per cent nickel and 15 per cent chromium or 35 per cent nickel and 15 per cent chromium). Mostly they are cast, though a few pressings are made in certain of the more malleable compositions. As with cast steel, it is essential there should be complete freedom from blowholes. Because of their composition, these pots are highly resistant to corrosion and the oxidation caused by high temperatures, and this gives them a long service life under conditions that would cause pots of the less expensive materials to deteriorate rapidly.

The service given by a lead pot is determined not only by the material of which it is made, but also by its design. It is an error to assume that walls and bottom must be exceptionally thick. In fact, too great a thickness may be detrimental and cause early decay of the pot. The reason is the different rates of thermal expansion of the interior containing the molten lead and the exterior surfaces, which set up severe structural stress in the metal, thereby weakening it. For the same reason, it is advisable to avoid sharp changes of section and sharp angles, particularly in those parts of the pot in contact with the molten lead. The greater the resistance to heat and scaling given by the metal of the pot, the less thickness it will require, so that all things being equal, a heat-resisting alloy pot will be thinner walled and thinner at the bottom than either a cast iron or a cast steel pot. Too thin a wall or bottom must be avoided, however, because this may lead to early cracking, beginning with a bulge, due to the inability of the thin section to withstand the weight of lead.

Most pots fail as a result of either the unsuspected presence of blowholes, wastage due to oxidation, or cracking. A cast iron pot usually ends its life with a crack. A cast steel pot does not often crack, but may fail as a result of a blowhole. Sometimes the effect of oxidation is to scale off the surface of the metal and show up blowholes, which increase the area of oxidation, besides weakening the metal. Heat-resisting alloy pots mostly crack towards the end of their lives, but may also fail as a result of blowholes or pinholes. Scaling is with them seldom a cause of failure. Pressed steel pots are usually discarded as a result of progressive oxidation. Pressed heat-resisting alloy pots fail in the end through cracks or oxidation.

The oxidation of the molten lead, already referred to earlier, is prevented or minimized by a suitable covering. This may be either solid or liquid. Many different coverings are used, the main factor being the type of heat-treatment and the temperature at which it is carried out. Wood charcoal, charred nut-shells, charred leather, and coke (for high temperature work only) are among the more commonly used solid coverings. Molten salts are liquid coverings widely used. The more delicate the part being heat-treated, the better the covering material should be.

It may be imagined that the protective effect of the solid covering is purely exclusive, the air being kept from contact with the surface of the molten lead by a carbonaceous blanket, so to speak. Actually, however, there is also a chemical action. The carbon-containing covering material slowly burns as soon as a certain temperature is reached, and gives off carbon monoxide, thus extracting oxygen from the layers of air directly over the lead surface itself. Thereby it reduces the power of this air to oxidize the molten lead. The combination of chemical *reduction* (or absorption of oxygen) and mechanical blanketing is so much more effective than blanketing alone, which is what we have before the covering burns, that in choosing a covering material of solid carbonaceous type, it is always advisable to give preference to one having a low kindling temperature, so as to bring into play at the earliest possible moment this advantageous combined action. Wood charcoal is probably the best from this point of view. The covering should not be of too large-sized lumps or pieces, because the larger the pieces, the less is the surface area exposed to the atmosphere, and therefore the less rapid will be the consumption of the oxygen by the carbon.

In course of time the covering is consumed and remains floating on the surface of the lead, whence it must be periodically skimmed off, together with the small but inevitable amount of oxidized lead that will, despite all precautions, have formed on the surface below the ash. Fresh material is promptly added. This regular skimming should not be neglected, as the ash layer is chemically inert and consequently less protective than the unconsumed material.

Molten salts are useful, though costlier, coverings because they produce clean work with a minimum of lead loss. They are quickly consumed, however, while they do not, as do the carbonaceous coverings, damp down the glare and lessen the heat radiated from the surface of the metal. Hence, more heat is dissipated and lost by radiation, while the operators are faced with more arduous working conditions. The salts mostly used are mixtures of sodium chloride ($NaCl$), sodium carbonate (Na_2CO_3) and potassium carbonate (K_2CO_3). Cyanide mixtures can be used, but only for very low production, as otherwise they prove uneconomical, but for carburizing they have a distinct use. See Chapter XXXIII.

Lead baths are not dangerous so long as the waste gases from the combustion chamber are properly vented (conducted out of the building by means of hoods and chimneys), and lead oxide dust is not allowed to permeate the air. No toxic (poisonous) emanations are given off by the bath surface.

The work must be perfectly dry before immersion in the bath, or steam may be formed leading to dangerous explosions.

Tempering in the lead bath is usually a batch process, i.e.

not continuous, the pot being charged to the maximum extent and the parts taken out when the requisite temperature has been attained. Continuous operation is usually adopted for hardening processes, as with files. The bath is kept at the hardening heat, and as the tools reach the correct temperature they are progressively removed and fresh work added to replace them.

Lead baths are sometimes used in the *patenting* of "high carbon" steel rod or wire as a preliminary to wire-drawing operations. In such instances the molten lead really becomes a *quenching bath.*

SALT BATHS

Salt baths, as their name suggests, are receptacles filled with a salt or mixture of different salts, which melt when heated, and so form a liquid heating medium. Into these the steel is inserted, and the communicated heat, as with lead baths, raises the temperature to the required point for the particular form of heat-treatment necessary. The salts used must be such as will not have any prejudicial effect on the steel, i.e. will not produce oxidation or decarburization, corrosion, or erosion.

It will be gathered that in some respects salt baths are competitive with lead baths, and we shall later summarize their comparative advantages and disadvantages.

The salts used are of three main classifications: those designed for low temperature heat-treatments, those for medium temperatures, and those for very high temperatures. The first group is mainly employed in tempering carbon or low-alloy steels. The second group is used for hardening, normalizing, or annealing the same types of steel, especially for steel wire and rod, and for the quenching of high-speed steels. The third group is used for hardening the high-alloy and high-speed steels.

The salts used for the low temperature heating of steel comprise *nitrates* and *nitrites* of the alkali metals. A nitrate is a salt of nitric acid (HNO_3) and a nitrite a salt of nitr*ous* acid (HNO_2). Typical examples are sodium nitrate ($NaNO_3$) and nitrite ($NaNO_2$) and potassium nitrate (KNO_3). Sodium nitrite is often mixed with potassium nitrate in the proportion 44 : 56, which mixture has a melting point of 145° C. Alternatively, sodium nitrate may be mixed with potassium nitrate in the proportions 48·7 : 51·3, and this mixture will melt at about 220° C.

None of these low temperature salts should be raised to temperatures higher than 590° C. The reason is that at higher temperatures they begin to react chemically with both the steel and the containing receptacle, damaging both. For identical reasons, care must be taken not to produce an overheated spot when the receptacle is being raised to the melting temperature of the salts. The heating of the receptacle must be uniform and gradual.

Which salt or salt mixture is to be used will largely depend on the range of temperature to be covered. Some salts have a smaller serviceable range than others, but are cheaper if the full range, i.e. from melting point to maximum safe temperature, is not required. The mixture of potassium nitrate and sodium nitrite is serviceable over the widest range and has therefore the maximum all-round usefulness, but as the lower temperatures are not always needed in a particular shop, it may be quite as effective to use a different mixture at lower cost.

The medium temperature salts are usually *chlorides* (compounds formed by the union of an element with the gas, chlorine, e.g. a salt of hydrochloric acid—HCl—or "spirits of salt"), or mixtures of chlorides and *carbonates* (salts of carbonic acid, H_2CO_3). Typical examples are potassium chloride and sodium carbonate in the proportion of 50 : 50, but this is seldom used for steel, being specifically designed for non-ferrous metals. The trouble so far as steel is concerned is that it causes soft skin or decarburization, though if sodium cyanide is added to the mixture, this decarburization is lessened, some nitrogen taking the place of the carbon. This method is, however, not greatly favoured.

For steel, calcium chloride and sodium chloride in the proportion 56: 44 are common salts. Of these, the second is the better, because calcium chloride absorbs water from the air, and so causes oxidation of the steel by virtue of the oxygen acquired as a result, while in itself it reacts chemically to some extent with the steel. The melting temperature of the calcium chloride bath is 504° C., and of the potassium chloride bath, 660° C.

These medium salts should not be raised to temperatures above 900° C., and although at the outset they do not chemically react with the surface of the steel, this passivity diminishes because a certain absorption of atmospheric oxygen by the molten salts occurs, which in time causes them to form compounds that extract carbon from the steel and so produce soft skins. This difficulty is overcome in practice by introducing into the bath at regular periods what is termed a *rectifying agent.* This may be either fused borax, boracic acid, or boric oxide. Its presence serves to convert the products formed by oxidation of the molten salts into a relatively harmless sediment capable of removal, when necessary. It should be noted, however, that *these rectifiers are not suitable for salt baths employing mixtures of chlorides and carbonates.*

The high temperature bath has salts comprising mixtures of barium chloride, borax, sodium fluoride, and silicates (i.e. combinations of silicon, oxygen, and some other element). A point of importance is that these salt mixtures do not, as do those previously described, remain solid until a precise melting point is reached. Like most alloys, they gradually soften until fully liquefied. The full melting range is actually from 870–1040° C. Another curious feature is that some of these baths may attack the steel slightly when quite fresh, but after a short period of service this attack ceases and the baths are quite safe for use even with delicate high-speed steel tools. Some users introduce a rectifying agent here also, in this instance ferro-silicon, as a preventive of decarburization or scaling.

Modern high temperature salt baths are also used for the preheating of steel.

Summing up, we may say that a salt for salt-bath use must not attack the steel; must be stable, i.e. must not alter in composition; must not form a sediment; must not give off injurious or corrosive vapours; must not adhere to the work in such a manner that cleaning is difficult; must not attack the receptacle in which it is held; must melt readily and be sufficiently fluid at the requisite heat-treatment temperatures; must not absorb moisture from the surrounding air; must not be prohibitive in cost; and must be economical in use.

It would be absurd to claim that a salt bath mixture fully meeting each of these requirements is available, but many good proprietary salts are on the market.

The disadvantages of salt baths, and their advantages, must be weighed one against the other in choosing a heating medium. Before considering these pros and cons, we will outline briefly certain operational points. A golden rule is to keep out of the salt bath any foreign body whatsoever, as otherwise there will be a distinct likelihood of contamination. Above all, *cyanide* *salts must never be brought into contact with nitrates, because if these are mingled when hot, a dangerous explosion may occur.*

Secondly, the salts should be bought in as pure a state as is possible and kept in that condition. Sulphates are undesirable, as they attack the surface of the steel, decomposing when heated and liberating sulphur trioxide (SO_3). There should be no accidental or careless mixing of one group of salts designed for a particular range of temperatures with another. If there is any reason to suspect the presence of harmful impurities in the bath ("harmful" being used in the sense of causing surface decarburization, oxidation, or corrosion of the steel), a good plan is to introduce into the bath a quantity of cast iron chips free from moisture and dirt, about one-twentieth of the total weight of the bath contents. These chips should be added when the salts are at nearly the maximum temperature for which they are suitable. The bath should then be vigorously stirred and chemical combination of the iron with the impurities will create a sediment. This should be given time to sink to the bottom of the container, then removed. The various rectifying agents mentioned earlier also have the effect of removing impurities.

The next important point is not to rush the preliminary heating designed to melt the salts, as this will only lead to overheating of the container, without any gain in earlier liquefaction of the materials, which cannot absorb heat faster than their nature will allow. To overheat the container is to reduce its life, while the layer of salts directly in contact with the overheated areas may not only corrode it as a result of their own overheated condition, but may also fundamentally change in chemical composition and so produce a dangerous lack of uniformity in the bath.

The salts will need replenishment from time to time. Such new additions are best made while the container with its existing salt contents is cold, otherwise sudden decrepitation (crackling) may occur, accompanied by a mild explosion. If the bath is being continuously operated, this will not be feasible. It may be also that owing to the complicated form of the parts being treated there is an unusually heavy loss of salts trapped and withdrawn when the parts are removed, in which case replenishment may need to be at intervals more frequent than is represented by the normal working period of the bath, i.e. between its heating up and being allowed to go cold. Here, again, adding solid new salts on top of cold, solid, previously used salts will not be practicable. In such instances, the user must take every precaution to ensure that the new addition contains no moisture, for reasons indicated earlier.

The melting point of the salt mixture is important, and is mainly a function of the size of the part or piece subjected to treatment. In lead baths solid layers of chilled metal form on a cold piece introduced into the bath. In salt baths a similar state of affairs is experienced. A large piece of steel will chill the layers of salt directly in contact with or near to it to such an extent that the salt will solidify on the surface of the steel. This naturally involves remelting this solid deposit before the steel can acquire the temperature even of the liquid bath. Hence, the lower the temperature at which the salt mixture melts, the sooner will the salt coating disappear and the steel acquire the desired degree of heat. The larger the work, therefore, the lower should be the melting point of the salts, or, alternatively, the work can be preheated to the temperature of the molten bath in advance of immersion.

When the parts to be treated are only small, the melting point of the salt mixture is less important, but it should not be too close to the working temperature. Preheating is not essential, but is an advantage. Where the number of parts to be treated is large, it is advisable to add a fresh batch as another is withdrawn. If the bath temperature is measured by a temperature-measuring instrument of the thermo-couple type, this should be taken out before the salts grow cold when a job is finished, or the contraction of the salts as they cool may cause damage by exerting pressure on the tube protecting the thermo-couple.

The salt bath can be heated by oil, gas, or electricity. Oil is mainly used for large receptacles, being less suitable for the smaller owing to the length of the flame, which would overlap so large an area of the container as to cause overheating. Gas-fired salt baths are fully adequate to their work, assuming reasonably good design. Electric salt baths, in which the heat is supplied by metallic alloy resistors disposed outside the container, are satisfactory for low and medium temperatures so long as the salts are not allowed to come into contact with the resistances.

Fig. 61 shows a salt bath furnace of electric type for hardening high-speed steel, designed by Birmingham Electric Furnaces, Ltd., in collaboration with I.C.I., Ltd. The furnace comprises a

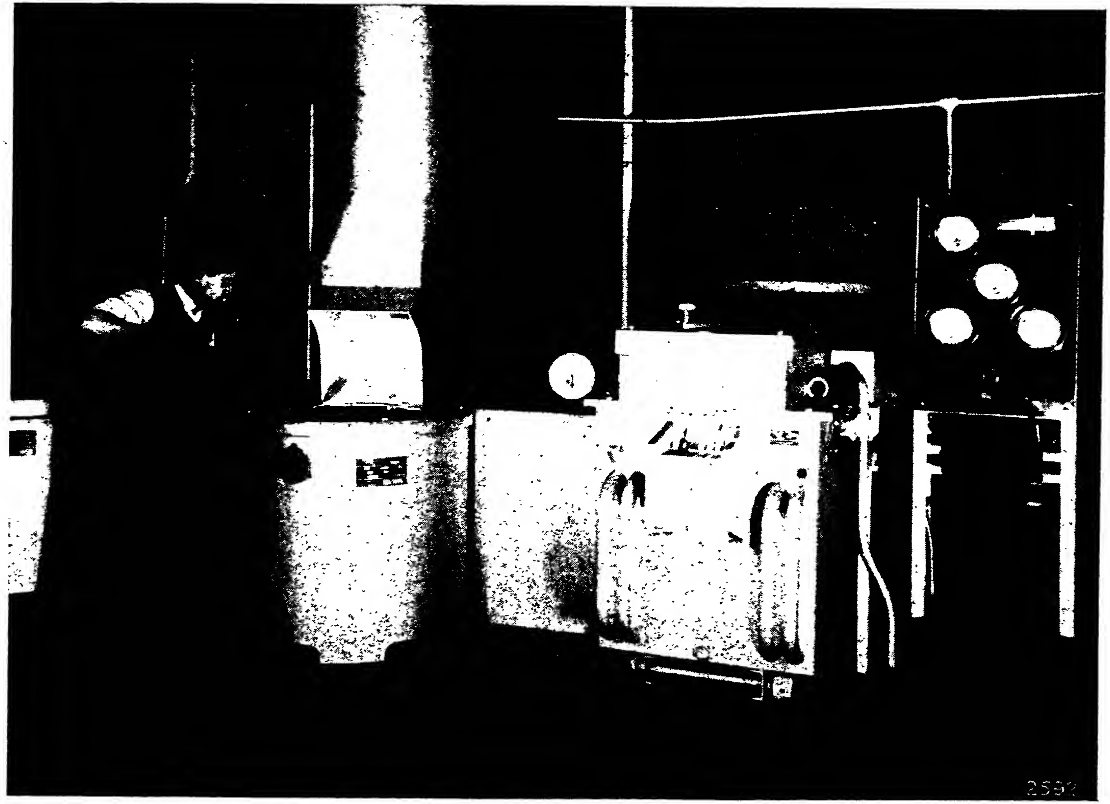


FIG. 61. SALT BATH ELECTRIC FURNACE FOR HARDENING HIGH-SPEED STEEL

pot or crucible of special refractory material having electrodes recessed in evenly-spaced, vertical slots in its sides. An alternating voltage of suitable low value is applied to these electrodes from a transformer, and the molten salt mixture in the bath, a proprietary brand known as "Carboneutral," is heated by the passage of the current through it. The bath temperature is indicated by a radiation type of pyrometer (see Chapter IV), and may be adjusted to any value over the full range required for hardening high-speed steel, by regulating the voltage applied to the electrodes. A selector switch, which controls the amount of current passing through the furnace, is fitted to the transformer for this purpose, and enables close temperature control to be obtained.

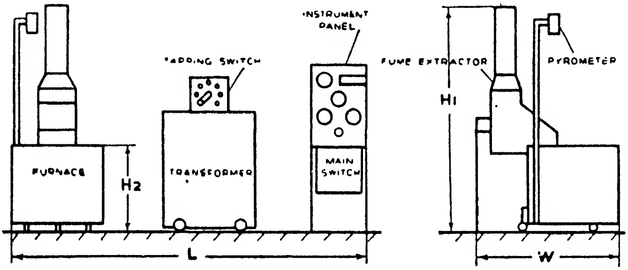


FIG. 62

The furnace incorporates a fan for extracting any slight fume that may be given off by the bath, thus ensuring correct pyrometer observations. The arrangement of this furnace is shown in Fig. 62, and Table XIX gives the corresponding dimensions.

A complete hardening unit, also by Birmingham Electric Furnaces, Ltd., is shown in Fig. 63. This equipment combines, in compact, self-contained form, a first preheater, a second preheater, a hardening furnace, and a quenching bath.

These are all arranged in a single casing of small overall size. By this means the rapid handling of work from one stage of treatment to another is, it is claimed, greatly facilitated. All controls are centralized under the constant observation of the operator. The first preheating stage comprises a forced air circulation furnace with full automatic temperature control for preheating tools rapidly and uniformly to 300° or 400° C.

The second preheating stage comprises an automatically controlled salt bath for final preheating from 300° C. to about

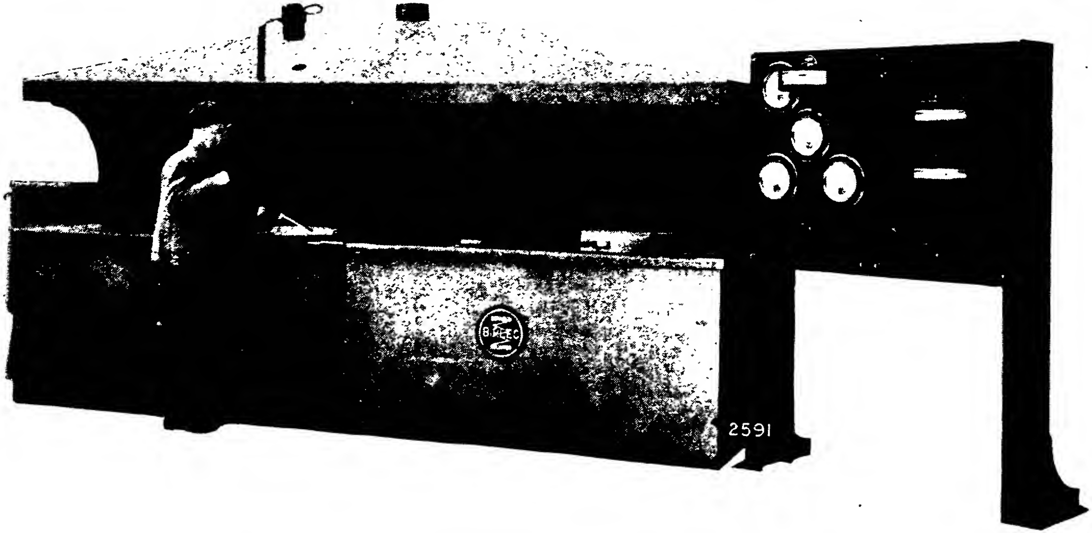


FIG. 63. COMPLETE HARDENING UNIT FOR HIGH-SPEED STEEL

TABLE XIX

Pit Size		Maximum Size of Work (See Note 1)				Output lb. per hr. (See Note 2)	Power in kW		Time to Heat Up (hr.)	Floor Space (See Fig. 62)			
		Flat Discs		Long Tools									
Dia. in.	Depth in.	Dia. in.	Thick in.	Dia. in.	Long in.		Start	Run		L. ft.	W. ft.	H.1 ft.	H.2 ft.
6	9	5	1	3	7	18–40	16	10	1	12	4-2/3	7¾	2¾
8	14	6½	1	4	12	50–75	33	19	1½	13	5-1/3	8	3
12	18	10	1	6	15	150–250	55	34	3	14	5-3/4	8¼	3¼

Note 1. Flat discs, such as thin milling cutters, are immersed on edge. Long tools, such as taps and wide cutters, are immersed on end.

Note 2. Output depends considerably on the type of work handled.

TABLE XX

Maximum Size of Work				Output lb. per hour	Total kW. Rating	Overall Dimensions (See Fig. 64)				
Flat Discs		Long Tools								
Diameter in.	Thick in.	Diameter in.	Long in.			L.1 ft.	L.2 ft.	H.1 ft.	H.2 ft.	W. ft.
5	1	3	7	18–40	47	11¾	20	7	3	7
6½	1	4	12	50–75	81	12¾	21	7	3	7½
10	1	6	15	150–250	120	14¼	22½	7	3	8½

900° C. The hardening stage is covered by a standard bath of "Carboneutral" type with pyrometer and manual voltage regulation (from the operator's working position) for temperature control. Finally, the quenching stage includes a special salt bath for quenching, using another special salt made by I.C.I., Ltd., for quenching high-speed steel. The diagrammatic arrangement of this furnace is shown in Fig. 64, and Table XX gives standard dimensions and details.

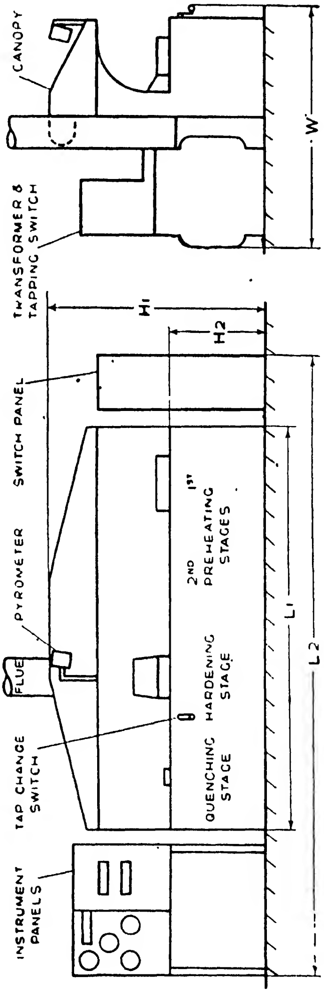


FIG. 64

Fig. 65 shows a Wild-Barfield electrode salt bath. In this, as in all salt baths made by reputable makers, temperature control is simple and easily maintained. Both the electrodes and inner brickwork, requiring periodical attention, are likewise readily accessible, and can be replaced when necessary with little trouble or delay. For almost continuous production, however, the makers recommend the inclusion of an additional bath.

The hood and fume extractor provided with the equipment are mounted separately, forming a fixture, but the bath is mounted on rollers, and, being provided with jacks, can be lowered and wheeled away without difficulty, the new bath being substituted at once. Great importance is attached to the hood, which gives definite protection to the operator, a gauze being fitted across the front of the opening. This enables the operator to see clearly, but keeps the salt from splashing in his face.

The bath is simple in operation, temperature control being effected by a tapper transformer with tapping switch, which enables the voltage to be adjusted as desired, the transformer casing serving also as a mount for the pyrometer, indicating lamp, and large scale ammeter. Control-means resemble those of other salt baths, but the tapping switch is of the off-load type, i.e. the voltage can only be changed when the current is switched off, having auxiliary contacts operated by a handle with a contactor provided, so that the effect of the combination is that of on-load

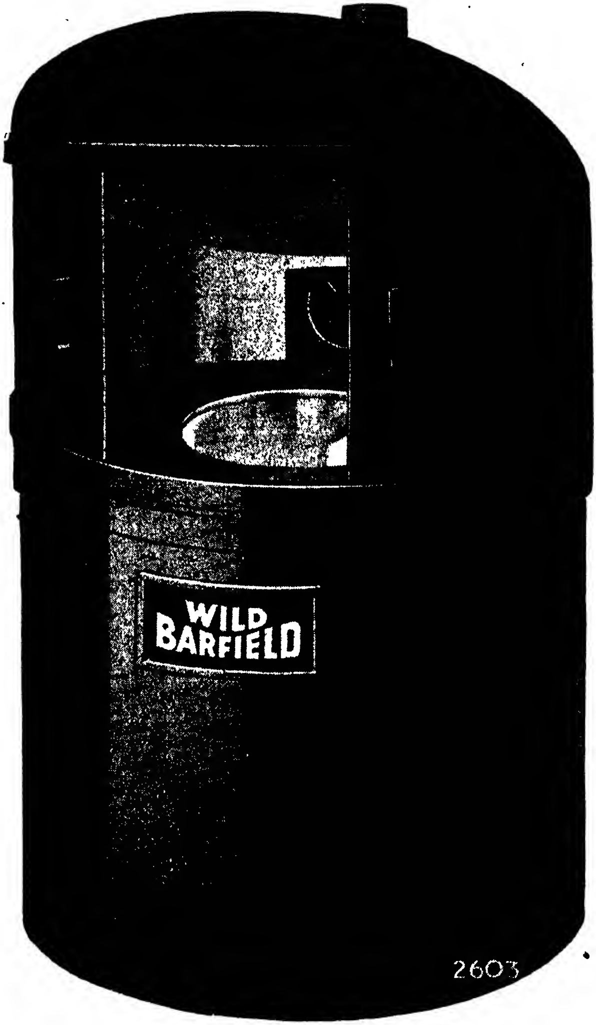


FIG. 65. WILD-BARFIELD ELECTRODE SALT BATH

operation. This arrangement has been chosen by the makers because in their experience the direct on-load switch is not sufficiently trustworthy for production equipment.

FIG. 66. SUSPENDED POT-TYPE SALT BATH FURNACE

There are three standard sizes, 6 in. × 9 in., 8 in. × 14 in., and 12 in. × 18 in.

Fig. 66 shows a suspended pot-type salt bath furnace made by the Incandescent Heat Co., Ltd., under licence from the Gas Light & Coke Co. This is a natural draught furnace. Working temperatures in the salt (or lead, for which this furnace is equally adapted) up to 900° C. are easily obtained without the use of high-pressure gas or air-blast. Pot strains and salt or metal explosions, due to an expanding liquid being imprisoned under a solid crust, are avoided by applying the heat first to the upper part of the pot, thus melting the surface layer before the lower portion.

A soft Bunsen gas-flame is so applied as to avoid direct flame impingement and localized heating, thus increasing the service life of the pot. The drawing in or induction of excess secondary air at low gas rates or speeds of flow is avoided by means of a single master control, linking the furnace damper movement with the main gas valve. This ensures efficient combustion at all times, and minimizes scaling of the pot.

Thermal efficiency, i.e. the maximum possible utilization of heat, is further increased by waste heat recuperators for preheating the secondary air. The standard sizes of this furnace are given in Table XXI.

TABLE XXI

Pot Diameter in.	Pot Depth in.
9	10
9	16
12	15
12	18
15	18
15	24
18	20
18	24

The furnace itself is built up on a solid cast iron base, with a circular outer casing and top of heavy mild steel plate. The refractory interior brickwork is backed with high quality insulating brick. Recuperator channels are provided within the brickwork for preheating the secondary air.

Four natural-draught heat-resisting steel burners are provided complete with injectors, air-regulators, and control-cocks. Each burner is housed in a specially moulded refractory insulating-block, itself housed in a substantial heat-resisting casting. The entire burner assembly is bolted to the furnace casing, and is readily removable.

The furnace has a solid pressed steel pot of suitable thickness, treated by an aluminizing or calorizing process that, by coating it with a layer of metallic aluminium or, rather, aluminium oxide, renders it highly oxidation-resistant. The circular hood is of strong mild steel plate, and has double sliding doors. Damper control is inter-connected with the main gas valve, to secure accurate regulation and proportioning of waste gas in relation to the duty of the furnace, thus maintaining correct atmosphere.

Comparing salt baths with lead, the following points should be noted: salts are more easily cleaned from the work than lead, because they dissolve in water. They are not heavier than the work they heat, so that there is no need for special fixtures to keep the steel in position. It can simply be hung. The salt mixtures are less expensive in first cost. They protect the work against corrosion when it is withdrawn from the furnace, and its surfaces need not be protectively covered when in use.

As against these advantages must be set the following: salts do not liquefy and attain the desired temperature as quickly as does lead. They absorb moisture from the air, and have to be specially stored in hermetically sealed receptacles until used.

They decompose slightly in use, especially at high temperatures and when used for hot quenching. They may on occasion attack both the refractory linings and the pot itself. More of them is wasted when the work is removed from the furnace by spillage, draining off, etc. Finally, they are less adapted to local heating than lead because of their lower heat conductivity.

As compared with an oven type of furnace, salt baths may give more even heating, since no contact with cold air is possible, though an air-tight oven furnace with proper laying out of work to ensure uniform heating of each surface is quite as efficient in this respect. There is no scaling, though much of this undoubted advantage has been reduced by the increasing development and use of furnaces with controlled atmospheres. The protective film of salt remaining on the work when removed eliminates scaling during cooling down or movement to other parts of the plant, but may retard quenching if not readily washed off by the quenching medium. Salt baths may decarburize the work, particularly if barium chloride is used as the salt. So, of course, may a badly controlled oven-furnace. On the other hand, the modern scientifically-composed salt mixtures cause negligible decarburization, but in this they are paralleled by the controlled-atmosphere furnaces.

Salts heat the work more rapidly, but this may not always be a boon, though it is an advantage for local heating. The first cost of the salts and their container make up an expenditure not incurred by an oven-furnace. The adherent salt on salt-bath treated parts may modify, by degrees, the composition of the quenching bath, unless this is of oil. Special care must be taken to remove all moisture from parts, and a little advance heating is desirable. These precautions are less essential for an oven-furnace. The attack of salts on many refractories as soon as the temperature rises above a certain figure is a factor to be considered, because it may render furnace maintenance cost heavier.

CHAPTER XIII

Quenching Equipment

In this chapter the quenching operation itself is not dealt with, except in so far as some explanation is necessary for the comprehension of what follows, but only the equipment necessary for properly carrying out that operation. Quenching can be done by more than one method, so that before any specific equipment is ordered, the user must decide whether he will use a liquid (oil or water), or gaseous (air) quenching medium. The media and their comparative advantages will be fully dealt with in a later chapter.

Most steels are quenched in either a liquid medium or an air-blast. The rate at which they cool is often enhanced by giving motion to the piece or part in the medium, or alternatively by causing the medium to circulate about the static steel part. Sometimes, as in the hand-quenching of files, the hot steel is merely plunged into the quenching tank and given a prescribed motion by the operator, according to its shape, so as to prevent the formation of steam pockets. Alternatively, the work, particularly if small and in sufficiently large quantities, may pass through the quenching bath on a power-driven conveyor; be carried by gravity along rollers, skid-rails, or plates; or, if of large size, be held by cranes and slowly moved about the tank. Another type of equipment is the revolving screen barrel, inside which is a *worm* or helical gear consisting of a continuous screw-thread wrapped about a cylinder. Caught up by the worm-threads, the quenched parts not only keep continually turning over and over, but at the same time progress in a forward direction through the medium.

Some small parts may be quenched by causing them to fall through the tank liquid into a work-basket, which can be removed bodily when full, or on to a conveyor located in the tank bottom, which causes the parts to move through the quenching medium after they have come to rest upon it. If the basket method is used, the essential factor is the distance of fall through the medium, which must be sufficient to make the parts surrender most of their heat before they alight. They must not be at too high a temperature in the basket.

The advantages of these various methods of imparting motion to the pieces undergoing treatment depend on the type, number, and size of the parts. Gravity-operated skid-rails, rollers, and plates, for example, give a slower rate of output, but, against this, keep the parts moving longer than a mechanically-operated conveyor would do, and so give greater assurance of thorough quenching. The moving conveyor is usually restricted to large quantities of small parts dealt with on a mass-production basis.

It is probably both more convenient and more economical, in some instances, to cause the quenching medium to circulate than to move the part or parts being treated. This involves the provision of some means of circulation, which may be either simple or intricate. The simplest form of circulation is that produced without the aid of any apparatus whatsoever.

When hot steel is plunged into a cold liquid quenching medium it turns the portions of the liquid with which it comes into contact into a vapour, and also conveys heat beyond the confines of the vaporized areas. As a result, not only does the vapour formed rise quickly to the surface of the bath, causing an immediate inrush of cold liquid to fill the gap, but the warmed liquid also rises and is replaced by cold. Hence, a steady, even if temporary, circulation of the liquid is produced by the convection currents thus set up continually withdrawing heat from the hot steel. The actual cooling speed will be governed by the precise character of the quenching medium.

The disadvantage of this natural circulation is its irregularity. Whenever, as may happen if the part has recesses, projections, and so forth, the vapour is denied easy emergence or uprush, it may collect, forming pockets that prevent the cold quenching medium from impinging further on the hot steel; oil or water vapour bubbles thus act as heat-insulators. As the object of quenching steel is generally to provide hardness, the steel, wherever these pockets have formed, will be unhardened, i.e. soft.

It is thus necessary to provide for a more uniform type of circulation, and in many (perhaps most) small heat-treatment shops where the work done is not of the most difficult character, the method of liquid flow is adopted and suffices. In this method the quenching medium is continuously introduced into the bath by means of a pipe let into the *bottom* and passes out through a pipe close to the *top*. Even so primitive a circulatory method as this enhances the speed of cooling as compared with the purely natural circulation, though for more modern and difficult quenching it is hardly adequate, being too slow. An improvement on this is the continued agitation of the quenching liquid by means of paddles or revolving blades driven by machinery and causing the liquid to move swiftly about the quenched parts. In some instances, liquid flow circulation and mechanical agitation are combined.

Yet another circulatory method is that known as *pressure quenching*. In this, the quenching medium is forced under pressure through jets, which may be either above or below the surface of the bath. This method gives either even quenching or specially quick cooling of a local area on which the jets are directed, as may be desired.

Where it is economical to install these pressure-jet equipments, the desired uniformity of quenching complicated pieces will often be aided by the provision of carefully designed fixtures.

Distortion, like decarburization, is a perpetual problem in hardening, and results from uneven quenching, causing unbalanced stresses in the quenched part. Hence, the prevention of irregular cooling also helps to minimize distortion. Fixtures should be designed with this factor in mind, and quenching methods should be calculated to avoid any warping. Shafts, for example, are not so likely to distort if revolved while horizontal in the bath as if kept motionless.

Uniformity of properties is most essential in heat-treated steels, and it is therefore highly desirable to ensure this uniformity by taking steps to keep the temperature of the quenching bath as constant as possible.

The first and most essential step is to ensure that the volume of the quenching tank is always great enough to provide proper quenching, i.e. rapid cooling, which means that there must be enough of the quenching medium to withdraw all the heat from the hot steel without raising the temperature of the bath itself to a degree that would produce a variation in the hardness characteristics of the quenched material. Unless there is enough volume of liquid, even forced circulation may not suffice. When oil is used as the quenching medium, its temperature, both during and after quenching of the steel, must be kept well below the *flash-point* (ignition temperature) of the oil, otherwise it will take fire.

It should be noted, however, that it is possible to have an adequate volume of liquid, and for the parts still to be imperfectly quenched. For example, if parts are plunged into one small area of the tank, one after the other in rapid succession, the liquid in this area will become hotter than that in the rest of the tank because there has not been time for the absorbed heat to dissipate itself throughout the entire volume of liquid in the bath. It is, therefore, vital that time and opportunity should be given for the heat absorbed from each part to disperse uniformly throughout the quenching liquid. Hence the advantage of either moving the part about the tank or circulating the medium about the part.

While it is theoretically possible to calculate the minimum volume of quenching medium that must come into effective contact with the steel in a specified period of time, this formula must not be used without due consideration for calculating the exact dimensions of the tank required to hold this volume. The formula itself is

$$\frac{W_1 \times SH_1 \times (T_1 - T_2)}{SH_2 \times W_2 \times TR} = \text{cub. ft. of quenching.}$$

In this formula W_1 is the weight of the material being quenched; SH_1 is the mean specific heat of the material quenched; T_1 is the temperature of the heat-treated material; T_2 is the temperature of the material at the moment of withdrawal from the bath; SH_2 is the specific heat of the quenching medium; W_2 is the weight per cubic foot of the quenching medium; and TR is the permissible temperature rise of the quenching medium.

The point to be borne in mind is that no use of this formula is valid unless the user takes into account that it covers only the *volume coming into effective contact with the steel.* Thus, it is not valid for calculating the dimensions of a tank containing no forced circulation of quenching medium *unless it is certain that all the medium is near enough to the steel to absorb heat, or that the period between successive quenchings is long enough to give the heat time to distribute itself evenly throughout the bath.* Moreover, if the quenched parts are not immersed in the bath beyond a certain depth (as is usual), the liquid below this point will never be heated. It cannot, therefore, be represented by the formula, and must be evaluated separately.

Again, if the formula is used to determine the volume to be supplied by pumps to the bath, it may give a misleading result, because not all the volume supplied may come into effective contact with the hot steel.

The purport of these qualifications is to show that a wide margin of safety should be allowed for when using the formula for tank and pump flow calculations, too much being far better here than too little.

We may now consider in more detail the methods adopted to keep the quenching medium cool. Where the number of parts to be quenched is extremely small, a plain quenching tank only will suffice, no cooling device or forced circulation being employed, but it should be large enough in capacity to ensure that all the heat absorbed by the medium is dissipated from the sides and surface rapidly enough to retain effective quenching properties. This is particularly important where the medium is oil, which, if allowed to get too hot, may catch fire.

Small heat-treating plants sometimes content themselves with placing a large water-cooling jacket about the tank, an inexpensive method, but one whose efficiency is in direct ratio to the tank size, since the bigger the tank in relation to its wall surface, the less effective the cooling provided by the jacket. An improvement upon this is to circulate the cooling water in the jacket. Still better, though costlier, is the cooling of the bath by means of a number of coiled pipes carrying a cold liquid, usually water or a salt solution. Circulation of the water in the coils is achieved by pumping, and some provision has to be made for externally cooling the liquid in the coils. (See later.)

In large heat-treatment plants, there may be a number of quenching tanks all fed from a larger central storage tank. Since the liquid in the storage tank is not in contact with hot steel, it is bound to be cooler than that in the smaller tanks, so that these can be replenished with a colder supply by mechanical circulation. Sometimes this central tank is itself provided with cooling coils. One advantage of this system is that it enables a tank to be drained out and cleaned when required, the liquid it contains being used in one of the other tanks, but the method is not favoured as compared with more positive methods of cooling.

A method, less popular to-day because low in efficiency, is to circulate the medium through coiled pipes external to the tank; the radiation of heat from these coils out into the air cools the liquid before it returns to the tank. The disadvantage of this method is that the radiation of the heat cannot be swift, and, in consequence, for cooling to take place quickly enough to be of value, as large a surface area of the liquid as possible must be exposed to the cooling of the surrounding air. This means a considerable extent of coil, and consequently greater expense and space.

As an alternative, therefore, instead of passing the medium through a cooling coil, or sometimes in addition to this, the medium is "atomized" or sprayed upwards so as to give each tiny droplet of the liquid a chance of transferring its heat to the surrounding air. This is a highly efficient method, because a relatively small volume of liquid is made to present a large surface area to the cooling action. If this method is used for cooling oil, however, there is some danger of fire, so that any spray plant should be suitably treated and safeguarded.

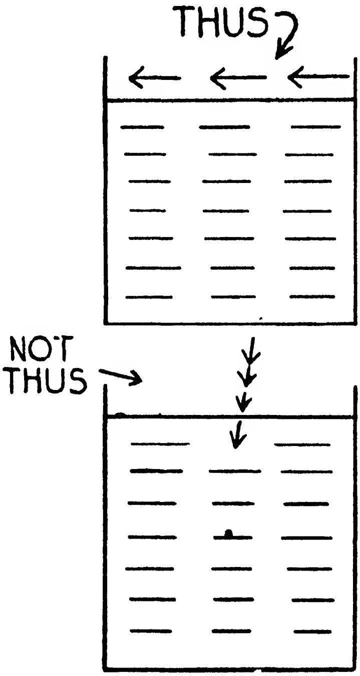
A different, but sometimes quite effective, method is to cause the quenching medium to circulate through a series of pipes wrapped about the tank itself, i.e. not necessarily in coils. Here, again, the cooling is achieved by dissipation of the heat out into the open air, or (in some plants) into a bath of cooling water. The success of this system depends on the volume of the quenching medium in relation to the surface area of the pipes through which it passes and the temperature of the surrounding air or cooling water. Such an equipment should be carefully planned.

The above system is sometimes reversed, and instead of the quenching medium passing through tubes, it is the cooling medium that goes through the tubes, the quenching medium either going round or passing over these in a shallow stream. This is an effective method occupying relatively small space, since the liquid travels in a thin layer across a large cooling surface area, but it is expensive in first cost.

It is possible to obtain complete cooling systems designed and constructed by private specialist firms. As a rule these embody individual features, but in principle their design is based on one or other of the methods described. They are all sound and compact.

In special circumstances it may be necessary to cool the quenching medium beyond what is possible by any of the above means. It will be appreciated that whether air, cold water or cold brine constitutes the cooling agent for the quenching medium, the latter can never be cooled to a temperature below that of the cooling medium, and is in all instances somewhat above that temperature. There is only one way in which it can be brought to a lower temperature than that of the surrounding air or coolant, and that is by mechanical refrigeration. This is feasible, and equipment for the purpose can be obtained. It is compact and effective, but expensive to buy, and by no means cheap to run and maintain, while the results are so often disappointing that it is much more satisfactory to use an atmospheric oil cooler at normal temperatures.

No chapter on quenching equipment would be complete without reference to one important factor--fire prevention, especially necessary when oil is the quenching medium. The temperature at which the oil will ignite (its *flash-point*) should be known, and every precaution taken to see that this temperature is not approached. If a circulating system is used, provision should be made for a spare pump to be coupled up in the event of a breakdown. If, despite all precautions, a fire does occur, the pump should be kept running, as the circulation will reduce the temperature of the oil. If it can be run faster, this should be done. There are, however, instances in which the pump should not be run, e.g. when it serves several tanks, only one of which is ignited, and, where the cooling is effected by direct contact between oil and air, when oxygen would merely be fed to the fire. An oil fire is not rapid in its action, and can sometimes be put out by a simple agitation of the tank. A good plan is to prepare a lid or cover for the tank capable of being readily lifted into position. This, clapped quickly on to the tank, will prevent air from getting to the fire and gradually smother it. If no such cover is available, a chemical extinguisher, preferably of the foam-forming type, should be used, its action being confined to the surface as shown opposite.



Water should not be used.

Speed is vital in quenching. Wasted seconds may make all

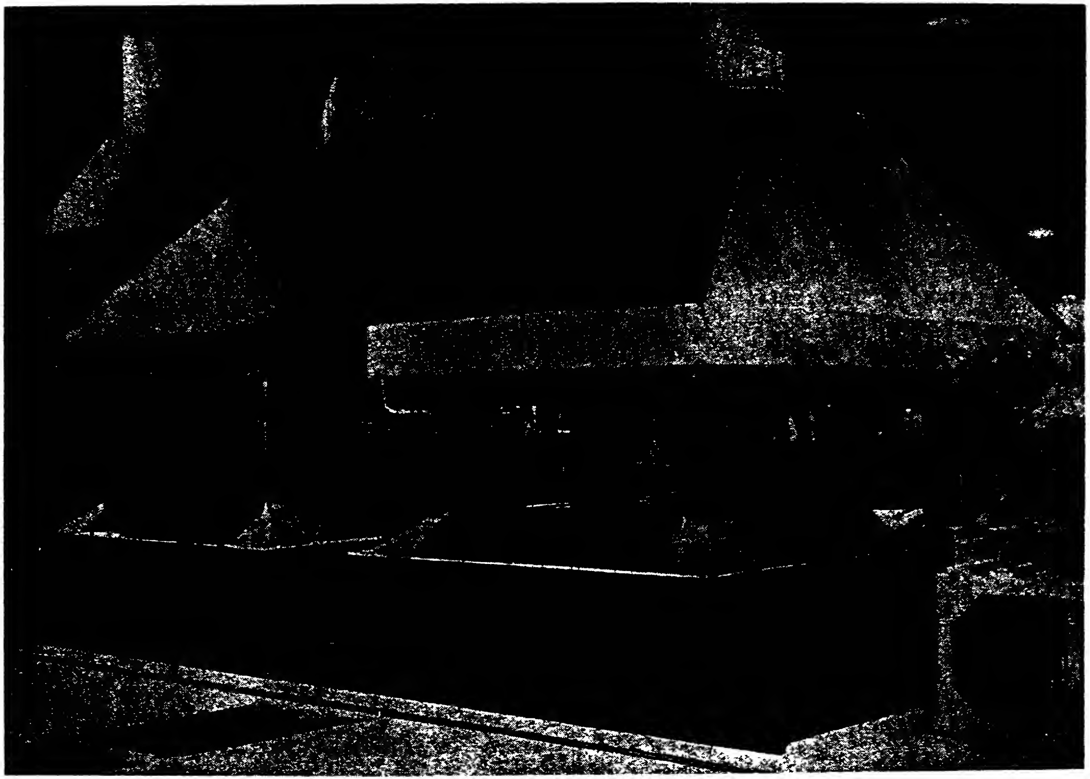


Fig. 67. Two Fully-mechanized Oil-quenching Tanks used in the Heat-treatment of Forgings

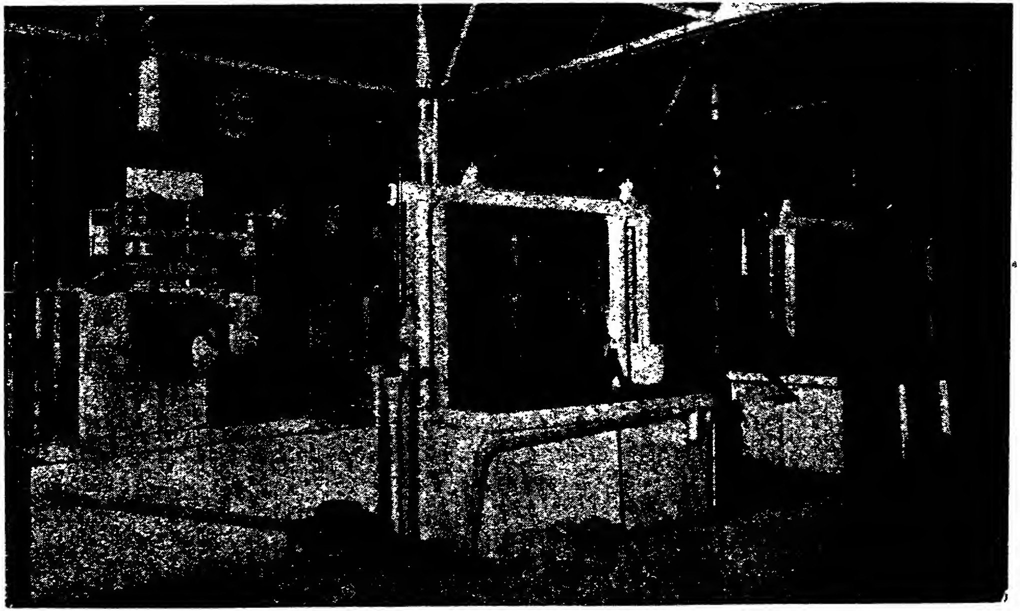


Fig. 68. Oil and Water-quenching Tanks used in the Heat-treatment of Aero-engine Components

the difference between a first quality product and a batch of rejected parts. Modern quenching and auxiliary equipment are mechanized to a high degree, resulting in a considerable reduction of transport delays from furnace to quenching tank. Fig. 67 shows two large fully-mechanized oil-quenching tanks forming part of a complete installation of furnaces and equipment for the heat-treatment of forgings. Each tank holds 15 tons of oil. The charge is raised and lowered on the quenching rack by means of a wire rope on which it hangs from an overhead drum, driven by *motor reduction gear* (gearing allowing the speed of hoisting or lowering to be reduced) and chain-gearing. The movement of the rack is controlled by a push button in conjunction with *limit switches* (to limit the up and down movement of the quenching rack). Overheating of the oil is prevented by oil coolers through which the oil is continuously circulated. Hoods are provided over the oil tanks, and fumes are withdrawn by fan exhausts located inside the ducts leading from these hoods.

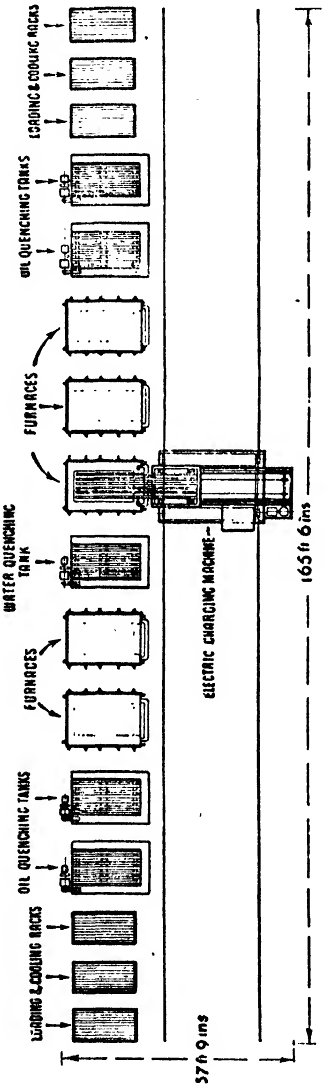


Fig. 69

The method of lowering the forgings into the oil in a fixed time is claimed to have the advantage that, during the entire lowering period, fresh oil is constantly being brought into contact with the load, not only by the convection currents set up during cooling, but also by the steady mechanical motion of the work through the oil. Thus, a uniform cooling rate is obtainable. The load can be given a backwards and forwards movement through the oil by suitable manipulation of the control buttons.

Rapid charging and conveying equipment carries the load from the furnace to the quenching tank on an all-electric charging machine moving at a speed of 250 ft. a minute. This equipment is made by the Incandescent Heat Co., Ltd., of Birmingham.

Figs. 68 and 69 show another installation made by the same company in which oil and water-quenching tanks are used for heat-treating aero-engine components. The quenching oil is water-cooled by water from the water-quenching tank, which is pumped through cooling pipes arranged in the sides of the oil-quenching tank. The quenching water is continuously replenished from the main supply, so that it remains at a reasonably cool temperature. The tanks are complete with loading baskets and hand-operated, geared, raising and lowering tackle. Some equipments employ electrically-driven wire mesh extractors.

CHAPTER XIV

Principles of Heat-treatment

Before all, the operator must know, when he heat-treats a piece of steel, what he intends to do and why he is doing it. Only if the general principles are thoroughly understood can the "how" of the subject be satisfactorily outlined.

It is not our purpose to go root and branch into the simplified technicalities of steel's structure. This has been done already in an earlier work.* Reference to this aspect of the matter is, however, inevitable, but will be confined to the points of importance in heat-treatment.

The purpose of all heat-treatment is to alter and improve the subject of treatment. As soon as heat is applied in any noticeable degree to a piece of steel, certain structural changes in the metal take place. Some of these are apparent to the eye alone. At a certain point the steel begins to glow a dull red, and *if the heating is maintained, not only will this hue become brighter (until with certain steels even a white heat may be perceived), but also the steel will soften.* A scale of oxide may form on its surface and flake off when rubbed with a scraping tool. The steel may even begin to melt, bubbles often occurring, for example, on the nose of a tungsten-cobalt high-speed steel cutting tool when heated to its hardening temperature.

These simple visible changes, while useful as rough guides, are not in themselves sufficient to ensure proper heat-treatment. The function of heat-treatment is not to give steel a bright glow, partly to melt or temporarily to soften it, but to set up certain *permanent* changes in a particular property or set of properties it possesses, these changes being beneficial for the purpose in mind. Such being the case, if the change in properties brought about is not that at which the operator aimed, but some other or others, the change will not be beneficial, and may even be prejudicial. For example, if we wish only to soften steel, but actually melt it, or to heat it to a correct temperature for hardening, and actually burn it by overheating, we have not only failed to ahieove our objective, we have considerably receded from it. Indeed, by

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* *The Structure of Steel* (Blackie) by the same authors.

faulty heat-treatment, the steel may be irrevocably spoiled, and is then valueless except as scrap for remelting.

The structure of steel is so complex and the alterations to which it is susceptible when heat-treated are so numerous that it is quite easy for the wrong result to be obtained if the fundamental principles of heat-treatment are not fully grasped. We therefore devote considerable space to these fundamentals so as to ensure their thorough comprehension.

While a good case could be made out for confining "heat-treatment" to those operations designed to bring about a permanent alteration in and improvement of a steel's properties, we have not wholly excluded from this book those operations of heating and cooling designed merely to prepare steel for certain forms of mechanical working. In this chapter, however, we voluntarily limit ourselves to heat-treatment proper.

We have referred to the necessity that the change in properties induced in a steel by heat-treatment should be permanent. This permanency is rendered possible by certain peculiar phenomena. When steel is heated through a sufficient range of temperature, there is a particular temperature (varying with each individual type of steel) at which a number of important structural changes begin to occur in it. Steel is composed of soft iron and a hard brittle substance or chemical compound called iron carbide, having the formula Fe_3C. At the particular temperature referred to—known as the *change point, arrest point, critical point, or transformation point*—the carbon, as carbide, and possibly other elements, according to whether the steel is a plain carbon or an alloy steel, begin to dissolve in the iron (i.e. the form of iron known as γ or *gamma iron*), thus forming a constituent known as *austenite*. When the steel is heated to still higher temperatures more of this dissolving, or solution, takes place, until, at a certain temperature, the structure consists entirely of austenite. The temperature range between this latter temperature and the first change point is described as the *critical range*. In this way, specific structural conditions, different from those of untreated steel, are set up. If, while at a suitable temperature above the critical range, the steel is then swiftly cooled by being plunged into a cold liquid—the operation known as *quenching*—the result will be a fixation of the structure. In some instances, the structure thus fixed may be nearly, but not quite, that prevailing when the temperature is raised above the critical range.

It is as if this structure were suddenly frozen or petrified before it had had time to change more than a small amount. Such quenched structures, similar to those existing at the high temperatures before quenching, are, however, only obtained as a rule from steels containing high proportions of alloying elements, e.g. stainless and heat-resisting steels, rich in chromium, nickel and other elements, and high-speed steels containing high proportions of tungsten, etc.

With carbon steels and the low-alloyed constructional steels of the nickel, nickel-chromium, nickel-chromium-molybdenum, manganese-molybdenum and chromium-molybdenum types, the high temperature austenitic structure is not retained by quenching. Nevertheless, the structure is entirely different from that obtained by cooling at ordinary rates or even by slow cooling. In such circumstances, the structure of the quenched steel consists of the micro-constituent known as *martensite*, in which the iron is in the α (alpha) magnetic condition. Martensite is intensely hard, but somewhat brittle—it is the essential constituent of any steel employed as a cutting tool.

For most structural purposes, however, as for instance in crankshafts, camshafts, connecting rods, propeller hubs, axles, shafts, etc., the martensitic structure is undesirable, although it may be a necessary preliminary. In such instances, even though this preliminary quenching or hardening treatment becomes indispensable, it is usually followed by the operation known as *tempering*. This comprises reheating the hardened steel to some predetermined temperature *below* its critical range, generally lower than 660° C., followed by cooling in air, water, or oil, the treatment being described as air-, water-, or oil-tempering accordingly.

It must be understood, too, that many alloy steels, e.g. nickel-chromium-molybdenum steels, possess distinct air-hardening properties, so that when simply cooled in air from temperatures above the critical range, they are, in effect, in the quenched or hardened condition and in consequence are known as *air-hardening steels*.

Let us revert, however, to the non-air-hardening steels, or, as they are called, *pearlitic steels* (the reason for which will be obvious from what follows). Suppose, for instance, instead of quenching such a steel from the requisite temperature above its critical range, we allow it to cool down normally, i.e. at a slower rate.

During cooling, changes take place in the reverse order from those that occur during heating. Thus the structural condition of the steel remains in the special dissolved carbide of iron in gamma-iron (austenite) form resulting from heat-treatment until we pass through the *critical range* again, but going down the temperature scale instead of up; in other words, cooling instead of heating. Then, alpha (α) iron or iron carbide, according to the chemical composition of the steel, is rejected by the gamma (γ) solid solution (austenite) and is thus precipitated or thrown out of solution. This process continues until eventually, at the temperature of the lower critical point on cooling, i.e. the end of the steel's critical range, the residual austenite itself splits up into *pearlite*, which is a mechanical mixture of α-iron (*ferrite*) and iron carbide (*cementite*). When cold, therefore, the steel is composed of its original structural constituents, ferrite and pearlite, or pearlite and cementite, according to its carbon and alloy contents.

It should be noted here that the cooling critical range, or temperature transformation range, is not identical with the heating critical range, being actually some degrees lower, the extent of this lowering depending on the rate at which the steel is cooled. This is due to sluggishness of readjustment of the particles or atoms in the steel.

It was stated above that *under certain conditions* the steel will regain its original structure. The essential condition is that cooling shall not be artificially hastened or artificially delayed. It follows from this that if cooling rates are varied, considerable structural variation, which means considerable variation in properties, is obtainable in steel when finally cooled to the normal temperature. In other words, we can so arrange matters that a particular structure can be almost "frozen stiff" and stay frozen if we go about it in the right way.

As indicated, the exact structural conditions in which steel can be thus obtained are best studied in *The Structure of Steel—Simply Explained*. The cardinal points for the practical heat-treater are briefly recapitulated.

(*a*) Critical changes corresponding to a particular temperature range occur in steel when heated. When the lower critical point, which marks the beginning of the critical range, is passed, and as the steel increases in temperature, its structure and properties greatly change, the iron carbide being dissolved in the gamma (γ) iron, this being one of the allotropic forms in which the iron in steel exists, and the only form capable of holding the carbon in the solid solution known as austenite.

(*b*) A critical range corresponding to a particular range of temperature occurs in steel when cooled normally. When the lower limit of this temperature range is passed, as the steel loses heat, its structure and properties revert in varying degree to their original form, so long as cooling has not been unduly rapid or unduly delayed. (Exceptions to this are found in the heating and cooling of castings, etc., when normalized or annealed. Here, the structural constituents remain the same as before, i.e. ferrite and pearlite, but *the operation results in a redistribution of these constituents*, which, generally, improves their mechanical properties.)

(*c*) The critical range, on heating, is some degrees higher than the transformation range on cooling.

(*d*) If steel heated above the critical range is suddenly cooled in a quenching bath, it is not allowed to revert to its normal condition, but its structural condition becomes, to some extent, permanently set or "frozen."

(*e*) This petrified or arrested structure will not be identical with that of the steel when heated above the critical range, but will be martensitic and hard. In other words the iron carbide, instead of being dissolved in the gamma iron (austenite) will be held in some way in the other allotropic or alpha (α) form of iron (ferrite).

(*f*) If the steel is deliberately cooled at rates more rapid or slower than the normal, it is possible to produce in the cold steel various structures as required, differing from those it originally possessed, and having different properties.

(*g*) It is the difference in the ability of these two essential constituents of steel, γ-iron or austenite and α-iron or ferrite, to dissolve iron carbide, carbon, and other alloying elements, that renders possible in steels the attainment of an extensive range of properties through planned and skilful heat-treatment.

From the above it will be plain that a first essential is to know the heating and cooling change points and critical changes in steel, or, in other words, the temperatures to which they must be heated, and/or from which they must be cooled, in order to obtain the desired structural condition on which the ultimate properties of the steel depend. Secondly, we must know what properties correspond to the various structural conditions. Thirdly, we must know the rate of cooling necessary to "fix" or set the desired structural condition. Fourthly, a point not yet discussed, we must know the *period of time* the steel is to be maintained at the temperature to which it must be heated. We must also know the *rate* at which it is to be heated up to the required change point and beyond; the succession of operations, i.e. whether tempering is to follow quenching, or some other operation, e.g. *ageing* or *normalizing*, is necessary; and how these are to be carried out.

It is hoped that the answers to these questions will emerge as this chapter proceeds, at least in so far as general principles are concerned. The more specific details will be found in the later chapters devoted to the treatments of individual steels. One other influential factor in heat-treatment is the shape and mass or dimensions of the part or piece of steel being treated. This, since it is dealt with later in the chapter, we shall pass over for the time being.

The heating process must obviously, for any serious change in properties to be effected, carry the steel to a temperature above the critical range. But steel can be heated both quickly and gradually. There are usually serious objections to too rapid a heating rate. As a result of operations carried out on the steel before it reaches the heat-treatment stage, e.g. forging, rolling, pressing, etc., unequally distributed internal strains may have been caused. When the steel is rapidly heated, the resulting swift expansion of the steel may suddenly release some of these strains, with the consequent development of a crack. With slow heating, on the other hand, this is far less likely to occur, just as two bulky people may get through a narrow shop doorway together if they give each other time and space, but will jam and possibly damage surrounding glass if they attempt to dash through. Even if cracking does not occur, the sudden release of internal strain, due to ultra-rapid heating, may cause distortion of the steel. In general, it can be laid down that the harder, more brittle, and more severely stressed the steel before heat-treatment, the slower and more careful should be the heating. It must not be assumed, however, that slow heating is correct in every instance. Some cold-worked steels are liable to become coarsely crystalline in structure (usually a bad condition) when heated slowly. In other words, the individual grains of which they are composed "grow" or expand, so that to prevent this it may be advisable to heat them rather quickly through the temperature ranges within which such grain-enlargement is liable to occur.

The rate of heating should, however, be gradual in most instances. Hints on the specific rates for various groups of steels will be found later in the relative chapters. Factors affecting heating rates include the *heat conductivity* of the steel (the speed with which heat is conducted through it), the type of furnace atmosphere, e.g. whether "controlled" or otherwise, and the thickness of section of the material undergoing treatment. Variations in section, one part being thicker or thinner than another, mean that the thinner sections will rise to the required temperature more quickly than the thicker, which may have harmful results, stresses being set up as a result of unequal expansion and leading to warping or cracking of the steel. These practical problems of heat-treatment demand much care and foresight for their solution, and steps have usually to be taken to slow down the rate of heating of the thinner sections.

A final argument in favour of slow heating is that it renders the uniformity of temperature throughout the piece, essential to efficient heat-treatment, more readily obtainable.

The temperature to which the steel shall be taken is different for different classes of steel, being governed by the chemical composition, the type of structure and properties required, and the size of grain, which last point is beginning to be specified in connection with certain steels. In general, the higher the temperature to which the steel is heated above its critical range, the larger the grain-size.

Mild and medium carbon steels (containing less than 0·85 per cent carbon) are usually not heated much beyond their upper change points. Increase in temperature beyond this merely coarsens the grain structure, which is only advantageous, as stated, in a few special instances, where greater ease of machining is required from the steel or, in a still more limited number of instances, where a greater depth of hardening is required, which, however, can as a rule be attained in more efficient ways. In steels intended for wire-drawing, a coarse grain is desirable and is obtained by heating to temperatures much above the critical range, but this is exceptional treatment.

For carbon steels containing more than 0·85 per cent of carbon, the temperature to which the steel is heated should be just high enough above the *lower* change point, i.e. the beginning of the critical range, to dissolve the iron carbide and form austenite, but no higher, otherwise a larger grain size is obtained and, if quenched, the steel is too brittle.

For alloy steels, no general rule can be laid down, but one broad effect they show is that, in cooling, the alloying elements they contain lower the temperature ranges during which the significant structural changes occur, and also make these changes more sluggish. In other words, alloy steels have lower cooling critical change points or ranges than ordinary unalloyed carbon steels. The reason, without going too deeply into the subject, is that alloys delay the throwing out of solution of the particular solid structural constituents originally dissolved as a result of the heating.

It is not sufficient in heat-treating steel simply to whisk it up to the right temperature, and the moment it has reached this point, take it out and quench it. The steel has to be kept at the maximum temperature, just as in baking bread, for a certain length of time, or *soaked*, before it is removed from the furnace. This is because time is needed for the solution of the carbides, etc., to take place, just as time is needed to dissolve a spoonful of sugar in a cup of tea even when it is stirred. A point to be borne in mind is that the higher the temperature of a steel, the greater is the freedom of movement of the atoms of which it is composed; the more readily can they rush about or intermingle and form their complex patterns. In other words, change in steel's structure is swifter at high temperatures than at low. Having raised steel to a particular temperature above the critical range, we thereby quicken and make easier the desired structural modifications which, as has been seen, are based on certain constituents being dissolved in others, the new (solid) solution then forming a different grain pattern known as austenite.

If, having once reached this point, we leave the steel at this temperature for a time, the result will be not only a retention but also an enhancement of the change. In other words, more of the constituents (carbides or alloys) capable of being dissolved (going into solid solution, as it is technically termed) are taken up by the solvent iron or austenite. This means that the austenite structure thus obtained will be more uniform and composed of rather larger individual grains, so long as the temperature concerned is above the prescribed range at which these transformations occur. Thus, there is some advantage in holding the steel for a reasonable period at the correct treatment temperature, just as meat must not be merely scorched, but actually heated right through, if it is to be properly cooked.

It might be assumed from this that it would be cheaper and better to heat the steel to a lower temperature and keep it at that temperature longer. This is not so, however. In practice, it is much quicker and better to take the steel some degrees higher in maximum temperature and hold it at that temperature for a shorter period, because in proportion the steel has to be maintained much longer at the lower temperature to make up for the difference. To make this clearer, let us assume a steel is heated for the two hours required to bring it to the correct temperature, and held for ten minutes to ensure completion of the structural changes. If, instead, it were heated for 1½ hr. to bring it to a lower temperature, the probability is that it would have to be maintained at that lower temperature not for ten minutes, but for a much longer period. *A general rule is that a total heating period of not less than one hour for each inch of cross-section or thickness is required in hardening, and from 1½ to 2 times this period for tempering.*

In the main, the temperature to which steel is heated is more important than the length of time it spends at that temperature. On the other hand, time at temperature becomes increasingly important as the mass of steel becomes greater, its heat conductivity lower, and its likelihood of surface modification by the atmosphere of the furnace greater. The bigger a piece of steel, the longer it will take for the heat to soak right through it. The lower its heat conductivity, the longer the heat will take in penetrating evenly to all parts. The greater the oxidizing, decarburizing, or other surface action of the furnace atmosphere, the shorter should be the period during which the steel is maintained at temperature. Consequently, we can state that the period of temperature maintenance should, in general, be sufficiently long to ensure uniform temperature throughout the body of the steel and to produce the requisite structural modifications, but not long enough to cause serious surface injury through scaling, decarburization, or grain growth.

Although the heating of steel, once carried above its change point or critical range, causes important modifications in structure, the actual desired structure, whether final or temporary, is not obtained until the steel has been cooled down again, either rapidly, as in quenching, or slowly, as in normalizing, or still more slowly, as in annealing. At a certain point, or over a temperature range, according to its chemical composition, when steel is cooled, the engines are reversed, so to speak, and the changes brought about by heating disappear, the dissolved carbides or alloys reverting to their original separate state, but to some other pattern or structure, according to the rate of cooling. The exact temperature or temperature range where this reversal or transformation occurs largely governs the mechanical properties of the cooled steel.

If cooling is comparatively slow, the steel will have a rather coarse structure, and will in character be of low strength, but may possess considerable ductility. As the cooling speed increases, the temperature at which the lower transformation takes place is depressed ever lower in the scale, until in the end it may even occur as low as 300–350° C. When it reaches the normal lower change point temperature, it is still not cool enough to produce the full structural restoration. In certain steels, if cooling is fast enough, the transformation may hardly take place at all, and this is sometimes required in special instances. On the other hand, steels in which alloying elements are almost absent, or present in low percentages, with less than 1·2 per cent of carbon in their composition, will always go through certain changes, however rapid the cooling, for the reason that even the most rapid rate of cooling will not completely suppress the tendency for normal changes to take place.

When the highest cooling speeds of all are used, as when the steel is quenched from the maximum temperatures in a very cold liquid, the change point or critical range is pushed down so low that it occurs almost at normal temperature (really not so much above that of an ordinary room). Furthermore, the transformation, when it occurs, is not complete, as already explained, and instead of carbide of iron and ferrite being precipitated from the (austenite) solid solution, we get a structure known as *martensite*, which is really an unstable and perhaps a super-saturated solid solution of carbon in alpha iron. (See *The Structure of Steel.*) This martensite is the constituent possessing extreme hardness, but it is brittle (lacking in ductility), and the steel containing it is invariably in a highly stressed condition internally, partly because the transformation, of which it is the result, has produced certain inevitable changes in volume, and partly because of the severe non-uniform quenching. These unequally distributed stresses are a source of weakness. They may cause cracks when the steel is reheated for some further operation, such as tempering, if great care is not exercised, and more particularly when hardened steel is allowed to stand for a long time without being tempered.

Cooling may be neither slow nor swift, but half-way between, as when a massive section quenched from the maximum temperature is rapidly cooled so far as the outer layers are concerned, but owing to the great thickness has a core less rapidly cooled, and consequently in a different structural condition. The half-way house lies between the fully hardened layers, which will have the characteristic martensitic structure of fully hardened steel, and the innermost core, which may even, if the section is thick enough, have the structural characteristics of a slowly cooled steel (consisting of pearlite alone, or a mixture of pearlite and ferrite, or pearlite and cementite). Between these two is this intermediate "half-way" structure, consisting of a mixture of hard martensite and relatively soft *troostite* (a constituent usually regarded as an ultramicroscopic mixture of ferrite and cementite) or even of troostite and excess ferrite or cementite.

From this it will be apparent that the more massive the section of steel, the more difficult it is to obtain a uniform structure throughout the heat-treated mass, i.e. to harden it right through. Mass is an important factor in heat-treatment.

Thus, a massive section can never be cooled so rapidly as a lighter one. Not only does it take longer for the chilling effect of the quenching medium to penetrate to the core of the steel, but also the structural transformations occur at higher temperatures, which means that the core must be softer, because less martensitic in structure, than the exterior. Obviously, therefore, the core will have different properties from those of the outer layers, and this, in consequence, may yield unequally distributed stresses leading to warpage and other troubles.

It is possible to get rather deeper hardening by heating the steel to somewhat higher maximum temperatures in advance of quenching. This produces a coarser austenitic grain structure, which has the effect of depressing the cooling change point to a somewhat lower temperature, with the result that the intermediate layers are harder than they otherwise would have been, or, in other words, the steel is more deeply hardened. This, however, is not a procedure to be recommended, as the steel is really overheated and, in consequence, may be more brittle, both in the hardened and hardened and tempered condition, than it should be with correct treatment temperatures. To compensate adequately for the influence of mass, we must introduce alloy elements, and in many specifications nickel and, in particular, molybdenum are for this reason mentioned as "optional" elements. Without them it is virtually impossible to obtain the desired mechanical properties in the larger sections.

All steel oxidizes to some extent when heated without special precautions, and the effect of this is to produce either a loosely or a firmly adherent scale. This scale is like a blanket round the steel, keeping away the chilling of the liquid (oil, water, etc.) in which the hot steel is cooled or "quenched." If this scale remains, it inevitably reduces the speed of cooling and, in consequence, produces an undesired effect on the structure and properties of the steel. Moreover, the scale itself may not be uniformly distributed. Patches may flake off here and there. In these circumstances there will be different cooling rates for the scaled and unscaled steel, and consequently variations in structure and properties in the affected areas of the steel. Where heavy scale is allowed to remain, and the steel is quenched, some parts may be left completely unhardened, producing what are known as *soft spots*.

Scale should, therefore, be removed or minimized before any cooling or quenching begins. Removal is usually mechanical or manual; prevention is by the use of a controlled atmosphere furnace.

We have seen that slow cooling of most steels produces a pearlitic or stable, unstrained, soft, and tough structure, whereas swift cooling gives rise to a martensitic or highly strained, hard, brittle, and unstable structure. The defects of the martensitic structure are such that for many applications the steel would be useless. Yet a combination of hardness and toughness is vital to many purposes. How can it be attained?

The answer is: by the further heat-treatment operation known as *tempering*, as a result of which a steel is obtained free from dangerous, unequally distributed internal strains, yet hard and tough enough to be of service. Tempering, with which we shall deal in more detail later, is designed first to remove from the martensitic steel the unequally distributed strains lurking like "fifth columnists" within it, and, secondly, to remove the extreme brittleness of structure of the quenched steel, and by restoring a degree of toughness and ductility (this degree depending on the actual tempering temperature), to make it less liable to break or fracture in service.

In tempering, the quenched steel is reheated to a temperature below the lowest heating change point. With tool steels, where hardness is the essential consideration, the tempering temperature is usually not greater than 250° C. and this may even result in enhanced hardness. Nevertheless, it evens out the hardening strains so that belated cracking does not occur. At higher temperatures the carbides precariously dissolved or suspended in the alpha iron precipitate out, diffuse, and join up together as the temperature is raised. These carbides are not thrown out as the little flakes or plates characteristic of pearlite, but, eventually, as tiny globules or spheroids of dimensions governed by the particular tempering temperature and the duration of tempering concerned. They are larger for higher temperatures or longer duration of tempering, which means in turn greater ductility and lower hardness of the steel. If the steels being tempered are of alloy type, they will generally need higher tempering temperatures or a longer duration of tempering than will the carbon steels, because the carbides are slower to precipitate and coagulate. On the other hand, these very conditions produce steels freer from stress, but possessing a superior combination of hardness and ductility than those of normalized and annealed steels.

Tempering, like hardening, has its dangers. Certain steels are brittle or less tough when tempered at temperatures of 300–350° C. or when allowed to cool gradually down from these temperatures. The remedy for this is to temper at temperatures below 300° C. or to cool quickly through this range of temperatures if the steel has been tempered at above 350° C.

The tempering operation is a most valuable instrument in the hands of the heat-treater, because by variation and duration of temperature a wide range of properties can be obtained from a previously hardened steel. The exact time or temperature to provide the properties desired is, of course, governed by the specific steel being tempered, its dimensions, and its structural condition at the time of tempering.

Throughout this chapter we have confined ourselves to general principles. These principles are sometimes violated by steels of unusual properties, e.g. austenitic manganese and nickel-chromium steels, but in the main they hold for all heat-treatable steels.

Before we leave general principles, we must deal at greater length than hitherto with the influence of the design of a piece on its heat-treatment. There are numerous instances in which the failure of a part or tool is caused not by inferior steel, but by imperfect design, particularly in relation to heat-treatment.

What is bad design from the heat-treater's point of view? It is that likely to cause severe localized internal strains in the steel when heat-treated, or to concentrate in a relatively small area the inevitable strains and stresses of service. The internal strains, when analysed, are found to be gravest and most harmful when produced in a piece of steel of which the cooling and quenching have not been uniform over the whole mass. The most prolific cause of these strains is bad design, which involves two aspects, (*a*) mass and (*b*) form or shape.

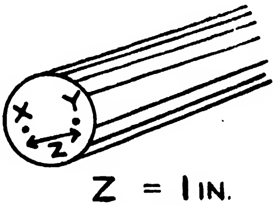

FIG. 70

To study this matter with accuracy, we must familiarize ourselves with a technical term—*temperature gradient.* This is "the rate of variation in the temperature of a metal over a given unit distance," or, in other words, the difference in the speed with which the metal cools in one place as compared with another. To make this clear, suppose we have a steel bar removed from the quenching bath before the quenching is complete. Suppose that the points X and Y in Fig. 70 are 1 in. apart and that X is at 350° C. and Y at 150° C. The temperature gradient between X and Y is then said to be 200° C. per inch. If Z is a distance of ½ in., the temperature gradient is regarded as 400° C. per inch; and if the distance is ¼ in., then the gradient is 800° C. per inch.

This question of temperature gradient is considerably affected, and with it, in consequence, design, by the type of quenching medium employed. Oil, for example, is less drastic in its cooling action than water or brine. This means that the temperature gradient or variation in cooling rate between particular points in the steel will be slighter. It may, therefore, be possible to quench safely in oil a part or tool that could not be quenched in water. Similarly, air cools at a lower rate than oil, and a part or piece can be air-cooled with little risk, when oil or water quenching the same design might easily lead to failure by cracking.

The first essential, then, is to design the part or piece with as few sharp variations in section as possible, so as to avoid the different rates of cooling inevitable with thick and thin sections in the one piece. If sharp changes are unavoidable, the designer should as far as possible specify for the part a steel that can be air-hardened. If a suitable air-hardening steel is not available, then an oil-hardening steel should be chosen, to avoid using water as a quenching medium. Fig. 71 shows a part badly designed for water-quenching, since quenching cracks are likely to occur at the corners.

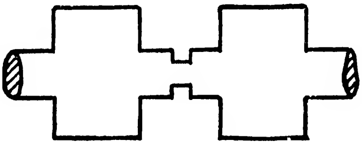

FIG. 71

The next requirement is the avoidance of sharp angles, as in Fig. 72. Not only do the internal strains set up by the hardening process occur most frequently at such angles, but also the service stresses may become localized there, and as the presence of the internal strains has a weakening effect, the combination may prove fatal. The aim of the designer of a heat-treated piece can, then, be summed up as (*a*) to reduce the temperature gradient during quenching as much as possible, (*b*) to avoid all sharp angles and corners and, wherever possible, to avoid any abrupt changes in section in one and the same piece.

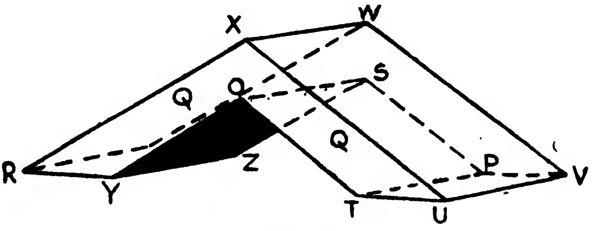

FIG. 72

We have already shown why uniform cooling throughout the piece is desirable and why, in very heavy sections, it becomes almost impracticable. This does not mean that the designer should not strive to attain the maximum uniformity even in heavy sections. What we have not yet dealt with is the influence of the external form of the part on the cooling rate. To revert to Fig. 72, certainly an extreme example, it will be seen that the section itself is uniform, without any sharp change in cross-section such as is shown in Fig. 71. One might therefore imagine that it would present no special difficulties. Nevertheless, from the point of view of the heat-treater, it is not well designed. In the first place the sharp corners *R*. *S*, *T*, *U*, *V*, *W*, *X*, etc., are open to the cooling action (whether air, oil or water) on three sides or faces, so that the chilling effect of the quenching medium is three times as great per unit of area as on any unit of flat surface area in *Q*. The side edges *WX*, *WV*, *VU*, etc., are chilled on two sides only, so that the chilling effect is twice as great per unit of area as on any equal unit of area in *Q*. *Q* is chilled on one side only, receiving heat during quenching from its "hinterland." The sharp angles *YOT*, *ZSP*, etc., not only present a very restricted surface area to the cooling action of the quenching medium, but are being continually fed with heat conducted by the supporting masses on either side. The upshot is that the metal in such angles is subject to drastic and varying cooling conditions, and will, therefore, even if dangerous stresses are not thereby set up, vary in structure and properties from the rest. Moreover, there is always the danger that these sharp angles will trap steam or oil vapour and, being thereby cushioned from the hardening effect of the quench, become relatively soft instead of being fully hardened. Thus, since such sharp angles are often points where the heaviest service stresses are encountered, we may have the threefold deadly combination of high internal strain, incorrect structure and properties, and soft spots. Such a design is almost certain to fail in use.

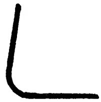
FIG. 73

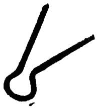
FIG. 74

This leads us to examine those parts or pieces in which heavy sections are inevitable, with occasional variations, as in the splines of shafts, the teeth of gears, etc., to see if measures can be taken in design to simplify their heat-treatment. Much can be done by rounding off sharp corners, and by giving a good degree of radius or curvature to angles (Fig. 73), particularly those of re-entrant type, or by filleting these, as in Fig. 74, which is, however, a drastic remedy. Another useful method is to give greater uniformity of cooling by piercing the heaviest masses with drilled holes, if this can be done without sacrifice of ultimate strength.

Again, consideration must be paid to balance. In a circular hollow shaft or arbor, for example, if two internal keyways are cut directly opposite to each other (say at points N and S of the compass) there is less weight of metal at these points than at the corresponding points (E and W) on the internal circumference at right angles to a line connecting the keyways. This means a variation in cooling rates, with the setting-up of strains and a probability that the part will be thrown out of round. If this trouble is persistent and serious, the remedy is to cut four keyways instead of two, thus equalizing cooling speeds and preventing distortion. Alternatively, the keyways should not be cut until the bars have been quenched and fully tempered. Here, the danger associated with the cold-straightening of hardened and tempered shafts, etc., by bending must be mentioned. When bent after heat-treatment, by cold-straightening, tensional and compressional strains are developed in the steel on diametrically opposite parts of the bar. Later machining, as in the forming of keyways, then results in the liberation of surface tensional or compressional strains, and inevitable distortion.

The teeth of hardened cutting tools should never be absolutely sharp  but given a slight radius, thus:  to prevent the destruction by heat of the sharp tip when the tooth is placed in the hardening furnace.

Another valuable and increasingly practised method, where the mass of a part is so large as to make hardening difficult, as in certain dies, is to build it up in sections, which can be hardened separately without difficulty.

Obviously to go more deeply into this branch of the subject would bring us into the realms of specialized tool and part design. Here, then, we shall end this chapter, leaving it to the reader to follow up design further, if he so desires, in the appropriate textbooks, or down the hazardous avenues of experiment.

CHAPTER XV

Heat-treatment Processes

THE specific processes of heat-treatment include normalizing, annealing, heating for hardening, quenching or cooling, tempering, case-hardening, nitriding, and surface hardening.

NORMALIZING

Normalizing is a cooling process designed primarily to give steel its "normal" tensile strength, yield point, elongation and reduction of area (terms corresponding to specific mechanical properties, and fully explained in *The Structure of Steel*). In addition, normalizing improves the surfaces of many steels when machined, and is specially beneficial for bars rolled at a low temperature, because it restores the degree of ductility they lose during rolling, and makes them at the same time more homogeneous in physical properties.

The process itself is actually a form of annealing, and differs from it only in the way in which cooling is carried out. The steel, in whatsoever manner it has earlier been treated, is heated to a temperature above the upper critical point or range. It is kept at that temperature for a period depending on the mass of the piece and the type of steel, and then left to cool freely in air, not, as in true annealing, in the furnace. The minimum period for holding (or soaking) at the normalizing temperature is 15 minutes; with larger sections much longer periods may become necessary, and it is not advisable that this temperature should be more than 50° C. above the upper critical point of the steel.

Normalizing is not an exact term, because the structure it produces varies with the dimensions of the piece, a thin section obviously cooling much more rapidly than a thick, where the internal structure may, as a result, closely resemble that of ordinary annealed steel.

The structures produced in steel by normalizing can be forecast with reasonable accuracy, because the relation between the amount of radiant heat given off by the material and the temperature of the atmosphere in which it cools is calculable.

Some comparison between normalizing and annealing is inevitable and necessary. In the main, normalized steels are somewhat less ductile than those fully annealed, as measured by the elongation values, but, against this, normalized steels give higher yield and tensile strengths and often, singularly enough, better reduction of area. Their grain structures are finer, and, in addition, they generally show a greater resistance to impact as measured by the Izod and Charpy tests. The improvement in certain properties shown by normalized, as compared with fully annealed, steels is perhaps more evident with the lower than with the higher carbon steels.

Normalizing is often advantageous as a preliminary to such operations as case-hardening, and in this instance the normalizing is carried out from a very high temperature to ensure that the grain structure of the steel becomes so enlarged that the part will be easily machined. Numerous steels having an *inherently fine grain** may show grain growth at 980° C. and others may need even higher temperatures. Normalizing is also used in advance of case-hardening to prevent distortion of the material after it is machined, as a result of the release of internal stresses set up by forging, rolling, etc., and to ensure uniform machinability throughout the piece.

With the specific normalizing treatment temperatures for particular steels we shall deal in the chapters devoted to those steels.

ANNEALING

Annealing is a reheating operation succeeded by slow cooling, usually in the furnace. It is designed to achieve, in the first place, the maximum softening of steel to enable it to be easily sawn or machined, or mechanically worked by such operations as cold-pressing, cold-bending, etc. Secondly, it may be employed to eliminate any internal stresses occasioned by too quick a rate of cooling, especially if this cooling rate varies considerably over different areas of the piece being treated, or by rolling, forging, casting, pressing, or other hot mechanical working. It can also be used as a means of improving the grain structure, and in some steels, viz., high carbon and high-speed steels, is a necessary preliminary to hardening, as otherwise these steels would crack during quenching. The temperatures involved in the reheating are usually above the lower critical point, and with "carbon" steels,

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* Inherent grain size will be discussed later, particularly in regard to case-hardening steels.

above the critical range, but sometimes a *sub-critical annealing* is carried out. This means that the reheating temperature is below the lower critical or transformation point, as in the spheroidization of the carbide particles in high carbon tool steels and in the softening of air-hardening steels of the nickel-chromium-molybdenum types.

The exact temperatures of annealing are governed by the percentage of carbon and alloy elements in the steel. If a plain carbon steel has below 0·9 per cent carbon, it is heated to just above its upper critical point. If it has more than 0·9 per cent, it is heated to a point just inside the critical range. Most high carbon tool steels are annealed between 760° and 780° C.

The steel must be held at the requisite annealing temperature for a specific length of time, after which it is allowed to cool down gradually to little above atmospheric temperature. The exact temperatures and periods of temperature maintenance are most important and must be strictly adhered to, otherwise the particular condition required will not be achieved. When the full annealing operation is complete, the steel is in its softest condition.

In ordinary annealing, there is always a risk that the surface layers of the steel will oxidize and scale as a result of heat. To prevent this, wherever prevention is essential, the material is sometimes, though nowadays seldom, packed in a mixture of burnt lime reduced to a very fine powder, and containing a small percentage of powdered charcoal. A carburizing box is first taken, and into the bottom of this is closely rammed down a bed of lime. The parts or pieces to be annealed are then laid on top of the lime bed, more lime being closely rammed down around and above them. When this operation is complete, this second thick lime bed is sprinkled with powdered charcoal. If there are more parts to be annealed than is represented by one layer, fresh layers can be added on top, using the same methods, until the box will hold no more. Finally the box is closed by a cover, and clay is used to seal it. The result will be that the annealed material emerges quite bright and free from scale.

For the annealing of rod or wire to be cold-drawn through dies, annealing in cast iron pots packed with cast iron borings or turnings is carried out.

While these methods have advantages where a special furnace for bright annealing is not available, they are slow and expensive. A much better method is to employ a furnace specially designed for bright annealing, in which the atmosphere inside the heating chamber is controlled.

To anneal and soften steel successfully, not only must the operator know what he is trying to do and the correct method of doing it, but he must also be able to apply his knowledge. Skill and judgment are needed in the insertion of the steel into the furnace, the control of gas composition and flow in the furnace, and the accurate estimation of the correct heating period to ensure even and thorough heating or soaking. It is essential that the steel should be thoroughly heat-soaked, because this not only gives the required structural uniformity, but also minimizes the heat-maintenance period, as well as the period during which the upper and outer surfaces of the steel are subjected to heat and the effects of the furnace atmosphere.

It is not enough merely to have an even heat in the furnace chamber. The heat must be evenly distributed through the mass of the steel itself, and in this respect great variation is rendered feasible by the method of disposing the steel in the furnace. The charge should be lifted above the floor of the furnace by resting it on supports, which may be either special refractory bricks or special heat-resisting alloy steel blocks. Moreover, each piece should be separate from its neighbour, and particular care must be taken not to overload the furnace, as this will result in an uneven distribution of heat, some portions of the charge being heated to a greater extent than others, the hot gases being obstructed in their flow by the excess of material, and failing to reach the entire furnace load.

In some electric resistor furnaces and those gas furnaces fired by radiant tubes, there is no flow of gases round the charge, but it is equally vital that the charge should be so arranged in the heating chamber that all parts of it receive an equal amount of the heat radiated by the resistor elements or the radiant tubes.

The structural effects and significance of annealing have been dealt with in *The Structure of Steel*, and we do not propose to consider them here. It should be remembered, however, that comprehension of what takes place in steel during annealing will greatly assist the operator in acquiring the maximum skill and judgment.

Of special importance is the heating operation, which should be slow and even. This rule applies to all steels. If the steel is heated too quickly it may crack, will probably fail to soften to the desired degree, and will, in consequence, be harder than is required for machining, sawing, etc., while, in addition, interior stresses may possibly be released non-uniformly and cause distortion, or even cracking. In general, the higher the carbon content of the steel, the more severe are the internal stresses it contains, as a result of its previous treatment by rolling, forging, etc., and therefore the slower should be the heating rate. So important is this that wherever the pieces to be annealed are of complicated form, or have abrupt changes of cross-section, it is advisable to warm them cautiously before they are introduced into the hot furnace. If the steel is a particularly bad conductor, as are many highly-alloyed steels, such as high-speed, it needs extremely gradual and skilful preheating.

In later chapters the specific annealing temperatures for different steels will be given. Generally, the annealing temperature is controlled by the chemical composition and particularly by the carbon content of the steel.

Some operators, in order to speed up the process, make the mistake of trying to ensure the heating of a mass of steel right through to its centre by elevating the furnace temperature to a point somewhat, or even considerably, above the correct annealing temperature. The result is, almost invariably, that the outer layers of the steel are heated to too high a temperature, with the structural damage associated with overheating and in extreme cases with *burning*. In either case, the steel is embrittled, even though it may be soft as measured by the Brinell hardness test. It is a golden rule not to raise the temperature of the heating chamber above the precisely known annealing temperature. While it may take longer to heat the charge slowly and gradually until thoroughly soaked, the result will be sound, as distinct from spoiled, material.

The period during which the heating is continued depends on the greatest cross-sectional dimension of the piece, since the flow of heat depends on temperature gradients. The structural condition of the steel in advance of annealing also has an important influence on the heating time. Bullens lays down as a general rule that about half an hour to an hour should be allowed for heating and soaking for each inch of section in wrought steel, but adds that this rule must be modified according to the individual operator's experience and the type of heating procedure.

In actual practice, it will be found that heating is faster than the above suggests, partly because operators desire to minimize the heating period and so avoid scaling, and partly because a greater output may be needed from the individual furnace. Atmosphere control, of course, does away with the risk of scaling.

A useful method, whereby rapidity of heating can be combined with uniformity of heat distribution, and a higher temperature adopted without coarsening of the grain structure, is to pass a current of electricity through the piece. The resistance of the steel to the passage of the current generates heat in the piece, and this heat is sustained until the whole mass is satisfactorily heat-saturated.

The final structural condition of an annealed steel is determined by the speed or rate of cooling. In general, the larger the mass of the steel, the more protracted must necessarily be the cooling period. It will be appreciated that there is much diversity in the surface areas and cross-sectional areas of bars and pieces, so that there will be equal diversity in the amounts of heat radiated away over a given cooling period. Furthermore, the cooling rate will be affected by the dimensions, type, and construction of the furnace. Hence, the exact cooling period can only be assessed as a result of trial and error under the specific operating conditions. In the main, however, it can safely be laid down that the slower the cooling through the critical range, the more thorough and satisfactory the annealing will be.

While true annealing is accomplished by allowing the steel to cool down in the furnace, this is not always feasible, particularly with very big pieces or where there is more steel to be dealt with than the existing furnaces can accommodate. In such circumstances, the only course is to try to imitate, as far as possible, the cooling conditions inside the furnace. With large pieces this can be done to some extent by withdrawing the hot material from the furnace and burying it in sufficient material, such as ashes, lime, or sand, of low heat conductivity, and allowing it to cool in this enveloping mass. Small pieces are buried in lime, and the cooling rate here may be rather less rapid in the final stages than even in the furnace. Large tonnages can be transferred straight from the annealing furnace to a cooling pit, lined with brick or metal plates and fitted with a metal cover. Here the steel may or may not be buried in ashes, and again a slower cooling rate achieved than would be obtained in a badly built and designed furnace. It is worthy of note that, generally, the slower a steel is cooled, the lower is its yield point and tensile strength. (Exceptions to this are the "austenitic" stainless and manganese steels.)

It should be stressed that in most of what has been written above it is assumed that the steel to be annealed is in a normal structural condition to begin with. In many instances, however, this is not so. The steel may have been subjected to a degree of mechanical working much heavier than is customary, and may even have been cold-worked. Again, it may have been overheated or may show a coarsely granular structure, as in steel castings at high temperatures, slowly cooled. The resulting structures, unless steps are taken to prevent them, may continue even after annealing. In general, it may be said that "cast" and "overheated" steels require longer periods of soaking than steels that have been mechanically worked at correct temperatures, since a coarse structure always takes a longer time to refine than a finer one.

Where abnormal conditions exist, the annealing methods used must be specially designed to overcome them. For example, the heat-saturation period may have to be prolonged far beyond the normal, even to as much as several days. Special heating procedures may be necessary, and a double instead of a single annealing treatment adopted as a remedy.

In some instances, the original structure of the overheated steel in advance of annealing may be such that neither single nor double annealing at the ordinary specified temperature proves effective. In these instances a higher heating temperature (100° or 150° C. above the upper critical point) may be advantageous. The steel is fully heat-saturated at this temperature, then allowed to cool to a point below the lower critical point, either in the furnace or in air, according to the extent to which the high heating has eliminated the original overheated structure, air cooling being adopted if complete elimination of faulty structural conditions has not resulted. After this, an ordinary full annealing treatment follows, and serves the purpose of refining the coarse grain structure produced by the high heat.

HARDENING

The hardening of a steel is essentially governed by the temperature from which it is quenched and the nature of the quenching medium, i.e. whether water, oil, or air.

If the steel-treater does not know beyond all doubt the exact hardening and quenching temperatures for the steel with which he is dealing, he is unlikely to succeed except at the cost of much spoiled material, loss of time, and vexation of spirit. As its name implies, hardening is a heat-treatment process designed, in contrast to annealing, to produce as hard a steel as possible, consistent with usefulness. To achieve this, the steel must be heated to a temperature above the critical point or range, but instead of being allowed to cool down slowly in air, as in normalizing, or in the furnace, as in annealing, it is cooled, chilled, or *quenched*, swiftly by immersion in a quenching medium such as water, oil, or air. In general, so long as the upper critical point is not exceeded, the higher the temperature at which this sudden immersion occurs, the harder will be the steel. Once the steel is heated *above* its upper critical point, however, the actual temperature of immersion does not make much difference to its hardness, but may considerably impair its toughness, making it brittle. Hence, it cannot be too strongly emphasized that no steel should be heated for hardening to a temperature much exceeding its upper critical point, although in practice from 30° to 50° C. above it must be allowed.

The properties of a steel are also greatly influenced by the cooling rate. If this fluctuates, the hardness of the steel will also fluctuate, and, in general, quicker cooling means harder steel. As the reader will see in the chapter on quenching media, different cooling media give different cooling speeds, so that the degree of hardness required in a particular tool or piece of steel may call for the choice of one type of quenching medium in preference to others. Hardness is also affected by the dimensions and mass of the piece. Small pieces can more easily be hardened right through than large for the simple reason that less time is needed for the chilling or quenching effect to travel from the exterior to the core or centre of the piece or, to put it in another way, there is a much steeper temperature gradient in a small piece during quenching than in a larger piece. This means that heat is drawn more rapidly from the central portions of small pieces and the speed of cooling accelerated.

As with annealing, it is not our purpose to detail the purely structural phenomena associated with hardening, which have been fully explained in our earlier book (*The Structure of Steel*). A reading of that book is, however, recommended as a means towards surer and more intelligent handling of practical hardening problems.

In its preliminary stage of heating, hardening does not differ greatly from annealing, though usually the hardening temperatures are slightly higher than the annealing. The vast difference in properties between annealed or softened steels and the same steels quenched or hardened is produced essentially, though not entirely, by the difference in the method and speed of cooling. It is this that changes the character of the structure in the cold steel. The drastic cooling by immersion may be likened to a cold wind springing up on a hot day. It stops the change into bathing costumes and flannels and compels the putting on of overcoats. In other words, it prevents the microstructure (austenitic) of the heated steel from breaking down into two different forms (cementite and pearlite), and compels them to change instead into another and harder form (martensite).

The microstructures developed by quenching are, on the whole, typical of the temperatures from which they are quenched. If alloying elements are added to a carbon steel, the result is to retard the breakdown of the original (austenitic) structure, which means that with a less drastic speed of cooling the same harder (martensitic) constituent can be obtained as would be developed in a carbon steel by a faster cooling rate. By still further reducing the cooling speed, the alloy steel may often be given a less hard (pearlitic) structure. It is possible, by maintaining the carbon content, and judiciously varying the alloy percentage and the cooling rate, to produce corresponding structures with virtually identical mechanical properties. It will be seen that the introduction of alloys into a hardenable steel renders possible a wide range of cooling speeds, hardness variations, mechanical properties, and microstructural conditions.

Thus it will be apparent that from the point of view of heat-treatment, the introduction of alloys is not so much (with noteworthy exceptions, of course) to produce steels with wholly different properties from those of the carbon steels, as to produce steels more sensitive to the heat-treater's skill, and with a wider range of mechanical properties obtainable by heat-treatment.

It must be borne in mind that if an ordinary carbon steel is hardened at the maximum possible quenching temperature, it still does not, if of more than extremely small cross-section, fully harden throughout its mass. It is impossible to conduct or suck heat from the central portion of a heavy piece as quickly as from the exterior. Hence, the outer layers will generally be more drastically quenched than the interior. By passing an electric current through a steel bar we can uniformly *heat* its entire mass, but we cannot by any means uniformly *cool* the bar. The heat can only escape by flowing outwards from the centre, i.e. as fast as the other layers of metal will allow it. It is like a theatre crowd dispersing from an auditorium. Those nearest the door get outside first, and the speed of emergence is in direct proportion to distance from the exits.

Since in hardening steel it is speed of cooling that causes the vital structural changes, the centre of a relatively large mass cannot have the same structure as the exterior. However, it is feasible to overcome this difficulty to some extent by control of the cooling speed, and consequently of the structural condition. Cooling speeds are usually assessed in terms of the thickness of cross-section fully hardenable under specific hardening or quenching conditions. The cooling rate, as earlier indicated, is also considerably affected by the type of quenching medium adopted.

Additional factors in the degree of hardening of which a steel is capable are the hardening temperature and the grain size. The effect of grain size on hardenability is interesting. It seems to be established that a steel with coarse grain will harden more deeply throughout its mass than a steel of fine grain, and vice versa. From this it would appear that the heat-conductance of a metal, such as steel, depends largely on that of its crystal or grain boundaries. In a fine-grained steel, there are obviously many more grain boundaries than in a large or coarse-grained steel, so that in the latter, there is less impediment to the outflow of heat during quenching; the piece as a whole is thus more rapidly cooled, with the consequence that it is hardened to a greater depth than a fine-grained steel. Deoxidation (see *Steel Manufacture—Simply Explained*) with titanium, abnormal amounts of aluminium, etc., will yield steels of inherently fine grain.

We are now in a position to sum up the various factors affecting the degree or depth of hardness a steel will acquire when heat-treated. These are: (*a*) Mass of the piece; (*b*) surface area per unit volume of the piece; (*c*) the extent to which heat is given time to soak thoroughly into and distribute itself over the entire mass; (*d*) the cooling speed; (*e*) the hardening temperature; (*f*) the alloy contents of the steel; (*g*) the carbon content; (*h*) the grain size; (*i*) the type of quenching medium; (*j*) the temperature of the quenching medium; (*k*) the speed with which the quenching medium is caused to circulate about the piece.

TEMPERING

When a piece of high carbon tool steel is taken out of the quenching bath or tank, it is hard (martensitic), but not in the most satisfactory structural condition. For one thing it will be brittle, and the quenching process, however carefully carried out, will have set up severe, unequally distributed internal strains. If the steel is put to work in this condition, it will probably (with one or two minor exceptions, such as a nickel-containing chisel steel and certain other alloy steels that are self-tempering) crack or break as a result of the spontaneous liberation of the excess stresses.

To give to steel the right (martensitic, troostitic, or sorbitic) structural condition combined with toughness and shock-resistance a further process known as tempering is required. This comprises a further reheating of the steel, followed by cooling in air, oil, or water. The effect of this is to relieve or equally distribute the hardening stresses and improve the material in the direction of less brittleness and greater toughness. Tempering is, in fact, akin to annealing in that it is fundamentally a softening process, but is carried out at much lower temperatures.

By careful control of the tempering temperature almost any required degree of hardness and toughness of which the steel is inherently capable can be obtained. It is important to note that a balance should be struck between hardness and stress relief. To keep too much hardness in the steel may mean that serious stresses are still left in it, while too great a relief of stress may result in too soft a steel, particularly in a tool-steel. As a general rule, high tempering temperature means high stress relief. Low tempering temperature means low stress relief, but the important point to bear in mind is that a low temperature tempering induces a *uniform* distribution of the internal non-uniform stresses set up by quenching. Low temperature tempering, too, say below 250° C., does not necessarily mean a lowering of hardness and tensile strength; with alloy steels a slight increase in these values may be obtained.

There is a curious phenomenon associated with the tempering of the carbon tool steels. This is the formation of *temper colours* on the surface of the steel being treated, corresponding fairly closely to the different tempering temperatures. These colours are due to surface oxidation of the steel, causing the formation of thin films of iron oxide. Table XXII shows the temper colours corresponding to the tempering temperatures for carbon tool steels. The steel is rubbed with emery after being hardened, and as it rises in temperature, the originally bright surface begins to acquire the characteristic oxide hues, which, pale straw at the lower temperature, change and deepen until they reach a deep greenish blue at about 330° C., passing through intermediate stages of brown, purple, and light blue.

TABLE XXII

TEMPERATURES OF TEMPERING COLOURS

Tint of Oxide on Surface of Steel	Centigrade	Fahrenheit	Suitable for
Dark blue	316°	600°	Hand saws.
Blue	293°	560°	Fine saw-blades, augers, boiler-makers' snaps, chisels, smiths' tools and cold setts.
Bright blue	288°	550°	Watch-springs, swords.
Purple	277°	530°	Table-knives, large shears and wood-turning tools.
Brown, beginning to show purple	266°	510°	Axes, planes and wood-working tools.
Brown	254°	490°	Scissors, shears, cold chisels, large drills, shear-blades, punches, and wood-cutting tools.
Golden-yellow	243°	470°	Penknives, hammers, taps, reamers, large lathes, planing and slotting tools, small drills, screwing, stamping, and cutting dies and miners' drills.
Straw	230°	446°	Razor blades.
Pale yellow	221°	430°	Small edge-tools, small lathes, planing and slotting tools.

Many steel-treaters rely on these oxide tints as their guide to tempering temperatures, but complete reliance is inadvisable. In the first place, colours can sometimes be misjudged because of bad or imperfect lighting conditions in the shop. The printed temperature-colour charts, sometimes asked for by less expert steel-treaters, are unreliable as a guide in temperature judgment. The colour of a heated steel (we are not now talking of temper colours) varies considerably with the amount of light in the shop, and what may be bright red to the treater's eye may be dull red on the printed chart. Moreover, no printer can exactly represent the glowing luminous colours of hot steel on the flat surface of a piece of paper. There is, therefore, a double risk of faulty temperature estimation.

Similarly with temper colours. The amount of light makes a difference to the colour interpretation. In addition, temper colours are modified to some extent by the length of the heating period once the full tempering temperature is reached. Temper colours are merely indications of *surface temperatures*, and as the surface grows hotter the colours correspondingly change. *When the final correct tempering temperature is reached, if heating is continued, the colour will change without any corresponding change in temperature.*

Finally, it is doubtful whether temper colours have any real relation to the structural state of the steel, but this is an abstruse question that need not detain us here. The view of the authors is that there is no royal road to temperature control and measurement, and that a trustworthy modern pyrometer is the first essential of successful heat-treatment.

In this connection, and with a similar caution, we mention a method of temperature measurement in which colours are applied to metal not showing temper colours when treated *at low temperatures*. In the ordinary way no discoloration of the steel occurs, and there is no visual indication that the metal has been subjected to heat-treatment. With these colours, however, a spot of the appropriate colour shows by a change of tint (*a*) that the object has actually been heat-treated; (*b*) that a minimum temperature of so many degrees C. has been attained. In addition, a range of colours changing *above* 800° C. is at present under test, with a view to extending their application to heat-treatment at the higher temperatures. The colours are brushed or sprayed on, and a range, known as "Thermindex," has been standardized on an exposure period of 10 min. They are made by Synthetic & Industrial Finishes, Ltd., and marked exclusively by J. M. Steel & Co., Ltd., London, to whom we are indebted for these details.

Temper colours may be obtained in two ways. For example, a colour may be produced by a brief heating at $X°$ C., or by a longer heating at a lower temperature. It is this that causes the doubt whether temper colour is any real indication of structural state. With many tools, where hardness right through the body or mass of the steel is not vital, the short heating at the higher temperature may suffice, since it will give at least a surface hardness adequate to requirements. On the other hand, stress relief will be less thorough, and structure less uniform. Where these requirements of stress relief and uniform structure are urgent and necessary, the lower temperature and the longer heating at the tempering temperature will be more satisfactory. There is, however, a third and better means.

If tempering temperature is judged exclusively by temper colour, the moment the right colour is reached, the steel must be cooled, because *the treater cannot know the exact moment when the colour will change again.* Even the most skilled operators can rarely gauge this point with exactitude. To cool by quenching is not always good practice, because it may reintroduce strains and a structural condition lacking in uniformity, while there may even be variation in hardness in one and the same piece. Hence, in modern tempering, the practice is to employ liquid baths for the heating operation, and thus dispense altogether with reliance on the superficial oxide tints.

The importance of observing the strict tempering temperature recommended by the steel manufacturer cannot be exaggerated. There is not a large margin of temperature to play with—not more in most instances than about 50° C.—while the structural changes induced by tempering occur quickly. Exact temperature control is, therefore, vital, and many tool failures can be safely ascribed to faulty tempering technique.

Tempering technique must, of course, be adapted to the work, and it is not feasible to deal in detail here with every method. There are six in general use. In the first, a cast iron plate with a smooth, machined surface is heated from below. The parts or tools to be tempered are placed on this, their position being changed from time to time, and as soon as the desired temper colour appears, they are quenched. In the second method, either the hot plate or a furnace can be used, but instead of placing the tools on to the plate or furnace hearth, the operator places them in a tray or dish filled with sand, which is then heated up either on the iron plate or in the furnace. The advantage of this method is that some form of temperature control may be exercised, since a thermo-couple can be used, the temper colours serving merely as an extra indication of temperature. The sand must, of course, be clean and dry, and will give a more uniform tempering. This method is, of course, suitable for small pieces only.

The next method is to use an oil bath, suitably heated to the exact temperature and maintained at this temperature without fluctuation. Temperature measurement is, therefore, most essential here. The oil bath is not suitable above 260° C., but gives excellent results below this temperature. The oil itself is usually of mineral type, though non-mineral oils have sometimes been used. The tools or parts to be tempered are placed in a wire basket suspended in the bath before the oil has exceeded 100–150° C. This ensures that the tempering temperature is not reached too quickly, and by gently relieving stresses prevents fracture due to a too sharp relief. Being suspended in the basket, the pieces are kept from contact with the hot casing of the bath, and thus from becoming locally overheated.

The period during which the parts are left at the tempering temperature varies with their dimensions and form, but 15 min. may be regarded as a minimum. Larger parts will need longer, and the small, if heated with them, will not be spoiled if left in the basket for the longer period, since no appreciable structural change will occur unless the temperature is raised.

After being tempered, small parts are withdrawn from the bath and cooled in the air. Very large pieces are often allowed to cool down in the bath so that stress relief shall be as complete as possible, to avoid danger of distortion or fracture.

For tempering temperatures over 260° C., a salt bath can be used, the usual mixture being 40 per cent potassium nitrate and 60 per cent sodium nitrate. Such a bath can be safely employed for tempering temperatures up to 540° C. The parts are contained in a basket as in the oil bath.

Lead baths are often used for tempering at temperatures above 330° C.

Lastly, there are the electric tempering furnaces. These are employed for such parts as springs, bolts, pressings, etc., and ensure uniform heating, throughout even a densely packed charge. They are of forced air-circulation type, and can be used at temperatures low enough for oxidation by the air to be negligible.

CHAPTER XVI

Quenching Media

THERE are something like thirty-two classified quenching media whose cooling rates are known, not all of them different in substance, but all differing in their effect on the cooling rate. For example, water originally at 0° C. will cool hot steel at a different rate from water originally at 25° C. and in this sense both can be regarded as separate and distinct quenching media. If we confine the media to those of different substance, however, we find twenty-six types whose cooling powers have been carefully calculated, by comparison with the cooling rates in water at 18·3° C. (65° F.) of hot steel at temperatures 720–550° C. (1328–1022° F.) and 200° C. (392° F.). The determination of the cooling rate has been obtained by taking a nickel-chromium alloy ball measuring 4 mm. diameter and quenching it in various media from 860° C., the cooling rate being measured over the temperature range 720–550° C. (The cooling rate in water at 65° C. is about 2105° C. per second over this range, and 432° C. per second when the steel is quenched from 200° C.)

A more drastic quench is required for those steels whose ability to acquire hardness is limited, or, as they are often termed, the shallow-hardening steels, usually of unalloyed carbon type, than for the deep-hardening steels, usually of alloy type. The cooling rate necessary to produce the type of structure consonant with hardness in unalloyed carbon steels is extremely high, and the nearer the steel approximates to pure iron (i.e. the lower its carbon content) the higher the cooling rate necessary and, in consequence, the more difficult it becomes to harden by quenching. Eventually, a point is reached at which a carbon steel cannot be quench-hardened satisfactorily, and if adequate hardness is desired, must be treated in some other way, e.g. by case-hardening or cyaniding. This is true of the very low carbon steels, containing less than 0·1 per cent carbon.

The commonest, cheapest and simplest quenching medium is water, and after it, though not the best in all instances, brine. The advantage these possess is a high cooling rate for the hot steel, and as the hardenable carbon steels demand this, they are the media most suitable for their quenching. The speed with which they cool the steel (982° C. per second) is extremely close to the minimum cooling rate essential for unalloyed carbon steels; thus it is evident that if anything interferes with, or obstructs, their action on the surface of the steel (e.g. steam pockets due to vaporization of the water by the heat of the steel) the cooling rate over these localized areas will fall short of what is required. In consequence, the requisite (martensitic) structure will not be developed within these areas, and the result will be the formation of unhardened or insufficiently hardened local areas, commonly termed *soft spots*. Thus, in hardening the carbon steels in brine, nothing must be allowed to impede the drastic cooling action.

Another point of great importance is that because the cooling action of brine and water on the outer layers of the steel is so sharp and swift, the rate at which heat is withdrawn from the centre of the piece must also be high. This involves a swift structural transformation varying in intensity from surface to centre and, in consequence, produces severe internal stresses where the transition from one structure to another is imperfect and incomplete. These stresses, in their struggle to achieve relief, may produce considerable warping of such pieces as are long, slender, complicated in form, or of thin and sharply varying cross-section. It is for this reason that the brine or water-hardening carbon steels cannot safely be used for parts in which distortion must at all costs be avoided. This applies to all the plain, i.e. unalloyed, carbon steels, and cannot be more than mildly affected by an alteration of the quenching medium. No change of quenching medium will, of itself, overcome this distortion without the sacrifice of a degree of surface hardness for carbon steels. It is possible to use different oils for quenching intricate parts of carbon steel, but unless these parts are of extremely small size the full hardness will still not be achieved, though distortion may be minimized.

Next to water and aqueous solutions, the most widely used quenching medium is oil. Here, an entirely new set of conditions obtains. Oil cools hot steel less rapidly than water, and the larger the piece quenched, the slower is the cooling rate. One immediate result of the slower cooling is a reduction in the danger of warping. Nevertheless, oil does not, as is sometimes mistakenly supposed, entirely eliminate distortion. With certain parts, the warping may, even with oil quenching, be so great as to make the choice of yet another, still slower-acting, quenching medium, such as air, advisable. Nor must it be assumed that even if distortion does not occur, the oil-quenched part is necessarily free from unequally distributed internal stresses, although it is true to say that the stress-distribution in an oil-quenched steel part is generally more *uniform* than in a water-quenched steel.

To compensate for the slower cooling rate of the steel when quenched in oil, with consequent sacrifice of hardness, it must contain suitable alloying elements, so that, in general, oil-hardening steels are more expensive in first cost than plain carbon steels (except in special instances, such as the high carbon tool steels of finest quality, into whose manufacture other price-raising factors than the prime cost of raw materials enter).

Where even quenching in oil gives rise to too much distortion, recourse is had to air as a quenching medium. Steel cools much less rapidly in air than in either oil or water, so that, here again, to make up for the sacrifice of hardness that would otherwise ensue, even more of the expensive alloying elements have to be added to make the steel fully hard, despite the slower cooling rate. Hence, air-hardening steels are, all things being equal, higher in first cost than oil- or water-hardening steels.

Other quenching media include liquid metals and special salt solutions which are roughly intermediate between oil and water in cooling rates.

The steel manufacturer is generally able to say that a specific steel of given dimensions will, or will not, develop the required degree of hardness as a result of quenching in water or oil. Two steels may, however, have almost identical chemical compositions and still give different degrees of hardness after identical quenching operations.

The quenching media can now be divided into five main groups: (*a*) brine; (*b*) water; (*c*) solutions of special compounds (e.g. sodium hydroxide and sulphuric acid in water); (*d*) oils; (*e*) air. The sequence in which these follow indicates their relative cooling powers, brine having the highest and air the lowest. The action of these media is, in addition, affected by their temperatures at the time of quenching, and by what is termed their cooling volume velocities. This means the speed at which the entire quantity of the medium available for quenching the part is circulated, mechanically or otherwise, about it. Other factors of importance are the volume of the quenching tank, the original temperature of the steel, and the way in which the steel is handled as it passes to, through, and from, the tank.

A curious point is that although brine solutions have the highest cooling power in actual practice, or, more accurately, have a more drastic quenching action than water itself, they do not actually disperse heat more rapidly than water—at all events the difference is negligible. Actually, the sharper quenching action of brine is due to a complicated series of successive changes. As soon as the hot steel is plunged into the brine solution it becomes enveloped in a "jacket" of steam, and crystals of salt are deposited on its surface. It has been demonstrated practically, by means of photographs, that the next stage is the "flying-off" of these salt crystals with explosive violence. These take with them the adherent *scale* on the surface of the steel, so that the later inrush of the cold brine solution then comes into contact with the almost scale-free surface. The rate of cooling is thereby increased, since the heat conductivity of the scale is enormously less than that of the steel itself. The main function of a brine solution is, therefore, to break away the adherent oxide or scale on the surface of the steel, and so accelerate its rate of cooling.

The quenching power of any medium is determined by (i) its ability to conduct heat, i.e. its *thermal conductivity*; (ii) its viscosity, i.e. its resistance to movement, whether due to mechancal or thermal causes; (iii) its *specific heat*, i.e. the amount of heat required to raise the temperature of a unit weight of it by one degree F.° or C.°; (iv) the temperature at which it vaporizes or gasifies. It may be of interest to indicate the particular respects in which these properties are important. Good thermal conductivity obviously enables a quenching medium to withdraw heat more rapidly from the steel, thus giving a higher cooling rate and, in consequence, a more drastic quenching action. Low viscosity means the easier generation of convection currents, and seems to increase cooling power at certain stages in the quenching operation. It also enables the oil to drain more easily from the parts when recovered from the tank, with the result that loss of oil is minimized. Specific heat and boiling point govern the rapidity with which the medium vaporizes, vaporization being a factor of primary importance.

When a hot mass of steel is plunged into a liquid quenching medium, the temperature of the medium is raised, and those portions in direct contact with the hot steel may turn to vapour. The longer this stage of vaporization lasts, the greater likelihood there is of soft spots, since cooling is much slower through a gas than through a liquid, owing to the enormous difference between their specific heats, and as the vapour formed creates a kind of envelope about the part, it may seriously hinder quenching. Hence, in a good quenching medium there must either be no vaporization at all, or what there is must be at a minimum and the vapour reconverted into liquid in the shortest possible time. Quite apart from the circulation of the medium about the part, or of the part through the medium, as a means of achieving this, it is noteworthy that vaporization time is shorter in proportion as the temperature of the quenching medium is lower. Hence, it is a golden rule that all liquid quenching media liable to vaporize (e.g. those containing water) should generally be kept as cool as possible, and preferably not above 20° C., although there are instances where quenching in a hot liquid medium is desirable, e.g. in the *patenting* of steel rod for drawing into wire and in the hardening of files by first quenching them in molten lead. It must be realized that the primary object of quenching is to depress the Ar point of the steel to such an extent that the hard martensite is formed—this occurs at temperatures between 150° and 300° C.

There is another method of minimizing vaporization in aqueous solutions. This is the introduction into the water of special substances such as calcium chloride or sodium hydroxide, though many other salts have a somewhat similar effect. On the other hand, the reverse effect is produced by soap dissolved in the quenching water or solution. A second golden rule is, therefore, not to allow any soapy matter to enter the water in the tank.

The percentage of salt added to make up an efficient quenching medium must be studied carefully. Too much salt actually reduces the cooling efficiency of the aqueous solution. Roughly, the percentage of salt in the solution should not rise above 10 per cent. It must not be supposed that oils used as quenching media do not vaporize. They do, but the vaporization is rather less serious, because actually at the vaporization stage the cooling rate of oil vapour is rather higher than that of water vapour, though once vaporization is over, the cooling rate is much less than with water. Nevertheless, vaporization should not be unduly prolonged, and as the lower the boiling point of the oil the longer vaporization lasts, the boiling point of the oil used for quenching should not be below, say, 380–400° C.

Oil, as is common knowledge, has a much higher boiling point than water, so that a few degrees in normal bath temperature do not make any appreciable difference to the vaporization period. This means that there is not the same urgent necessity to keep an oil-quenching bath cold, and actually, at a certain stage in the quenching, warm oil may cool more rapidly than cold, apparently as a result of reduced viscosity, the vapour being able to move away more rapidly, together with the heat it has acquired, from direct contact with the steel. Moreover, warm oil causes less internal stress in the quenched steel, and therefore less danger of distortion and cracking. This is because the added warmth takes the steel more gently through its critical changes, and so enables the internal structural adjustments to be effected rather more smoothly and evenly. Oil should, therefore, be kept, preferably, at about 45–50° C.

One point needs attention, however. While it is, on the whole, advantageous that quenching oil should be warm, care must be taken not to have it so hot that it will *flash* or ignite when the steel is immersed in it.

There are so many different proprietary quenching oils on the market, each of its own particular composition, that it is impossible in a work such as this to discuss them from the point of view of individual merit. Certain qualities to be looked for have already been outlined. Others, all of which can be ascertained by suitable known tests, are as follows: (*a*) minimum carbon content, which means that there is greater likelihood that the oil will maintain its efficiency during prolonged use. Carbon is essentially unstable in many organic compounds, and soon combines under heat to form a sedimental deposit in the bottom of the tank; (*b*) low water content, so that less water vapour is formed, and also to prevent too drastic and non-uniform a cooling action as a result of its presence; (*c*) low content of certain fatty oils, which smell unpleasantly under heat and also deteriorate and decompose. This means that, for preference, the oils should have a mineral base, but it is generally better to keep them within certain temperature limits by a cooling system.

The significance of oil tests is not all-important, however. The various tests must be regarded rather as safeguards to ensure that supplies of an oil already found suitable are fully up to standard.

The most vital factor in quenching oil is its ability to maintain its properties over as long a service period as possible.

Quenching oils should not give rise to unreasonable sedimentation, leading to the deposit of a heavy sludge on the cooling coils of the tank.

A point to be borne in mind is that some organic constituents in a quenching oil used for quenching cyanided parts are undesirable. The reason is that when these parts are withdrawn from the fused cyanide container they carry with them a coating of the salt. This has a harmful effect on the oil, causing its rapid deterioration. It is, therefore, advisable to use purely mineral oils without any organic matter.

To sum up, then, an oil for quenching should yield more or less uniform cooling rates; should not produce gaseous vapours at low temperatures; and should not decompose and thicken or oxidize with repeated use. It should be fluid when fresh. A change in its thickness will cause a noticeable variation in the hardness of the quenched steel.

In general, animal and vegetable oils of a semi-drying character are effective quenching media when fresh, but are not in a fully stable condition, and having an affinity for oxygen, are readily stimulated to combine with that element by the conditions set up in hardening. This oxidation causes their rapid thickening as a result of the presence of suspended particles of the oxidation products, and eventually a sludge is precipitated to, or slowly forms on the bottom of, the tank.

Mineral oils whose flash-points are low, i.e. which catch fire at relatively low temperatures, readily disintegrate as a result of the heat of the steel. The "lighter" portions or constituents are volatilized, leaving behind a thicker and heavier residue. This thickening up is undesirable because it leads to slower cooling, with the result that the steel may not be hard enough after quenching.

The primary object of quenching is, generally, to produce the hard martensitic structure,* whether the steel is intended for use as tools or for constructional parts such as crankshafts, axles, etc. In either instance, the hardened steel is later tempered, i.e. reheated. For a tool steel, where final hardness is the essential

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* In some exceptional instances, as with the austenitic nickel-chromium corrosion-resisting steels, the object of quenching is to produce the relatively soft austenitic structure.

consideration, the tempering temperature for a "carbon" steel is generally below 350° C.

Tempering at such temperatures may slightly lower the hardness of the steel, but this is compensated for by the fact that quenching or hardening stresses are more uniformly distributed, so that the hardened tool exhibits less tendency to crack.

For structural purposes, tempering temperatures between 550° and 680° C. are commoner. These produce a structural condition known as *sorbite*, which possesses the best combination of hardness or strength, toughness, and resistance to sudden shock and fatigue.

An important point, too, is that, in many instances, sorbitic steels possess most satisfactory machining properties, a point not always realized.

Whether for tools or for structural parts, however, the quenching medium employed has its influence on the final properties of the steel.

For the keen hardening of cutting tools, water or brine solution is necessary for carbon steels, excepting those of thin cross-section. If quenched in oil, they would not be sufficiently hard. By introducing alloying elements, such as tungsten, chromium, molybdenum, etc., into the steel, it then becomes possible to harden tools quite satisfactorily by quenching in oil and, indeed, in the highly-alloyed high-speed steels, simply by quenching in a blast of air.

It must also be realized that the properties of quenched and fully tempered structural steels are influenced by the original hardening treatment, i.e. whether quenched in water, oil, or air.

For carbon steels, water-quenching and tempering will generally yield a more satisfactory combination of mechanical properties than oil-quenching and tempering, particularly in regard to tensile strength and impact values and where the larger sizes are concerned. One great drawback of water-quenching, however, is the risk of abnormal distortion during hardening, although, with bars, this can be rectified by straightening after tempering.

With the introduction of nickel, chromium, and/or molybdenum, and even abnormal proportions of manganese, into the steel, satisfactory hardening then becomes possible by quenching in oil, with the consequence that the risks of cracking and distortion are minimized. and with certain combinations of the first three elements all that may be necessary is to cool the parts in air. Such steels are known as air-hardening steels. In each instance, i.e. whether oil- or air-hardened, the steels respond in a similar manner when afterwards tempered.

Tempering generally implies cooling in air from the tempering temperature, but in some instances it may become necessary to quench in oil or even in water from this temperature, in order to obtain satisfactory impact values with the larger sizes of low-alloyed steels.

It will thus be seen that in practical heat-treatment the composition of the steel and the purpose for which it is to be used play an important part in the choice of the quenching medium both in hardening and tempering.

CHAPTER XVII

The Plain Low Carbon "Non-tool" Steels

In this chapter, we deal with that wide range of plain carbon steels not generally suitable for use as tools of cutting or forming type, but with carbon contents ranging from 0·05 to 0·6 per cent. This is too wide a range to be treated *en bloc*, and for the purposes of this chapter we shall break it down into four main classes: (*a*) Those steels containing up to 0·25 per cent carbon; (*b*) those between 0·25 and 0·35 per cent carbon; (*c*) those between 0·35 and 0·45 per cent carbon; and (*d*) those between 0·45 and 0·6 per cent carbon.

The first (*a*) group are usually termed *mild steels* and have multitudinous applications. Those steels of this group used in case-hardening are dealt with in the chapter on carburizing. The particular features of these mild steels are their plasticity and ductility. They are neither strong nor hard, so that they are not suitable for parts requiring high tensile strengths. On the other hand, they are easy to turn, drill, shape, plane, forge, roll, or mechanically work in other ways. The exact uses to which they are put depend primarily on their carbon contents, but there may be some variation in the manganese contents (the usual range being 0·3–0·9 per cent), and this is not without effect on the properties of the steel. For an explanation of the effect of manganese on steel the reader is referred to *The Structure of Steel—Simply Explained.*

These steels do not respond to a hardening treatment such as gives to the much higher carbon tool steels their fine *temper* and keenness of cutting edge. Nevertheless, heat-treatment is influential. A modified hardening treatment in which the steel is heated to 870° C. for the lower carbon percentages and 840° C. for the higher carbon percentages, followed by a quenching operation, will prove highly beneficial as a means of improving the strength and structural condition after mechanical working operations have been carried out on the material. Quenching may be in water or oil, according to the properties desired. Care should be taken not to go much above the temperatures mentioned, unless specially advised to do so by the makers of the steel, as this will probably result in abnormal distortion, as well as the formation of excessive scale on the surface of the steel. On the other hand, temperatures below those given will fail to bring about the fully refined grain structure aimed at.

Except with the mildest of these steels, i.e. those below 0·2 per cent carbon and less than 0·6 per cent manganese, it is necessary to temper after quenching, for the same reason as with other steels, i.e. improving ductility and toughness, and reducing any brittleness. The best tempering temperature is within the range 450°–550° C.

When the quenched steel is of large mass, particularly if it has been quenched in oil, as is desirable, it is not absolutely essential to temper, as the steel will probably possess a sufficient measure of toughness for most purposes. Nevertheless, there is still considerable advantage to be derived from the operation, as not only will distortion be minimized, but internal stresses will be relieved, although strength is thereby maintained.

A further type of heat-treatment given to these steels when necessary is *process annealing* or normalizing.* This is particularly given to steel strip and sheets that have been subjected to heavy mechanical working processes, and need a further treatment between the stages of working. The object of this treatment is to facilitate the carrying out of these further operations by putting the steel into a suitable plastic condition in which internal strains are minimized and physical properties improved.

The temperature at which this normalizing is carried out is not standardized, but a good *average* process normalizing temperature for this class of steel is 880° C. The main point is that the operation should be carried out just above the critical range of the particular steel. Much will also depend on the steel's structure and state and the type of mechanical working to which it has been subjected. In general, the heavier the working and the higher the temperature at which it has been completed, the higher the normalizing temperature, but, with this exception, low normalizing temperatures are generally advisable because oxidation is less and grain structure superior. The heating should be as quick as possible, and the duration at the normalizing temperature brief. Cooling is usually in air and not in the furnace, though where *bright annealing* (annealing in which the steel is required entirely free from scale and with as bright a surface

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* With this class of steel, normalizing and annealing cannot be placed in separate water-tight compartments.

as possible) is essential, as with strip, the steel may be heated and left to cool in a furnace with efficient atmosphere control.

Many of the steels in group (*a*), in the form either of bars or of plates, are used in the *as-rolled* or normalized condition. Thus, for welded containing-vessels, boilers, and many riveted or welded structures, no heat-treatment after rolling is required, but steels containing 0·18 to 0·25 per cent of carbon, intended for such purposes as shafts, axles, automobile forgings, etc., should always be normalized or fully heat-treated by quenching and tempering before being finally machined. Otherwise, distortion may occur during machining in consequence of the release of unequally distributed rolling or forging stresses and strains.

Again, in plate and sheet form, steels of this class are often cold-pressed into intricate forms, as in the manufacture of motor-vehicle wheels, chassis frames, brake-drums, etc., where a preliminary annealing or normalizing treatment becomes an essential operation in order that distortion and even cracking or splitting during pressing may be avoided.

Group (*b*) are usually known as *medium carbon steels*, and can be employed for a varied range of parts and purposes. Their special features are plasticity, machinability, weldability, and, in particular, a greater response to heat-treatment than steels of group (*a*). They are widely used for constructional work and parts of machines not too severely stressed. Having higher carbon contents, they are stronger and harder, for a given treatment, than the steels of the (*a*) group. Typical uses include marine-shaftings, axles, connecting and piston rods, couplings, crankshafts, washers, steering arms, shafts and rotors in electrical and general engineering, lugs, hot-pressed frames, weldless steel tubes, etc. In practically all these cases, the steel must be subjected to a normalizing or quenching and tempering treatment before being placed into service.

The quenching range for these steels lies within 850–880° C., *the higher temperature corresponding with the lower carbon percentages, and the lower temperature with the higher carbon.* The higher temperature is also adopted when the mass of the piece is considerable, because it quickens the fall in temperature throughout the critical range, and so gives a more satisfactory grain structure.

Softening of these steels should be carried out at 800–830° C., but it is important for maximum softness that cooling should be slow, for which reason it should take place either in the annealing furnace, in lime, or in ashes. Sub-critical annealing or softening at a temperature between 680° and 700° C. may become necessary when the steel is later subjected to severe cold-work by drawing or deep-pressing. Some indication of the influence of such treatments is given in Table XXIII.

The third (*c*) group have no particular name, but have a wide range of uses. Their particular features are relatively high strength, fair machinability, and ductility. Typical applications include axles, crankpins, crankshafts, rotor-shafts, etc. They are particularly suitable for forged parts. With steels in this class, with normal manganese contents, the tensile strengths in the normalized condition are apparently directly related to their carbon contents. Thus, in the normalized state a 0·35 per cent carbon steel will usually have a tensile strength of about 35 tons/sq. in. and a 0·45 per cent carbon steel a tensile strength of about 45 tons/sq. in.

Being responsive to heat-treatment, they need more attention than those of the previous two groups. In the first place, the mass of the piece makes a considerable difference to heat-treatment by oil- or water-quenching. Small sections need rather different procedure from large. With these smaller pieces the temperature range is between 830° and 870° C., the exact temperature being governed to some extent by the grain size of the steel in its original state and by its actual chemical composition. Quenching may be in either oil or water, but must be followed by tempering for stress relief, ductility-improvement, and easier machining.

The heavier pieces of large cross-section will be heat-treated as a rule only when the mechanical properties required in the finished part demand it, since to heat-treat large pieces or parts (e.g. heavy forged shafts) is a costly business, and is only to be carried out when economically justified.

Extreme skill on the part of the operator is called for in dealing with these heavy sections, particularly if, as is sometimes the case, faulty mechanical working has presented him with a mass of steel in a highly overstrained or overheated condition. Hence, he should as a first step acquaint himself with what has been done to the steel before it reaches him. This means that he should know (*a*) the composition of the steel; (*b*) the purpose for which it is intended; (*c*) the type of mechanical working to which it has been subjected; (*d*) the approximate temperature to

TABLE XXIII

Carbon %	Silicon %	Sulphur %	Phosphorus %	Manganese %	Treatment	Typical Tests		
						Tensile Strength tons sq. in.	Elongation (4 in.) %	Izod Imp. ft.-lb.
0·25/0·30	0·20 max.	0·05 max.	0·05 max.	0·4/0·7	Normalized 870° C.	34·0	28	—
,,	,,	,,	,,	,,	Annealed 870° C.	32·0	32	—
,,	,,	,,	,,	,,	Spheroidized 680° C.	27·5	35	—
0·30/0·35	,,	,,	,,	,,	Normalized 860° C.	35·4	26	—
,,	,,	,,	,,	,,	Spheroidized 680° C.	29·3	32	—
0·25/0·35	,,	,,	,,	,,	O.Q. or W.Q. 880° C. Tempered below 660° C.	35/45	25 min.	30 min.
0·32	—	—	—	0·7	O.Q. 870° C. Tempered 650° C.	36·0	34	90, 91, 92

TABLE XXIV

Carbon	Manganese	Treatment	Tensile Strength	Elongation (4 in.)
0·35/0·45	0·40/0·80	Annealed 850° C.	36·8 tons/sq. in.	25%
,,	,,	Spheroidized 680° C.	30·2 tons/sq. in.	30%

which it was heated for this working; (*e*) the holding or soaking period; (*f*) the approximate finishing temperature; and (*g*) the rate and method of cooling.

Armed with these facts, he will, from knowledge and experience, be able to gauge to some extent the structural condition of the material with which he is called upon to deal.

For masses of cross-section ranging from 8–18 in. it will probably be found that a heating to 850° C. will, *on average*, prove satisfactory if followed by quenching in water, but as with other carbon steels, it may be necessary to heat to a rather higher temperature for steels where the final hot-working temperatures have been too high.

Some of these large masses are treated by heating to 900° C. and cooling in either oil, water, or air. There is little need to fear any ill effects from hardening by water-quenching, so long as the steel is clean and its surface is good, and the quenching has been carefully carried out at correct temperature, when the steel should be in stress-free condition. After quenching, a tempering for toughness is necessary, and the range of temperature for this operation is 500°–650° C.

Plates and sheets containing between 0·35 and 0·45 per cent carbon can be cold-pressed if in a satisfactory structural condition. The best treatment is a sub-critical annealing, or spheroidizing, at about 680° C., although orthodox annealing at 850° C. may suffice if the amount of cold-deformation at each operation is not too severe. These pressings are used for such purposes as high-tensile brake-drums for heavy motor vehicles and brake-drum liners for aircraft, etc. Typical mechanical test values before pressing are given in Table XXIV.

The group (*d*) steels, having higher carbon contents, are necessarily harder and less tough than those of the three previous groups. For this reason, the operation of quenching heavy sections becomes fraught with danger due to abnormal distortion and cracking, which may be internal and only reveal themselves in service, when a possibly disastrous failure occurs. For this reason, it is seldom attempted in large sections, even though, if successful, it might be attended with beneficial results in the way of better mechanical properties.

Small sections, however, such as are used for pliers, screwdrivers, spanners, dies, gears, small diameter bars, etc., are another matter. These respond readily to hardening and tempering, and can be water-quenched if care is employed. The carbon cutting tool steels and the carbon spring steels are dealt with elsewhere.

If the pieces have been forged, an annealing operation is advantageous because it relieves forging strains. A secondary advantage is their softening sufficiently to facilitate the removal of *burr* or *fash* (surplus material or ragged edges) by trimming with suitable tools. Machinability is also improved. The annealing temperatures vary with different steels, but lie, *on average*, between 810° C. and 850° C., the steel being allowed to cool down in the furnace to about 600° C. Sometimes normalizing over the same temperature range is adopted instead of annealing, but annealing is better if full softening is desired. Hardening temperatures vary with the carbon and manganese contents, but the range lies between 800° and 850° C. Hardening is in either water, brine, caustic soda solution, or oil, according to the type of tool and the degree of danger of distortion. A stress-relieving tempering operation is generally adopted for certain hand tools, to eliminate any possibility of breakdown in use as a result of unequally distributed quenching strains. This is carried out between 150° and 250° C. according to the type of tool. Steel containing between 0·50 and 0·60 per cent carbon is used for laminated railway and automobile springs. In the "as-rolled" condition, this steel possesses a tensile strength between 45 and 55 tons per sq. in. with more than 12 per cent elongation on 8 in., but for springs it is hardened by quenching in oil or water from 810°–830° C., followed by tempering at temperatures between 350° and 450° C. For this purpose the most important test is the *camber* test, i.e. the ability of the steel to spring back after being bent. (Steels containing about 0·60 per cent carbon are used for hot saws, usually in the hot-rolled or normalized condition.)

CHAPTER XVIII

"Carbon" Steel Castings

CARBON steels used for castings usually contain between 0·25 and 0·35 per cent of carbon, although the dynamo-magnetic, electrical steel castings are much softer than this, approximating to iron, their carbon contents being as low as 0·1–0·15 per cent.

Heat-treatment of steel castings was extremely primitive before the war of 1914–18. It was not uncommon for a cast part to be heated to a "red heat" in a furnace and allowed to cool, after which all the treatment necessary had, it was believed, been carried out. Many castings were not even given this modicum of attention, and were put to use just as they came from the *fettling* (cleaning) or machine shops.

The position to-day is much improved. In every steel foundry of repute a heat-treatment department exists for the express purpose of scientifically giving to the castings their correct treatments.

The first essential is a furnace capable of yielding a uniform temperature readily controllable. On the whole, a furnace fired by producer gas is perhaps the most suitable, because the gas and air can be regulated by the operator in such a way as to minimize oxidation and the scaling to which it gives rise, while the furnace temperature can be kept constant when the required degree of heat is attained. The furnace should be equipped with a recording pyrometer, in order that a full record of the furnace temperature from lighting-up to cooling down may be available. In this way the operator is enabled to determine the length of the heating period during which the correct temperature has been held and the rate of cooling of the steel.

Heat-treatment of steel castings covers annealing, normalizing, or quenching and tempering.

Annealing. The first step is to raise the castings to a temperature at least 50° C. above the Ac_3 point of the steel as indicated in the iron carbide diagram, Fig. 75, where these temperatures are shown by the dotted line. The castings are heated at the appropriate temperature for several hours to ensure that the heat shall have thoroughly permeated their mass, the exact soaking period being decided by the dimensions of the piece. As in most heat-treatment operations, a soaking period of one hour per inch of cross-section is usually sufficient. Cooling down in the furnace usually follows.

It is vital that the heating should be uniform and the heating rate should not be too rapid, particularly where the castings are large, as otherwise the heat has not time to permeate the entire mass of the casting.

The object of this annealing is to remove the strains set up in the casting as it cools down to room temperatures from the molten to the solid condition. Most castings contain differences of section, i.e. they have thicker and thinner parts. The thin parts will obviously cool more rapidly than the thick, and as cooling involves shrinkage or contraction, there will be severe strain where the metal in the thinner portions tries, as it contracts, to pull away from the more plastic metal in the thicker portions. These strains may be so great in some castings that, in any event, the pieces would have to be put into a furnace before they had cooled down to red heat, or else cracks would occur and destroy the usefulness of the parts concerned.

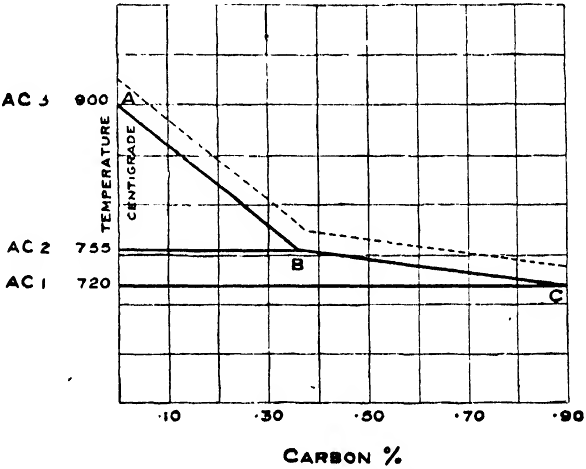

Fig. 75. Iron Carbide Diagram

Another effect of annealing is the refinement of the grain structure. This is extremely coarse when a casting comes from the mould, and the refinement gives a better combination of tensile strength and ductility.

The annealing temperature should not be higher than the limit indicated. As a guide to the period of temperature maintenance, one hour per inch of the heaviest section may be taken as a good average figure, but in no instance should the time be prolonged more than 12 hours.

Normalizing. In this, the casting is first annealed as described above, then raised to a temperature 50° C. above the Ac_3 point (Fig. 75) (usually about 850° C.) and cooled in air. This treatment gives a finer grain structure than annealing, and also somewhat increases the tensile strength and the yield point, the elongation per cent remaining practically the same, except where the castings are made from a material having a fairly high tensile strength, when the elongation per cent is lessened. Impact resistance and reduction of area per cent are also improved.

Normalizing is not advisable if there is considerable variation in the thickness of the metal in different parts of the casting, owing to the danger of cracking. The steel is not quite so soft after normalizing as after annealing, but as against this there is a much shorter tie-up of furnaces, since the steel is taken out for cooling.

Quenching and Tempering. This method is not often adopted, because the drastic cooling action combined with the variation in section of the castings causes great danger of cracking, or, perhaps, of undue distortion. Some metallurgists argue, however, that if the castings are well designed and have been properly annealed there is no undue risk of cracking, and point to the fact that, in some foundries, steel castings are quenched commercially without bad results. There are, however, in any event, certain castings in which the section is virtually uniform throughout, and these can be treated successfully in this way. The annealed casting is heated up to approximately 50° C. above the Ac_3 point (Fig. 75) (usually between 885° C. for lowest and 855° C. for highest carbon contents) and quenched in either water or oil. Which medium is chosen depends on the composition of the steel, cold water being used for the lower carbon and warm water (50° C.) or oil for the higher carbon contents. The casting is then reheated to some temperature below the Ac_1 point (Fig. 75) (usually between 450 and 675° C.), and allowed to cool in air. The purpose of the quenching and tempering treatment is to raise the ultimate strength of the casting and also its yield point and elastic limit. (These terms are defined in *The Structure of Steel.*) Resistance to shock is also improved, as indicated by the Izod impact test. The tempering temperature should be higher in proportion as ductility and toughness are preferred to strength and hardness.

Figs. 76, 77, 78, and 79 show photomicrographs of a piece of steel casting in the "as cast," annealed, normalized, and quenched and tempered conditions. Typical tests from a mild steel casting are also shown in Table XXV.

FIG. 76. STRUCTURE AS CAST 200 MAG. CARBON 0·22

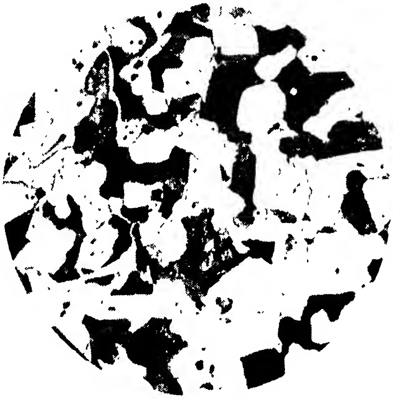

FIG. 77. ANNEALED AT 920° C. 100 MAG.

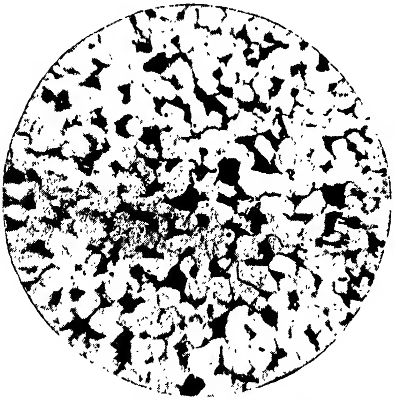

FIG. 78. NORMALIZED AT 920° C. 200 MAG.

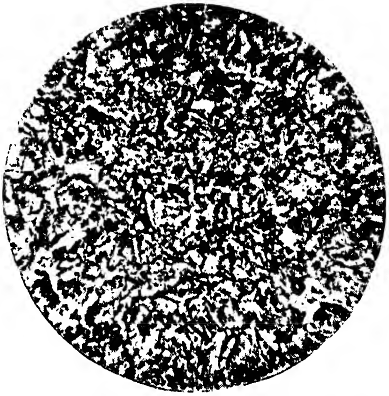

FIG. 79. QUENCHED IN WATER AT 920° C., REHEATED TO 600° C. AND COOLED IN AIR

It will be apparent that quenching and tempering greatly improve the tensile properties, but it would be unwise and possibly even disastrous to treat the majority of steel castings in this way.

TABLE XXV

Mild Steel Casting	Annealed	Normalized	Quenched in Water 920° C. Tempered 600° C.
Yield point tons/sq. in.	14·5	16·5	22·2
Ultimate stress tons/sq. in.	29·2	31·4	33·8
Elongation per cent	29·0	27·0	26·0
Reduction of area per cent	45·4	44·0	46·4

Each casting has to be considered in the light of its mass and form. Tempering should follow directly on quenching. Because of this there may still be some heat left in the castings, and if so, they should not be inserted into a dead cold furnace, but into one preheated to about the same temperature as that of the warm castings.

The castings should be held at the proper temperature, i.e. "soaked," for at least 15 min. per inch of diameter or thickness for quenching, and a minimum of *two hours* per inch of section for tempering.

A treatment sometimes used, but not to be attempted unless the operator is highly skilled, knows exactly what he is doing and why, and can exercise rigid control, is *differential quenching*, in which only a portion or portions of the casting are quenched by means of immersion or a controlled jet of water directed on to the particular area to be quenched. The remainder of the casting is shielded from the quenching medium. Tempering generally follows. There is another method in which the same, or a similar, effect is achieved by differential heating by means of an oxy-acetylene flame directed on to the parts required hard, after which the casting is quenched. The reader will learn more of this process from Chapter XXXV.

General. Certain points need attention in heat-treating steel castings. Since uniform heating is highly desirable, great advantage will be derived from careful charging of the furnace to ensure this. The usual practice is to rest the castings on racks or supports, so that there is a continuous circulation of the hot furnace gases about them. If the castings were placed on the hearth itself or straight on to the bogie bottom (a *bogie* is a wheeled truck on to which the castings are loaded before being wheeled into the furnace), this free circulation would be impeded.

It is advisable to let the castings of greater mass occupy the outer edge of the load, the smaller pieces being in the centre. Then, if the heavy castings are heated evenly through, it is certain that the smaller ones in the middle will also be heated through, whereas the reverse would not necessarily occur if their respective positions were changed. Moreover, the heavy castings prevent the small from becoming overheated. Where the charge is of uniformly sized pieces, the outer layers must not be left too long or they may be overheated.

Castings of large mass obviously need a longer heating period than the smaller parts, and it is advisable to load them into the heat-treatment furnace as soon as the moulds are broken open. This applies also to castings of highly intricate form.

Castings should not be withdrawn from the annealing furnace before they have fallen to a temperature below 500° C.

A casting will sometimes emerge from the mould slightly warped or bent, but not so badly as to render it unusable. By a straightening operation it can be restored to its original form. This is done either by catching the casting before it has cooled down too far and is still somewhere between 360° and 480° C., or, preferably, by heating it to some temperature within this range and then carrying out the straightening operation.

Large or thick castings are sometimes *step annealed.* This means that instead of bringing the casting straight to the full annealing temperature, it is first raised to an intermediate point, and held long enough at this point for uniform heating to be ensured. The temperature is then raised, and again held. This takes place as many times as has previously been laid down as desirable. Its object is, of course, to ensure perfectly uniform heating of the entire casting.

When castings have been subjected to heavy machining operations, it may be beneficial to heat them gradually and evenly to 450°–600° C., followed by cooling in the air. The machining sets up stresses in the casting, and the treatment outlined relieves these.

It is injudicious to heat-treat simultaneously in one and the same furnace castings of the differing carbon groups as classified in the preceding chapter, as their carbon contents call for different temperatures.

A good plan is to heat up simultaneously with the charge, and intermingle freely with it, test pieces of identical composition and of diameter or cross-section equal to the largest diameter or cross-section of the charge. This does not, of course, apply to the very heavy sections. When the castings are withdrawn from the furnace, these test pieces, which should be so located that they represent all layers or areas of the charge, are broken for visual and microscopic examination of the structure. This examination will reveal the grain structure, and show whether the temperature has been uniformly distributed over the entire mass of the castings.

CHAPTER XIX

Carbon Spring Steels

THERE are many and varied types of springs and it would be difficult to detail them individually. The object of this chapter is to present an account of the general heat-treatments applicable to the four broad groups classified below.

SMALL FLAT SPRINGS

Cold-formed from carbon steel plates not exceeding $\frac{3}{16}$ in. in thickness and of composition—

TABLE XXVI

Steel No.	Average Carbon Contents	Average Manganese Contents and Method of Hardening
1	0·5%	1·0% Water
2	0·6%	0·9% ”
3	0·65%	0·8% Oil
4	0·85%	0·7% ”
5	1·0 %	0·5% ”

The springs may be produced from cold-rolled, hardened and tempered, or hot-rolled and normalized, material.

The usual quenching temperatures are—

800° to 830° C. for Steels Nos. 1 and 2.
780° to 810° C. for Steels Nos. 3 and 4.
780° to 800° C. for Steel No. 5.

The quenching medium for Steels Nos. 1 and 2 is water, and oil, under circulation, for Steels Nos. 3, 4, 5.

The usual tempering temperatures are—

370° to 450° C. for Steels Nos. 1 and 2.
425° to 450° C. for Steels Nos. 3 and 4.
350° to 450° C. for Steel No. 5.

It is important to bear in mind that tempering must be maintained for a sufficient period of time to allow of complete absorption of the heat at the specified temperature. No special method of cooling is then needed.

SMALL SPIRAL SPRINGS

These are produced from "round" wire or rod having the following compositions—

TABLE XXVII

Steel No.	Average Carbon per cent	Average Manganese per cent
1	0·5	1·0
2	0·6	0·9
3	0·65	0·8
4	0·85	0·7
5	0·9	0·6
6	1·0	0·5

The springs may be produced from cold-worked, hard-drawn, oil-hardened and tempered, or annealed wire. It is usual to quench only after normalizing. Cold-worked, hard-drawn and oil-hardened and tempered wire is, after coiling, given a low temperature treatment designed to eliminate strains set up during the process of coiling, and also to improve the elastic properties of the steel. The low temperature treatment consists of heating the springs to between 150° and 400° C. (the precise temperature being determined by the composition of the material).

The usual quenching temperatures are—

800° to 830° C. for Steels Nos. 1 and 2 (in water).
780° to 810° C. for Steel No. 3 (in water).
780° to 800° C. for Steels Nos. 4, 5 and 6 (in oil).

The usual tempering-temperature ranges are—

235° to 350° C. for Steels Nos. 1, 2, 3, and 4.
165° to 190° C. for Steel No. 5.
250° to 350° C. for Steel No. 6.

If the wire or rod is in the annealed condition the tempering-temperature range may be—

370° to 450° C. for Steels Nos. 2 and 3.
425° to 450° C. for Steel No. 4.
425° to 480° C. for Steels Nos. 5 and 6.

As with other types of springs, it is important to soak the steel at the tempering-temperature for a sufficiently long period of time.

LARGE SPIRAL SPRINGS

Two types of steel are in general use in this country.

TABLE XXVIII

Steel No.	Carbon	Silicon	Manganese
1	0·9 to 1·1%	0·3% max.	0·45 to 0·70%
2	0·5 to 0·6%	1·5 to 2·0%	0·6 to 1%

The steel is heated not more than 900° C., coiled, and cooled in air.

The coiled springs are then reheated for quenching as follows—

850° to 875° C. for Steel No. 1.
925° to 950° C. for Steel No. 2.

The heating time for coiling and quenching should be calculated on one hour per inch of thickness, the quenching medium, in all instances, being oil under circulation.

The tempering temperatures for both steels are generally between 450° and 500° C.

Here, also, it is important that tempering should be maintained for a sufficient period of time to permit complete absorption of the heat.

No special method of coiling is needed.

VOLUTE SPRINGS

The treatment recommended for large spiral springs is applicable also to the volute type of spring, although hardening direct from the coiling operation is quite common practice, and this procedure is also adopted for some types of large spiral springs.

LAMINATED SPRINGS FOR ROAD TRANSPORT VEHICLES

Only one class of steel is now in general use, having the following chemical composition—

TABLE XXIX

Carbon	Silicon	Manganese	Sulphur	Phosphorus
0·50–0·60	1·50–2·0	0·60–1·0	0·05 max.	0·05 max.

Any cold working of the material is avoided, and all mechanized operations such as cutting to length, centre-nibbing, spear-ending and tapering in plate-end thickness are carried out with the material heated to 900° C.

All centre holes are drilled, and the plates so prepared then annealed.

For bending to the required shape, the plates are heated to 900° to 950° C., bent to shape, and quenched in oil, freely circulated.

The tempering temperature range is 480° to 540° C., cooled in air to give a specified Brinell impression between 3·2 and 2·9 mm. diameter, i.e. a Brinell hardness number between 364 and 444 (= approx. 79/97 tons per sq. in. in tensile strength).

Laminated Springs for Railway Requirements

Four classes of steel are in general use, having the following compositions—

TABLE XXX

	Steel No.	Carbon	Silicon	Manganese	Sulphur and Phosphorus
Oil-hardening .	1	0·50–0·60	1·50—2·0	0·60–1·0	0·05 max.
Water-hardening	2	0·33–0·50	,,	,,	,,
Oil-hardening .	3	0·65–0·75	0·1 – 0·2	0·60–0·80	,,
Water-hardening	4	0·50–0·60	,,	,,	,,

Treatment of these steels is the same as for that of Table XXIX.

Steel No. 3, Carbon Steel Oil-hardened

For bending to the required shape, the plates are heated to 800° to 850° C., bent to shape, and quenched in oil, freely circulated.

The tempering temperature is between 450° and 550° C., cooled in air.

Steel No. 4

Mechanical operations may be carried out with the plates either as rolled or heated, depending on the width and thickness of the plates.

All centre holes are drilled.

For bending to the required shape the plates are heated to 800° to 850° C., bent to shape, and quenched in water, freely circulated.

The tempering temperature lies between 450° and 550° C., cooled in air.

CHAPTER XX

Carbon Tool Steels

In dealing with tool steels, we are confronted with a range of materials of relatively high carbon contents whose hardnesses are, all other things being equal, largely a reflection of their carbon contents. The highest carbon content usually corresponds to the hardest steel. There are, in the main, though individual steel manufacturers may vary in their grouping practice, six groups of these steels, and these groups are sometimes known as *tempers* and numbered or lettered to correspond with the particular carbon content. Thus, Edgar Allen & Co., Ltd., make six different tempers, Nos. 1 and up, the first or No. 1 being the highest in carbon.

(The interpretation of the term "temper" in regard to tool steels must not be confused with "tempering" as a heat-treatment operation.)

A point of importance is that these temper numbers or carbon groups, though an indication of *hardness*, are not necessarily an indication of *quality*. Most makers of carbon tool steels make several distinct qualities, some higher, some lower, in each of the temper groups. The carbon only confers final hardness. The quality is given by the raw materials used, the method of manufacture, and the degree of working to which they are subjected. One well-known firm makes no fewer than six distinct qualities in each of the six temper groups, making thirty-six different carbon tool steels. This will give some idea of the wide range of choice before the user.

The six main temper groups are as follows: (*a*) 0·6–0·75 per cent carbon; (*b*) 0·75–0·9 per cent carbon; (*c*) 0·9–1·05 per cent carbon; (*d*) 1·05–1·2 per cent carbon; (*e*) 1·2–1·35 per cent carbon; (*f*) 1·35 per cent carbon and upwards.

These different temper groups correspond in a measure to a different range of applications. The purposes or applications corresponding to each group are as follows.

Group (*a*) are for boilermakers' tools, hammers, miners' tools, stamping and pressing tools, hot forming or heading dies for short runs, hot impact work in general, concrete breakers, set screws, and rivet sets.

Group (*b*) are for cold chisels, hot sates, blacksmiths' tools, small cold shear blades, mining drill steel, flatteners, heavy screwing dies, etc.

Group (*c*) are suitable for cold chisels, hot shear blades, hot sates, taps, reamers, miners' drills, mill picks, threading and trimming dies.

Group (*d*) are suitable for large turning tools, cutters, taps, reamers, drills, punches, blanking tools, etc.

Group (*e*) are for lathe tools, drills, small cutters, cold chisels of small size, shear blades, pincers, and certain types of dies.

Group (*f*) are suitable for "extra-hard" planing, slotting, and turning tools, drills, brass and wood-cutting tools, razors, and small taps.

The first essential in heat-treating any of these steels is that heating should be gradual and uniform, and the heat should be given full opportunity to permeate the entire mass of the steel. This applies whether the heating be for forging or for hardening. If the heating is too rapid, too localized, or uneven, the steel will be severely strained by the unequal expansion of its parts, and will be extremely liable to crack when plunged into the quenching medium.

Carbon tool steels should be hardened at the lowest heat that will give the requisite hardness. In this connection the operator can tell a great deal from a study of the fractured ends of the heat-treated bars. If he first "nicks" a bar-end, hardens it, and breaks it off, the fractured surface may show either a coarse-grained scintillating appearance with bright specks, or a close, even-grained texture as uniform and fine as that of porcelain. The first condition is an indication that the steel has been overheated. The second shows that heating has been correctly carried out.

Another vital point is that forging should not be carried on after the steel has cooled down to a certain temperature (usually, with all these steels, about 700° C.). Otherwise the structure of the steel will be seriously impaired by the acute deformation produced, and the cutting edge of the eventual tool may break down in service. Thin sections should not be heated to so high a temperature as the thick. Moreover, if the amount of reduction is small, the lower end of the heating range should be adopted, the higher end being used for the heavier or swift reductions. After the steel has been forged, it is usual to place the tool in lime, mica, or ashes so that it will cool gradually.

For groups (*d*), (*e*), and (*f*) the steel should be heated to a cherry-red heat (850°–900° C.), and for groups (*a*), (*b*), and (*c*), to a bright red heat (900°–950° C.), after which it should be forged to shape and allowed to cool somewhat slowly in the manner above indicated.

The next operation is normalizing. This, for reasons amply outlined in the chapter on general principles, is essential, and must be carried out in advance of hardening in order to unify the grain structure and relieve the strains set up by forging. The steel should be so placed in the heating furnace that as much of the surface area as possible is exposed to the heat. (Groups (*a*) and (*b*) should be heated to 820°–840° C., groups (*c*) and (*d*) to 780°–800° C., and groups (*e*) and (*f*) to 760°–780° C.) Heating should be slow up to about 700° C. The normalizing temperature should be maintained long enough to allow of uniform permeation of the steel by the heat, after which cooling freely in air follows.

Some modifications in heating rates may be rendered necessary when the piece being normalized is of large section. As a rough guide, these large sections may be heated for 45–60 min. per inch of diameter or thickness, and it is advisable to maintain them at the normalizing temperature for about one-third to one-half of the heating time.

After normalizing, the steel must be returned to the furnace and reheated as evenly as possible. Groups (*a*) and (*b*) should be heated to 800°–820° C., a bright cherry-red heat; group (*c*) to 780°–800° C.; group (*d*) to 760°–780° C.; and groups (*e*) and (*f*) to 760°–780° C., a dull red heat. Water or brine quenching follows. The steel must not be permitted to cool to a temperature lower than the boiling point of water (100° C.) before tempering is begun. A quenched tool will not be softened by plunging it into a bath of boiling water, but its hardening strains will be uniformly distributed, with a lesser degree of cracking. Table XXXI gives an approximate relation between colour and temperature and will serve as a rough guide if a pyrometer is not available. Close control of hardening temperature is, however, vital to success.

Users of carbon tool steels in remote overseas districts have to overcome the disadvantage of operating at a great distance from the source of supply, possibly with native labour. In this connection, where the necessary skill in hardening may be

TABLE XXXI

HEAT-COLOUR TEMPERATURES

Colour	Centigrade	Fahrenheit
Just visible red . .	500–600°	932–1112°
Dull cherry-red . .	700–750°	1292–1382°
Cherry-red . . .	750–825°	1382–1517°
Bright cherry-red . .	825–875°	1517–1607°
Brightest red . . .	900–950°	1652–1742°
Orange	950–1000°	1742–1832°
Light orange . . .	1000–1050°	1832–1922°
Lemon	1100–1200°	2012–2192°
White	1200–1300°	2192–2372°

difficult to find, it may be useful to know that a water-hardening steel can be successfully hardened in oil if the tool made from it is of extremely thin section.

The lower temperatures in the ranges given above for the different carbon or temper groups should be used for hardening small or complicated sections. The higher temperatures are for such tools as cold heading and striking dies.

Tempering is designed, as previously indicated, to remove the excessive brittleness characteristic of a newly hardened tool, without reducing to any appreciable degree the hardness at the cutting edge. As a polished steel surface oxidizes when subjected to heat, and the colours caused by this oxidation vary according to the temperature, it is feasible to use them as a means of tempering. In this connection, however, the earlier notes on tempering should be carefully borne in mind. Table XXII (page 190) shows the approximate temperatures equivalent to the oxidation colours on the steel's surface.

The tool should be heated to just the hardening heat, and the cutting edge alone quenched in water. The tool is then rapidly withdrawn in order that enough heat shall remain in the body to reheat the part to be tempered. As soon as the portion to be tempered has attained the correct colour, the tool is once more quenched in water. Milling cutters and tools of similar type can first be hardened and afterwards warmed up on a plate until the required tint is attained, being then re-quenched in water.

A normal practice is to clean the surface of the portion to be tempered after the tool-hardening operation by rubbing it with a piece of sandstone, or an emery cloth, in order that the temper tint may be clearly perceptible.

Finally, we come to annealing or softening. For this, the steel should be heated slowly and evenly in a closed receptacle to some temperature between 700° and 800° C., enough time being allowed for the heat to permeate the steel thoroughly, after which slow cooling down in the furnace follows, although if the carbon content is less than 0·85 per cent, this slow cooling is not really necessary. The rate of cooling of the higher carbon steels should be not more than 25° C. per hour down to about 550° C., after which, if desired, the steel can be withdrawn from the annealing furnace and allowed to cool in the air. It should be noted that at least one to four hours *at the annealing temperature* will be required according to the cross-section, apart from the heating and cooling periods. This means that the steel will be particularly liable to oxidation or other injurious effects of the furnace atmosphere. It is for this reason that a closed receptacle is advised, but an alternative is bright annealing, in which the furnace atmosphere is rigidly controlled.

To conclude this chapter, we give below a number of specific advised heat-treatments for certain classes of tools.

Polished Drill Rods (Silver Steel). Forge at 950°–1000° C. If it is desired to harden in water, heat extremely slowly to 760°–780° C., a dull red heat, and plunge vertically into water, moving the steel slowly in the water until it is cold.

For hardening in oil, heat the steel gradually to 800°–820° C., a cherry-red heat, immerse it in linseed or olive oil, if these can be obtained, and move it about quickly until it is cold. There is nothing whatever to be gained by exceeding the temperatures given, and the most satisfactory temperature is the minimum at which the steel becomes glass hard. Little tempering is then necessary, although it is always advisable to temper at a temperature of about 200° C.

Mining Drill Shanks. These are usually made of steels with carbon contents of either 0·85–0·95 per cent, 0·70–0·75 per cent, or 0·65–0·70 per cent. The first two should have about 8 in. heated to temperatures between 800° and 825° C., and quenched in oil. With the 0·65–0·70 per cent carbon shank steel, the end of the shank should be heated to 810° C. and about 1 in. quenched in water for about 10–15 sec., being kept in motion, either vertically or horizontally, to avoid *straight line hardening.* If the tool is not moved in this way after immersion in the water, there may be a sharp line of demarcation between the hardened and the unhardened parts, which may fracture or break when later placed in service.

After hardening, the steel should be laid on the floor and allowed to cool normally to atmospheric temperatures.

If the steel has been taken out of service because of fatigue, it can be restored to a proper structural condition before hardening by normalizing. This comprises inserting the entire tool in a furnace, heating it to 825° C., removing it from the furnace at this temperature, and allowing it to cool down freely in the air. Precautions should be taken to ensure that the drill, while hot, is not thrown on to a wet floor; otherwise an unequally strained condition will result, and the steel may even be locally hardened. This would be extremely harmful and perhaps lead to premature fracture.

This treatment is, of course, useful only where fatigue has caused strains in the steel, but is useless if cracks have already occurred.

Mining Drill Cutting Bits. Heating these steels for forging is important, and the smith's skill will greatly affect the steel's later behaviour. Malleability increases and is progressive as temperature rises, but although the steels may be more easily shaped at high temperatures, these high temperatures may yield harmful results, particularly when the hot-working (forging) is *finished* at a high temperature.

Heat should be applied uniformly and slowly to ensure even penetration, and thus avoid forging cracks. The forging operation should be completed as near to the critical temperature range as possible, but care must be taken to avoid the setting up of strains by cold working the steel below the critical range. The success of these drills depends largely on the temperatures at which forging is carried out. The steel should be heated to an "orange" colour (1050° C.) and the bit forged to shape. To avoid cracks, the forging should not be continued below 750° C. The steel should then be allowed to cool normally, and not be quenched direct from the forging heat.

Decarburized skins occur in certain bits, e.g. the four-point cross-bit, but may be removed by a hot milling operation, in which the cutting edges are milled by a suitable milling cutter. This process ensures greater accuracy in form and size, and absence of forging cracks, while the cutting edges harden more keenly than those made by normal forging methods.

For this operation the forged cutting edges should be heated to a temperature not exceeding 800° C.

There has been considerable controversy concerning the best hardening temperatures for the cutting portions or bits of mining drill steel; and a good deal depends on the furnace equipment available. However, the temperatures yielding the best results can be fixed, and recommendations are given below.

TABLE XXXII

Carbon Percentage	Permissible Hardening Range (deg. C.)	Recommended Temperatures (deg. C.)
0·62–0·68	780–800° C.	780
0·72–0·78	770–790° C.	770
0·87–0·93	760–780° C.	760

It is generally recognized that the higher the temperature to which the cutting edge is heated, the greater the possibility of a coarse grain structure. This applies to all qualities, but steels high in carbon are much more susceptible to maltreatment and grain-growth. If the bit is hardened from too high a temperature, the drills often break or the cutting edges chip off.

Some smiths argue that a higher hardening temperature makes a harder bit. This may be true, but the increased grain size increases the brittleness and renders the drill more liable to chip in service.

As the stresses imposed on percussion drills are severe, the hardening temperatures must be kept within the limits mentioned. Fig. 80 shows the structure (martensitic) of drill steel in the hardened condition.

Varying Drill Steel Hardening Practices. Some mines use oil-fired furnaces for hardening. In these a firebrick slab in front of the combustion chamber contains a number of $\frac{7}{8}$ in. diameter holes through which come short flames. A drill bit is placed in position outside the furnace, a distance of $\frac{1}{2}$ in. from each hole, so that the flame coming through impinges on the cutting edge, raising it to the desired hardening temperature. Thus, only the cutting edge is heated above the change point, and the temperature gradually tapers off the farther one recedes from the cutting point.

When the bit has been in position long enough to have been raised to the hardening temperature, it is plunged into deep water well over the heated portion and allowed to cool right off. The result is an extremely hard cutting edge with a gradual diminution of hardness extending as far back as the heat originally penetrated.

The following claims are made for this method: (*a*) the drill cannot be overheated, because the flame is not hot enough to raise it above the hardening temperature; (*b*) the main heat is concentrated on the cutting edge, where the greatest hardness is required; (*c*) the danger of hardness going too far in from the cutting edge is averted.

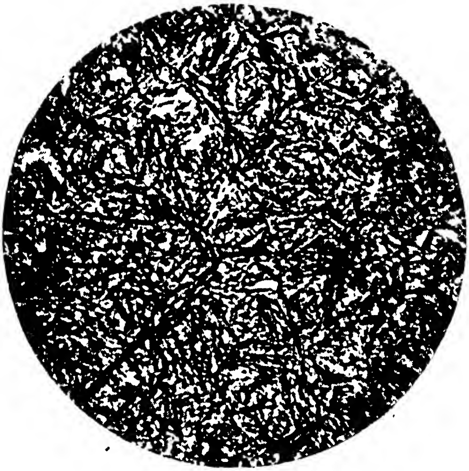

FIG. 80. MICROGRAPH OF MARTENSITIC STRUCTURE, SPECIMEN IN HARDENED CONDITION

It is claimed that the hardness penetrates to a depth of ¼ in. and that the extreme cutting edge gives the following Rockwell hardness values—

0·75 per cent carbon—65–66 Rockwell.

0·90 per cent carbon—66–67 Rockwell.

This procedure will yield excellent results if the furnace conditions are carefully and accurately controlled.

Other mines obtain good results by heating the cutting edge in a blacksmith's hearth as far behind the bit as the forging heat penetrated. The steel is dipped in water over the heated part and cooled off to a just visible dull red. The drill is then stood on a bar in the quenching tank so that the cutting edge is immersed to a depth of about $\frac{3}{8}$ in. It is left in this position to cool. The water must be circulated to maintain a constant temperature and prevent the formation of steam envelopes.

Control of the temperature of the water is essential. If it exceeds 60° C., there will be a rapid and progressive decline in the hardness of the bit and in the cutting efficiency of the drill.

The object of this treatment is to make the steel tough and of uniform structure behind the cutting edge, and to make the cutting edge hard enough. It is virtually a hardening and toughening treatment combined. This method is much better than heating the steel to the hardening heat and standing it directly on the bar in the quenching tank to cool off. In this latter method a much more pronounced line of demarcation between hardened and unhardened structures is formed in the steel. This line is obviously one of weakness.

CHAPTER XXI

Heat-treatment of Carbon Steel Gears

CARBON steel gears present a difficult problem to the heat-treater, for one thing because of the ease with which they will distort under treatment if carelessly handled, and the serious consequences from the mechanical point of view of such distortion. The risk of distortion increases in direct proportion to the percentage of carbon in the steel. In order that the reader may appreciate the relative amount of risk, a list of the carbon gear steels commonly used is given below.

TABLE XXXIII

Steel No.	Average Carbon per cent	Average Manganese per cent
1	0·4	0·75
2	0·45	0·75
3	0·45	0·5
4	0·5	0·75

This is not the only point. A higher carbon content usually means that even after treatment the steel will retain a measure of "brittleness" sufficient to reduce its ability to withstand shock, although this is, to a large extent, governed by the heat-treatment temperatures. In consequence, the tendency is to use alloy steels for gears wherever shock-resistance is particularly important, as in automobiles and aircraft.

The size of the gear exerts a great influence on its heat-treatment. This is so important that it can be regarded as a fairly safe rule to use the higher carbon steels for the larger gears, and the lower carbon steels for the smaller gears. Even then, however, we have not reached the end of the limiting factors, because the rate of cooling from the quenching temperature must also be taken into account. This should be slower for the higher carbon gears and faster for the lower carbon gears. Hence, the quenching medium for the 0·35 and 0·4 per cent carbon gear steels should be water or brine, which give rapid cooling. The 0·45 carbon, 0·50 manganese steel can be quenched in either water or oil, according to the design of the gear or the extent to which avoidance of distortion is important. The 0·45 carbon, 0·75 manganese steel, and the 0·5 carbon steel are best quenched in oil to give the necessary slower quenching rate.

In general, carbon steels are employed only for those gears where the mechanical and abrasion resisting properties required in service are not great, and where price is an important factor. Their lower price results, of course, from the absence of expensive alloys in their composition and from the relative ease with which they can be machined.

From these general considerations we may now turn to the specific operations.

Forging. The steel should be heated slowly and evenly in a furnace pyrometrically controlled to a temperature of 1150°–1280° C. This is a fairly wide temperature range. The higher heat is adopted when the amount of forging to be done on the piece is considerable. In general, as stated earlier, the forging temperature should be kept as low as possible consistent with the work to be done, and forging should in no circumstances be carried on after the temperature has fallen to about 800° C.

Gears of carbon steel are usually machine-forged (*upset*) because of the better fibre-direction obtained in the gear teeth (see *The Mechanical Working of Steel*), but they can, of course, be hammer- or drop-forged, if the service they are expected to give is not too exacting.

Normalizing. The object of this treatment is a refinement of the grain structure, which may be large or coarse as a result of the forging operations. It also relieves the internal stresses set up and consequently reduces the risk of later distortion when the gears are heat-treated, while at the same time making the steel easier to machine.

The steel should be heated to a temperature of 850°–870° C. and allowed to cool in the air.

Annealing. It is sometimes necessary that the steel should be even more easily machined than it is when normalized, perhaps because of cost. In these circumstances, a full annealing (or softening) treatment for machining, in advance of hardening, is required. This is achieved by well soaking the steel at a temperature of 850°–870° C. and cooling in the furnace.

Hardening. The hardening range is relatively wide, the steel being heated to temperatures between 830° and 850° C. The precise quenching temperature is governed by the carbon percentage, the dimensions and form of the piece or its section-thickness, and the cooling rate in the quenching medium. It is most essential that heating should be uniform and, if possible, in an atmosphere-controlled furnace to avoid oxidation, soft skin, or even case-hardening. One factor is most important, namely, the cooling rate during quenching. The more drastic the effect of the quenching medium, the lower should be the quenching temperature. All things being equal, it is generally advisable to adopt the lower rather than the higher quenching temperatures in order to minimize distortion.

Quenching Media. Because of the risk of distortion, the choice of a quenching medium for carbon steel gears assumes extreme importance. The general instructions for the various gear steels given above need some amplification. Oil is naturally the least drastic of the possible quenching media, apart from air, and is therefore advisable when distortion is most to be feared, e.g. when the gear form comprises thin sections or its carbon percentage is high. Because it is not so effective in producing much depth, and a high degree, of hardness, it is not to be recommended for larger gears. Quenching oils for gears should never be used in the cold state, but should be warmed within the temperature range 30°–50° C.

Most carbon steel gears are hardenable in water, and water only will produce the greatest depth and highest degree of hardness of which they are capable. This hardness is, however, often, if not invariably, attended by a greater risk of warping and cracking, so that gears with abrupt changes of section should not be water-quenched if it can be avoided. It may prove advantageous to warm the quenching water to reduce these risks, as this will lessen the drastic quenching action to some extent, but in no circumstances should the temperature of 50° C. be exceeded.

A special quenching medium designed to produce the maximum depth, degree, and consistency of hardness in the larger gears is a caustic soda solution containing at least 4 per cent caustic soda by weight. This solution should be used warm to produce the best results.

There is an advantage in using the time-water-quenching method for those gears whose forms or compositions do not enable them to be fully water-quenched. By this means, the interiors or *cores* of the gears are obtained in such a form that they offer the greatest resistance to shock and fatigue, i.e. the steels are in their toughest condition.

This method comprises an immersion of the gear in the quenching bath for a brief period only. The aim is to keep the central mass or core of the steel hot enough to reheat the cooled external portions to a temperature very nearly that of tempering. The gear is removed from the bath as soon as the right point is attained, and cooling in air follows until the internal heat has uniformly spread to the exterior, after which cooling by any other means may be adopted. This method demands extremely precise and accurate control of the period of immersion and the moment of withdrawal, and as a rule in the modern shops automatic machinery is employed both for deciding the correct time of immersion and for removing the gears.

Cyaniding as a means of treating carbon steel gears is dealt with in a later chapter.

Tempering. The objects of this process have already been precisely defined. The only points that need special mention here are the holding time at the tempering temperature, which may vary from one quarter to one hour, or more, according to the dimensions and form of the gear.

It is impossible to indicate a specific single tempering temperature for the reason that so many variables are concerned, e.g. the cooling rate, the degree of depth of hardness required in service, and the type of steel. Broadly, the tempering temperature for these gear steels lies within the range 200°–450° C. In those instances where an exceptionally high degree of final machinability is called for, it may be necessary to temper the gears at somewhat higher temperatures than 450° C., but this will be at the expense of surface hardness.

CHAPTER XXII

Heat-treatment of Carbon Forging Steel and Forgings

IN this chapter we deal first with certain matters of general heat-treatment importance. Although their explanation here refers specifically to forgings, they should be borne in mind in connection with other products subjected to heat-treatment.

The first point is the *mass effect.* Many forgings are of extremely large size, e.g. the propeller shafts of Atlantic liners, and this makes a thorough understanding of the mass effect essential. Let us suppose we have two steel parts of identical composition, but differing greatly in cross-section or mass, and we heat-treat (i.e. quench and temper or normalize) these in exactly the same way. It might be supposed, since they are of identical chemical composition, that the mechanical properties developed by the heat-treatment would be the same for both. In fact this is not so. There will actually be a considerable difference between the mechanical properties of the two steels after such identical treatment.

Why does this difference exist? In the first place, the greater the mass or cross-sectional area of the piece, the lower are its tensile strength and elastic limit for a given heat-treatment. As against this, the steel gains in ductility or plasticity, but not necessarily in resistance to impact. In general, the bigger the mass, the less easy it is to harden it right through. It is for this reason that many forgings are made of alloy steels, the alloys introduced increasing the steel's hardness (they vary greatly in ability to achieve this), and so counteracting to some extent the mass effect. If alloys are not used, then the heat-treatment of the part or piece must be modified to allow for the mass effect, and this usually takes the form of modified quenching and tempering temperatures.

Many carbon steel forgings are made from bars and billets up to and including 4 in. square or diameter. These bars have to be heated as a preliminary to the forging operation, and as the success of the forging may be marred by this preheating, we make no apology for dealing exhaustively with it here. Many variables are involved, all of which make close attention to the principles laid down expedient and beneficial.

The first point to be studied is the heating period, which should be just long enough to ensure that the central core of the billet or bar has just attained the requisite temperature. Table XXXIV gives a rough indication of the times usually allowed in practice, though a longer heating period is advised by many metallurgists.

TABLE XXXIV

Carbon per Cent	Bar, Diameter or Square	Minimum Time of Heating for Forging to Ensure that Centre of Bar is just at the Forging Temperature
0·1–0·5	½–3 in.	5–6 min. per inch of diameter or thickness
0·5 and up	3 in. and up	6 min. and up per inch of diameter or thickness

It is impossible to lay down hard and fast rules as to the heating period, because this is affected by the size, form, and mass of the forging, the type of steel used, and the particular forging process adopted. In certain instances, as with intricate or heavy forgings, it may be necessary to ascertain the heating period by means of the special arrangement of a thermo-couple pyrometer. The general principles given in earlier chapters should be noted, particularly the importance of keeping the bars separate during heating, and ensuring adequate size in the furnace heating chamber.

The troubles most often met with are overheating and burning. These cause *grain growth* or crystal enlargement in the steel, leading to lowered mechanical properties and an eventual failure in service. Overheating may be general, due to too high a temperature, or local, due to the flame's striking directly on to the steel at some point or points.

Some confusion exists in the minds of many operators in regard to *overheating* and *burning.*

In regard to burning, the mind at once imagines a charred or (to use the steelmaker's term) *crozzled* surface, and this is generally in accordance with fact, the charred or crozzled appearance being essentially the result of heating at very high temperatures in furnace atmospheres containing an excess of oxygen or air and, to a less extent, of sulphurous gases. At the same time, however, *burning may occur even in the atmosphere-controlled furnaces.*

Burning is essentially the partial fusion of the steel. In furnaces containing abundant oxygen, this results in the formation of oxides (mainly oxides of iron) or oxide-sulphide complexes, possessing relatively low fusion or melting temperatures. In furnaces having controlled atmospheres, burning may be accompanied by the actual melting of normal constituents of the steel. In either instance, burning in the technical sense is essentially a question of temperature, although it cannot be dissociated from the chemical affinity of iron for oxygen, hydrogen, and other gases.

When steel is burnt, the liquefied constituents move towards the crystal or grain boundaries, and since these constituents, either liquid or solid, possess little cohesion, the steel as a whole easily disintegrates when worked either hot or cold.

Overheating is often confused with burning but whereas burning inevitably results in overheating, the converse is not necessarily true. Truly burnt steels are useless, except as scrap for remelting, although if the effects are confined to the surface layers only, it may be possible to utilize the material, if in bar form, by machining it to a lesser diameter or cross-section than was originally intended. It is essential, however, that the burnt layers be completely removed; otherwise, the steel lacks ductility and, in particular, offers little or no resistance to impact or sudden shock. In addition, the steel may crack when hardened.

A steel having a burnt structure cannot be recovered or *restored* by heat-treatment. On the other hand, steels overheated by having been raised to excessively high temperatures can often be completely restored by a later reheating to, and cooling from, suitable and proper temperatures, which vary with their particular chemical compositions.

In short, the recrystallization that accompanies the reheating of any steel to a temperature just beyond its upper critical change point will completely refine its structure. When steel is burnt, however, normal heat-treatment temperatures such as those utilized in normalizing, annealing, or quenching and tempering, have little or no influence on the properties of the weak oxide, or oxide-sulphide, films existing between the crystal or grain boundaries, since these heat-treatment temperatures are generally far lower than those of the melting points of the constituents formed by burning along these crystal boundaries.

Thus it is of vital importance not to let the steel become overheated or burned.

We now come to forging temperatures. As regards heating periods, there are many variables involved. In general, higher carbon percentages usually necessitate lower forging temperatures, for the reason that with a rise in carbon content there is a rise in plasticity when the steel is heated to a given temperature, if its carbon content is less than 0·85 per cent. Although plasticity can be improved by raising the steel to higher temperatures, the danger of overheating is then greatly increased, and burning is, indeed, almost unavoidable unless not only a high degree of skill, but also the most modern pyrometric and controlling equipment, are available. Hence, the tendency is to employ lower forging temperatures at the expense of somewhat higher working cost.

Another trouble experienced in heating steel for forging is decarburization or the formation of soft skins. This is especially liable to occur in furnaces without controlled atmosphere, when the temperature exceeds 1000° C. Hence, every care should be taken to avoid the conditions likely to cause it, as otherwise the steel will not respond adequately to proper heat-treatment, and will not possess the mechanical properties desired. Oxidation must be minimized. Decarburization may occur without oxidation or scale formation, but oxidation is inevitably associated with decarburization. Atmosphere control in the furnace is the most effective remedy, while excessive temperature is always liable to cause excessive scaling. A good plan to minimize scale on the surfaces of the larger forgings is to preheat the steel to a temperature not exceeding about 760° C. and so minimize the heating period at the higher temperature.

It is never good practice to continue forging below its own proper temperature, varying with the steel's quality, as the steel rapidly loses plasticity with fall in temperature, and may even fracture, or burst, or damage the forging tools, if it is too cold, or an inadequate forming result may be obtained from the effort expended. In any event, the forging operations will have left excessive and possibly unequally distributed strains and, perhaps, an unsatisfactory grain structure in the steel. This makes a normalizing operation advisable as a means of improving the structural condition, relieving strains, and improving the machinability of the material. The finishing forging temperature should not be below about 750° C.

Certain forgings, particularly those of high carbon percentage or intricate form, are liable to distort during cooling down. To prevent this, it is a sound plan to bury them in ashes or lime so as to slow down their cooling rates. Alternatively, they may be inserted in a previously heated furnace and allowed to cool down inside it. Slow cooling is also advisable for forgings of large diameter or cross-section, and if the piece exceeds 3 in. in diameter for a considerable part of its length (say 6 in. or over) cooling should be retarded until it is proceeding less rapidly than would be the case if the forging were left to cool down in the air in the normal manner.

The heating period will need to be more protracted in order to ensure thorough and gradual heat penetration, and to eliminate any possibility of internal cracks. It is not inappropriate here to note the cause of these cracks. When a large piece of steel is heated, the surface layers, obviously, are the first to receive the heat. Heat causes expansion and these surface layers thus expand.

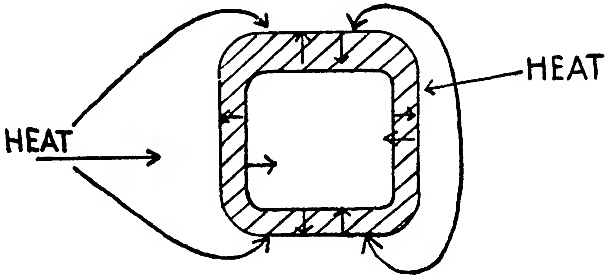

Fig. 81

Fig. 81 shows by arrows the impingement of the heat. The shaded area represents the surface layers in this state of expansion, and the arrows in this layer show the directions in which expansion is attempted. It will be seen that the inward expansion is inevitably checked by the harder central mass, whereas outward expansion meets with no opposition, at all events on three sides, the fourth side resting on the furnace floor or support. In consequence, expansion takes place outwards rather than inwards, and if too rapid as a result of too swift a heating rate, results in the state of affairs represented by Fig. 82, the severe pull on all sides causing an internal crack or *clink.*

The precise heating period will be determined by the mass of the forging and the temperature of the furnace at the beginning of heating.

If the forging ingots are cold when loaded into the heating furnace, a good general rule is to allow 1 hr. per inch of cross-section when the steel has reached the furnace temperature, after which soaking should be carried on for about ¼ hr. per inch. Alloy-steel forging ingots do not conduct heat so readily, and must therefore be given a more extended heating and soaking period.

Annealing, or the slow cooling, of large forgings of alloy steels after completion of the forging is always expedient, and sometimes vital, and the temperature of the piece should not be allowed to fall too sharply until it has cooled below 300° C., in order to prevent cracks, flakes, or other defects.

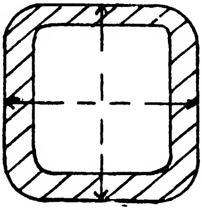

FIG. 82

Sometimes only a part of a large forging ingot is used at a time, and it is desired to keep the rest for another occasion. In such instances, it is advisable either to give the ingot an annealing treatment or to allow it to cool slowly by covering it with ashes. Otherwise, there is the risk that the ingot or the blooms produced from it will crack during cooling, and these cracks are then further developed during later forging or rolling.

More than one annealing operation may be needed if the final forging operations are carried out at a high temperature, each annealing being at a lower temperature than its predecessor. This is necessary to produce the best type of structural condition, and is better than an unduly protracted single anneal.

If the final annealing of these larger forgings does not suffice to give the mechanical properties desired, it may be necessary to normalize, and even to quench and temper after normalizing. Much will depend on the forging dimensions, form and steel, and on the final properties required. Tempering is carried out at temperatures considerably below the critical range. Normalizing followed by tempering usually raises the maximum stress to a minor degree, but increases the elastic limit and yield point and slightly lowers the ductility. A quench and temper treatment after normalizing is not really to be recommended unless the user demands the rather superior physical properties this treatment will give, and is prepared to risk the cracking and distortion that may result from so severe a treatment. As a rule, solid forgings over 10 in. in diameter or square or hollow forgings with a wall thickness above 8 in. are not treated in this way, though it is nevertheless feasible given the utmost care and the proper equipment.

CHAPTER XXIII

Heat-treatment of Alloy Steel Gears and Springs

THE word "gear" covers a multitude of dimensions, from the huge gears for driving a rolling mill or tubular grinding mill to the tiny toothed wheels of a wristlet watch. In this chapter, however, we confine ourselves to those *uncarburized* gears used in the construction of automobiles and aircraft. The heat-treatment of the larger gears will be found by implication in the chapters relating to forgings and castings, while the steels for case-carburized gears will be found in the later chapter on case-hardening.

The number of different alloy steels used for gears is unnecessarily large, but in Table XXXV is given a list of those referred to in these notes, with their average compositions. This includes both British and American specifications.

TABLE XXXV

Type of Steel	Carbon % (approx.)	Manganese % (approx.)	Chromium % (approx.)	Vanadium % (approx.)	Nickel % (approx.)	Molybdenum % (approx.)	Tungsten % (approx.)
A 3% Nickel	0·3	0·5	—	-	3·0	—	—
B 3½% Nickel	0·45	0·75	—	—	3·5	—	—
C Nickel Chromium 1	0·4	0·75	0·6	—	1·25	—	—
D Nickel Chromium 2	0·5	0·75	0·6	—	1·25	—	—
E Nickel Chromium 3	0·35	0·45	1·05	—	1·75	—	—
F Nickel Chromium 4	0·3	0·6	0·75	—	3·35	—	—
G Nickel Chromium 5	0·3	0·5	1·25	—	4·25	—	—
H Chromium Molybdenum	0·45	0·75	0·95	—	—	0·2	—
I Nickel Molybdenum	0·4	0·65	—	—	1·8	0·25	—
J Chromium 1	0·4	0·75	0·95	—	—	—	—
K Chromium Vanadium 1	0·5	0·7	1·0	0·2	—	—	-
L Chromium Vanadium 2	0·4	0·75	1·0	0·15	—	—	—
M Nickel Chromium Tungsten	0·35	0·4	1·25	—	1·9	—	0·45
N Nickel Chromium Molybdenum	0·25/0·35	0·4/0·8	0·5/1·0	—	2·0/3·0	0·4/0·7	—

It would, of course, be possible to extend this list almost indefinitely by the incorporation of innumerable special and "freak" compositions, but most of the familiar pre-war gear steels will be found in the table above.

There is no great difficulty in forging the steels of these varied compositions. Most of them respond satisfactorily to mechanical hot-working between temperatures of 1150 and 1250° C., with the exception of the nickel-chromium steel 4, for which 1100° to 1200° C. is advised; nevertheless, with most of the other alloy steels strict control of forging and rolling temperatures is most important; and, for this reason, pyrometric control should be exercised wherever possible. With none of these steels should mechanical working be continued at temperatures much lower than 900° C.

The mechanical working, whether by hammer or machine-forging processes, will almost inevitably set up unequally distributed strains in the steel. (In this connection, the reader may refer with advantage to the notes on forging gears in *The Mechanical Working of Steel.*) These strains must be equalized or removed by a softening process.

Many of these steels possess pronounced air-hardening properties when heated and cooled, even in still air, from temperatures above their lower critical points or temperatures, e.g. steels F, G, H, I, J, K, L, M, and N. To soften these steels after forging or rolling so that they may be satisfactorily machined, reheating to temperatures between 660° and 690° C. is usually employed, i.e. the steels are "sub-critically" annealed (see *The Structure of Steel*).

For other steels in Table XXXV, i.e. steels A, B, C, D, and E, a straightforward normalizing or "true" full annealing from temperatures above their critical points or ranges may suffice to remove the strains induced by mechanical working and, at the same time, soften them so that they can be readily cut or machined to shape, but, even with these steels, a sub-critical annealing or softening treatment may often be employed with advantage. An important point to bear in mind, however, is that any sub-critical softening treatment involves a heating period of at least double that required for a "full" normalizing process.

When either normalized or sub-critically annealed, according to its chemical composition, the steel is generally cooled in air, although in special instances slow cooling in the furnace may be necessary.

The temperatures given in the following table relate to the steel and not merely to those of the furnace—an important point—since, again, it cannot be too strongly emphasized that the "soaking" period is of the greatest importance.

The somewhat protracted treatment indicated for most of these steels is, in many of the mass-production factories, telescoped quite effectively by raising the steel to a normalizing temperature, then quickly cooling it down in the furnace at a cooling rate of about 100°–125° C. per hour until the critical range is attained. It is then cooled more slowly throughout this range so as to obtain the best possible structural condition, after which it is cooled down in the furnace to the temperatures given in Table XXXVI.

TABLE XXXVI

Type of Steel	Anneal or Soften at	Hourly Cooling Rate
A 3% Nickel	820–840° C.	25° C. down to 480° C.
B 3½% Nickel	815–830° C.	25° C. ,, 480° C.
C Nickel Chromium 1	815–840° C.	25° C. ,, 540° C.
D Nickel Chromium 2	815–840° C.	25° C. ,, 540° C.
E Nickel Chromium 3	815–840 or 660–690° C.	25° C. ,, 540° C.
F Nickel Chromium 4	660–690° C.	In air or in the furnace, although the latter is not really essential.
G Nickel Chromium 5	660–690° C.	
H Chromium Molybdenum	660–690° C.	do.
I Nickel Molybdenum	660–690° C.	do.
J Chromium 1	660–690° C.	do.
K Chromium Vanadium 1	660–690° C.	do.
L Chromium Vanadium 2	660–690° C.	do.
M Nickel Chromium Tungsten	660–690° C.	do.
N Nickel Chromium Molybdenum	660–690° C.	do.

After the necessary machining operations have been carried out, the next process is hardening. In raising the gears to the hardening temperature the note given in an earlier chapter on the importance of gradual and even heating should be borne carefully in mind. The hardening and tempering temperatures for the steels given in Table XXXVI are indicated in Table XXXVII.

TABLE XXXVII

Type of Steel	Quench at °C.	In	Temper at ° C.
A 3% Nickel	810–830° C.	Oil	200–250° C.
B 3½% Nickel	800–825° C.	,,	,,
C Nickel Chromium 1	800–825° C.	,,	,,
D Nickel Chromium 2	780–800° C.	,,	,,
E Nickel Chromium 3	810–830° C.	,,	,,
F Nickel Chromium 4	800–820° C.	,,	,,
G Nickel Chromium 5	820–830° C.	Air	250 (max.)
H Chromium Molybdenum	830–850° C.	Oil	230–260° C.
I Nickel Molybdenum	810–830° C.	,,	200–230° C.
J Chromium 1	825–850° C.	,,	,,
K Chromium Vanadium 1	850–870° C.	,,	,,
L Chromium Vanadium 2	850–870° C.	,,	,,
M Nickel Chromium Tungsten	840–850° C.	,,	200 (max.)
N Nickel Chromium Molybdenum	820–840° C.	,,	200 for 100 tons tensile 600 for 65 tons tensile

It should be noted that if the gears are heated in a salt bath furnace slightly lower quenching temperatures (about 10° C. below those indicated) may be adopted.

The heat must be given adequate time to soak right through to the centre of the gear, while, if possible, a controlled atmosphere furnace should be used to eliminate any risk of oxidation or the production of soft skins. With the exception of steel which possesses very marked air-hardening properties, the steels should all be quenched in oil maintained at a temperature between 30° and 50° C. and kept briskly moving. After quenching, the gears should preferably be thoroughly cleansed to remove all traces of oil.

Re-heating for tempering is usually carried out in a salt bath or electric tempering furnace, and the tempering temperature should be *maintained* for at least 30–40 min. After tempering, the gears should be cleaned.

It should be understood that the tempering temperature must be chosen to suit the particular mechanical properties required.

HEAT-TREATMENT OF ALLOY STEEL SPRINGS

In general, the heat-treatment of alloy steel springs follows similar principles to those laid down for carbon steel springs. The main differences relate to composition of the steels used and the temperatures adopted.

Small Flat and Helical Springs

These are often made from a chromium-vanadium steel containing on average 0·5 per cent carbon, 0·65 per cent manganese, 0·9 per cent chromium, 0·15 per cent min. vanadium, which may be supplied in either the cold-rolled, the annealed, or the oil-tempered condition. The cold-rolled and the oil-tempered steels need not be quenched, but should be tempered at 230°–340° C. The annealed steel is quenched in oil at 850°–870° C., and afterwards tempered at 230°–340° C.

Large Laminated or Flat and Helical Springs

Three main types of alloy steel are used for these, one of which, the first, is mostly used in America. It is a silicon-vanadium steel containing, on average, 0·9 per cent carbon, 0·5 per cent manganese, 0·6 per cent silicon, and 0·15 per cent vanadium. The second contains, on average, 0·5 per cent carbon, 0·8 per cent manganese, 1·1 per cent chromium, and 0·15 per cent vanadium. The third is a silicon-manganese spring steel containing, on average, 0·5–0·6 per cent carbon, 0·6–1·0 per cent manganese, and 1·5–2·0 per cent silicon.

The first of these three steels is normalized at 885°–900° C. and quenched in oil at 870°–880° C., being afterwards tempered at 400°–565° C.

The chromium-vanadium spring steel is normalized at 870°–885° C., heated to 850°–870° C., and quenched in oil. Tempering is within the range 455–565° C.

The silicon-manganese spring steel is normalized at 870°–885° C., quenched in oil at 870°–890° C., and tempered within the range 480°–550° C., to give Brinell hardness numerals between 341 and 429.

CHAPTER XXIV

Heat-treatment of Permanent Magnet Steels

THE newer ("Alnico" nickel-iron-cobalt-aluminium and "Nial" nickel-iron-aluminium) steels—alloys would be the better word—for permanent magnets are not susceptible to normal forms of heat-treatment, though methods have been suggested. The original chromium-cobalt and tungsten steels, many uses for which still remain, can, however, be heat-treated, but some important points must be stressed in this connection.

The first is that annealing these steels is to be avoided wherever possible, because of the harmful effect this operation has on the magnetic properties of the material, an effect known as *spoiling*, and apparently a consequence of crystal or "grain" growth. This spoiling of magnets by annealing is, so far as the tungsten steels are concerned, apparently exaggerated by high silicon contents.

Obviously, the designer of magnets made from these steels should, therefore, endeavour to eliminate machining if this involves a preliminary annealing.

Most permanent magnets of chromium or tungsten steel are brought to shape by heating and forming while hot. This involves temperatures between 760° and 980° C., averaging for preference about 870° C. To exceed 980° C. is to run the risk of impairing the efficiency of the magnet on account of excessive grain-growth and the consequent influence on its magnetic properties. These steels yield their best magnetic properties only when their structures are fine-grained.

The air-hardening magnet steels have to be annealed for machining after they have been hot-formed, in which case the steel should be raised to the annealing temperature quickly, given just sufficient time for penetration, and allowed to cool gradually in the furnace so as to prevent the possibility of air-hardening effects. When the temperature has declined to 540° C. the steel can be removed from the furnace and cooled in the atmosphere, since all risk of air-hardening ceases below 540° C. Slow cooling from 540° C. may, indeed, be harmful.

Table XXXVIII shows the principal magnet steels of the hardenable type. Of these, steel No. 1 should be heated up to

TABLE XXXVIII

Steel	Range of Composition, per cent
1	Carbon 0·8–0·9, silicon 0·2–0·3, manganese 0·2–0·4, chromium 5·5–6·5, tungsten 4–5, cobalt 34–36.
2	Carbon 1·1–1·2, silicon 0·2–0·3, manganese 0·2–0·4, chromium 9·5–10·5, cobalt 15·0, molybdenum 1·7–1·9.
3	Carbon 1·0–1·2, silicon 0·2–0·3, manganese 0·2–0·4, chromium 9·5–10·5, cobalt 9·0, molybdenum 1·7–1·9.
4	Carbon 1·0–1·2, silicon 0·2–0·3, manganese 0·2–0·4, chromium 9·5–10·5, cobalt 6·0, molybdenum 1·7–1·9.
5	Carbon 1·0–1·2, silicon 0·2–0·3, manganese 0·2–0·4, chromium 9·5–10·5, cobalt 3·0, molybdenum 1·7–1·9.
6	Carbon 0·65, silicon 0·25, manganese 0·25, tungsten 5–6, chromium 0·3–0·5.
7	Carbon 0·7, silicon 0·5, manganese 0·4, chromium 6·0.

700°–750° C. for a short time only after forging or forming, and allowed to cool in the air before hardening. It should then be heated up fairly quickly to 950°–1000° C. Immediately the steel has reached the temperature of the furnace, it must be quenched in thin, cool oil.

Steels Nos. 2, 3, 4, and 5 should be subjected to a triple heat-treatment to ensure the best results. First, these steels are heated up quickly to 1150°–1200° C. and cooled in the air. They are then reheated to 700°–750° C. and cooled in the air. Finally, they are reheated to 970°–1000° C. and air-cooled until the steel becomes magnetic, after which the magnets are cooled in oil.

When a piece of highly-alloyed steel cools, it attains a critical point at a certain temperature. This is the point at which the carbides come out of solution (see *The Structure of Steel*). There is a giving out of heat and an expansion of the steel. This is known as *recalescence*. In the magnet steels Nos. 2–5 it is possible to cool and retain all the carbides in solution at room temperature, and it is only on a later reheating that they once more come out of solution. During this secondary heating the steel actually shows at a certain point a sudden expansion and evolution of heat readily visible in a darkened room.

If a furnace full of magnets all heated to a uniform temperature is watched just below the point at which recalescence takes place, they will be seen to glow, one by one, in a remarkable manner, until they are some 40° hotter than the temperature of the furnace in which they are placed. In some works this lighting up is known as *moonshining.*

Steel No. 6 is an ordinary tungsten magnet steel and is usually softened at 780°–800° C. and hardened in oil from about 850° C.

Steel No. 7 is heated slowly to 650° C., then rapidly to 900°–1000° C., for forging. As previously explained, annealing is to be avoided, if possible. After being forged, however, the magnet blanks have frequently to be machined, and in such instances the steel may be lightly and sufficiently softened by heating to 700° C. for two hours, then allowing it to cool slowly in the air. It is vital that this steel should not be raised to too high a temperature, nor should the temperature be maintained too long, as otherwise the steel will not produce the required magnetic properties when hardened.

Some users alternately boil these magnets and cool them in cold water several times, instead of continuously tempering them at 100° C. The magnetic properties thereby obtained are lower, but have greater stability.

Steel No. 7 should be hardened in oil at 850° C.

Water-quenching steels for magnets are now seldom used because of the great danger of cracking, distortion, and fracture during hardening. In hardening magnets, it is inadvisable to maintain them at the hardening temperature for a longer period than is necessary to ensure complete penetration of the heat. Ten minutes at the hardening temperature is usually regarded as long enough.

Once magnets have been hardened, their magnetic properties can be seriously impaired by any rise in temperature above 100° C., and if the temperature is allowed to rise to 150°–200° C. the real value of the magnet may be lost in consequence of induced structural transformations. It is possible, however, to reharden magnets not irretrievably injured and so restore some part of their original properties, although it is seldom possible to restore them in full.

Magnets, when tempered, are rarely heated above 100° C. so as to avoid adverse effects on their magnetic properties.

Reverting to the Alnico and Nial types of magnet alloys mentioned at the outset of this chapter, it may be explained that the proposed heat-treatments comprise heating to an

TABLE XXXIX

Type of Steel	Analysis											Heat-treatment	Magnetic Properties		
	C	Si	Mn	W	Cr	Co	Ni	Al	Mo	Ti	Cu		Br (gauss)	Hc (oersted)	B-H max.
Carbon .	0·90	0·20	0·35	—	—	—	—	—	—	—	—	W.Q. 760° C.; T.200° C.	9,000	55	200,000
Tungsten .	0·65	0·20	0·40	6·0	0·5	—	—	—	—	—	—	O.Q. 850° C.; T.200° C.	10,000	70	260,000
Chrome-tungsten .	0·95	0·15	1·10	4·0	5·0	—	—	—	—	—	—	O.Q.800° C.; T.250° C.	10,000	65	280,000
Cobalt-tungsten .	0·90	0·20	0·40	9·0	3·0	15·0	—	—	—	—	—	O.Q.900° C.; T.300° C.	9,000	160	450,000
Chromium .	1·00	0·15	0·40	—	6·0	—	—	—	—	—	—	O.Q.480° C.; T.250° C.	9,000	70	250,000
Cobalt-chromium	0·90	0·20	0·40	—	9·0	5·0	—	—	0·5	—	—	A.C. from 1150° C.; reheat to 700° C. and A.C.; reheat to 1000° C. cool to 300° C. and O.Q.	7,500	145	450,000
	1·00	0·20	0·30	—	9·0	15·0	—	—	1·0	—	—		8,200	185	600,000
High Cobalt-tungsten .	0·95	0·20	0·30	5·0	—	35·0	—	—	0·5	—	—	O.Q. 930° C.	9,500	235	900,000
Nickel-aluminium*	0·08	0·60	0·30	—	—	—	27·0	12·5	—	0·25	3·50	A.C.1200° C.; T.650° C.	8,000	450	1,750,000
Nickel-cobalt-titanium	0·05	—	—	—	—	25·0	25·0	0·25	—	1·20	—	As cast	6,500	800	—

* Alloys of this type are also placed into service as castings; to get the best magnetic tests the rate of cooling after casting is then modified to suit the cross-sectional area.

extremely high temperature (in the region of 1250° C.). The material is then quickly cooled and afterwards given a precipitation treatment at 650°–700° C., or by cooling at an experimentally determined rate. By quick cooling from about 1200° to 1250° C. these alloys are made to consist of *supersaturated solid solution* crystals and the effect of the heating to 650°–700° C. is to *precipitate* or deposit finely divided, or *discrete*, particles of the constituent previously held in the state of supersaturation, the consequence being both enhanced hardness and greatly improved magnetic properties. Both the above treatments definitely improve the coercive force (*Hc*) of the materials and, in particular, the value *B-H max.*, an energy factor of the greatest importance in the construction of electrical machinery.

Electrical engineers will recognize B-H max. as the maximum value obtained from the product of *B* (the residual magnetism) and *H* (the negative magnetizing force) from the descending part of the B-H loop of the magnetization curve.

Some indication of the influences of chemical composition and heat-treatment on the properties of magnet steels is given in Table XXXIX.

CHAPTER XXV

Heat-treatment of Stainless and Heat-resisting Steels

THE number of *stainless* (corrosion-resisting), steels is almost legion, but they can be broadly grouped into chromium (*martensitic*) steels, chromium-low-nickel (*martensitic*), chromium (*ferritic*) "irons," and nickel-chromium (*austenitic*) steels. Of these, only the straight chromium and low nickel steels can be hardened by heat-treatment, but all four types can be forged, though forging is never so easy as with the mild carbon steels owing to their resistance to heat and to the softening caused by heat, which consequently reduces their plasticity under the forging hammer.

In general, therefore, stainless steels, to whatever group they belong, demand preheating, before forging, to about 800° C., while the heat must be given ample time to penetrate evenly to the very heart of the mass, which will take longer than for mild "carbon" steels. In Table XL we give the commonly used "straight" chromium stainless steels with their analyses and heat-treatments. These steels, excepting those of very low carbon contents, will harden by cooling in air, so that as they are forged their cooling causes them to grow harder. In these circumstances, forging cannot be carried out indefinitely, and extensive operations may need several reheatings, as forging temperature ranges are rather narrow for these steels. Cooling from the forging temperature should be gradual and uniform, so as to avoid *clinks* (internal or external cracks). Forging should always be carried out quickly and by rapid repeated blows, at temperatures between 1150° C. and 900° C., and should on no account be continued below 850° C., because working of the steel below this temperature sets up excessive internal strains. In reality, forging or working below this temperature (850° C.) amounts to a cold-working so far as the structure and properties of the steel are concerned.

Some of these steels, as will be seen from Table XL, have higher carbon contents than others. The higher carbon steels must not be heated to too high a temperature for forging. The reason is that a rise in carbon percentage, as earlier explained, calls for a lower forging temperature. Too high a forging heat

TABLE XL

Steel No.	Ranges of Composition* per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Soften at ° C.	Anneal at ° C.	Preheat at ° C.	Harden at ° C.	Temper at ° C.	Typical purposes for which used
1	4–6 chromium, 0·05–0·25 carbon (max.), 0·5 manganese, 0·5 (max.) silicon.	1065–1090	900–925	—	845–860	—	980–1010 (water)	Up to 750° acc. to purpose.	Preheater tubes, etc.
2	12–16 chromium, 0·12 carbon (max.), 0·4 manganese, 0·2 silicon.	1090–1150	900–915	760–790	845–870	790–815	970–995	do.	Turbine blades.
3	12–14 chromium, 0·15 carbon (max.), 0·2–0·4 manganese, 0·2–0·4 silicon.	1090–1150	900–925	760–790	845–870	790–815	970–995	do.	Pressings and general engineering fittings.
4	12–15 chromium, 0·12 carbon (max.), 0·3–0·4 sulphur, 0·45 manganese, 0·25 silicon.	1150–1200	900–950	—	705–790	790–815	990–1000	do.	Easy machining.
5	12–15 chromium, 0·3–0·4 carbon, 0·35 manganese, 0·2 silicon.	1065–1120	925–955	760–790	855–885	790–815	950–1000 (oil or air for intricate sections).	175–750 acc. to purpose.	Cutlery, turbine blades, steam and oil pumps, valve parts, etc.
6	15–18 chromium, 0·55–0·75 carbon, 0·45 manganese, 0·4 silicon.	1065–1090	925–955	760–790	885–910	790–815	990–1050	175–425 acc. to purpose.	Pocket knives, etc.
7	15–18 chromium, 0·9–1·0 carbon.	1040–1090	925–955	790–818	925–955	760–790	995–1050	do.	Cutlery and cutting instruments.
8	15–18 chromium, 0·9–1·1 carbon, 0·4 manganese, 0·45 silicon.	1010–1065	925–955	790–815	925–955	760–790	995–1050	do.	Ball races and bearings

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* In addition to their chromium and carbon contents, many of these steels contain small percentages (seldom more than 1·0 per cent) of other elements such as tungsten, molybdenum, aluminium, copper, selenium, etc., while No. 4 may contain as much as 0·4 per cent of sulphur in order to improve its machinability.

leads to excessive grain growth and consequent difficulties in hardenability.

When these steels are required for machining purposes, the bars are usually fully tempered, which renders them readily machinable. The fully annealed or softened condition is not necessarily the most suitable for easy machining.

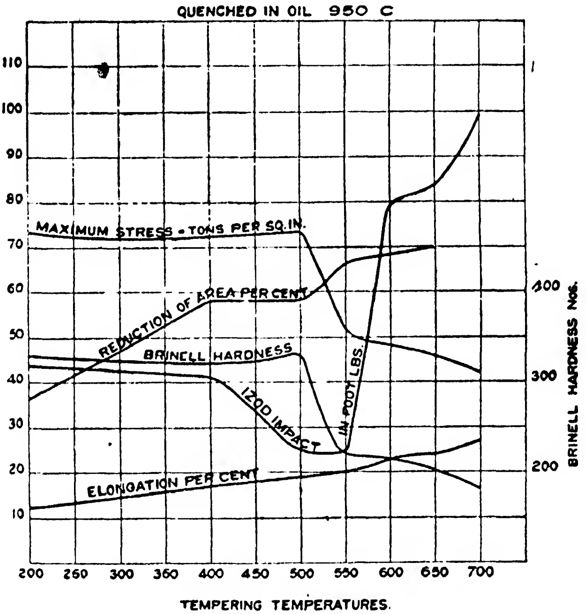


FIG. 83. STRAIGHT CHROMIUM "CUTLERY" STAINLESS STEEL

Fig. 83 is a chart from which can be ascertained the most suitable temperatures for different purposes.

It should be noted that the Brinell hardness obtainable from these steels depends largely on the section of the article being hardened; for example, a much higher Brinell (e.g. about 625) can be obtained when a knife blade of approximately $\frac{1}{32}$ in. thickness is hardened than on a round bar of $1\frac{1}{8}$ in. diameter, when the Brinell number will probably be in the region of 475.

After hardening, these high-chromium steels give a wide range of mechanical tests if the tempering temperatures are varied, and Fig. 83 gives an approximate idea of the test results that may be expected. If the steels are quenched and then tempered between 450° and 600° C., corrosion resistance will be considerably reduced. The "straight" chromium steels are liable to *line corrosion* (caused by reheating to a temperature of about 500° C., as away from the bolster of a knife blade during the brazing on of metal handles). This must be removed by annealing at 750° C.

The chromium "irons" of very "soft" type, i.e. containing little carbon, will not harden, and are designed specifically for purposes demanding considerable ductility and malleability combined with resistance to corrosion. They need careful preheating, and soaking, in advance of forging, the soaking temperature being the same as that for the straight chromium steels. Forging should begin with light rapid blows, and slow down as the temperature declines. Care should be taken not to forge at too high a temperature, and the operation should not be carried much below 900° C. Overheating must be avoided at all costs, as it produces enlargement of the grains with a consequent loss of ductility and toughness. The most satisfactory structural condition will be obtained if the forging operation is finished at a low temperature. It may, on occasion, be advisable to anneal at 750°–800° C. and cool in air, so as to relieve the strains set up by forging. As each particular job varies, the steel manufacturer should be asked to recommend specific temperatures and times for any particular instance. Table XLI shows the principal steels of this group and their forging temperatures.

TABLE XLI

Steel No.	Composition	Begin Forging at	Finish Forging between
1	16–18 chromium, 0·12 carbon (max.), 0·5 manganese (max.), 0·5 silicon (max.).	1040°–1090° C.	930°–950° C.
2	Ditto with 0·35–0·4 sulphur for easy machining.	1095°–1150° C.	930°–950° C.
3	20–23 chromium, 0·35 carbon (max.), 0·5 manganese (max.), 0·5 silicon (max.).	1040°–1090° C.	900°–960° C.
4	23–30 chromium, 0·35 carbon (max.), 0·5 manganese (max.), 0·5 silicon (max.).	1040°–1090° C.	900°–960° C.

Nos. 1 and 4 steels contain 0·5 (max.) of nickel. No. 2 contains 0·4 of molybdenum.

The austenitic stainless steels cannot be hardened by heat-treatment. The only way of hardening such steels is to cold-work by cold-drawing or cold-rolling. Softening is, however, quite often necessary in the production of certain articles, owing to the effect of cold pressing or hammering to shape, causing *work-hardening*. Work-hardening is invariably found when operations of this kind are carried out on almost any ductile metal, and such processes as pressing and spinning both give the steel a considerable amount of hardness and leave behind severe internal strains.

This means that where the cold-working processes are numerous, it is essential to soften the steel in between one cold process and another. Austenitic stainless steels of the 18/8 (18 per cent chromium, 8 per cent nickel) type are entirely re-softened after work-hardening by heating to approximately 1100° C. and thoroughly soaking at this temperature. If circumstances do not allow the obtaining of so high a temperature, a good degree of softness can be had by heating to 1000° C. and upwards. Cooling in air or even water-quenching from this temperature should follow.

As some degree of oxidation is caused by this heat-treatment, the surface will need to be cleaned by a *descaling* (scale-removing) process, after which it should be well washed in running water, to remove all traces of the acid.

Descaling, or pickling, is carried out by plunging the article into an acid solution of water and commercial hydrochloric acid in equal parts, with an addition of 5 per cent of the total volume of commercial nitric acid and about 2 per cent of the total volume of a *restrainer* or *inhibitor*. Inhibitors are organic chemical compounds of the *pyridine* type and are really bases which unite chemically with part of the acid. Their influence is to "restrain" the attack of the acid on the steel, once the oxide or scale has been removed. Proprietary inhibitors or restrainers are on the market, such as that known as Ferro Cleanol II. This solution should be heated, before the parts are immersed in it, to between 50° and 60° C. Renewal of the mixture is necessary from time to time.

Immersion loosens but does not eliminate the scale, so that the articles should be removed from the bath after a brief period and washed or wiped to take away the slimy scale found on the surface. If any scale still adheres firmly, replace the articles in the bath for a further short period.

Forging of these steels is not easy, and much more effort is necessary to produce the required form or size than to produce an identical result with mild steels. Hence, they must be carefully preheated to 815° C. and well soaked at this temperature. All but the last two steels in Table XLII must be maintained at the first forging heat for a considerable period. Without exception, forging of all these steels must on no account be continued below 900° C. If forging is carried on below 900° C., not only will work-hardening set in, but also there will be a liability to excessive brittleness.

Typical austenitic stainless steels are given, with their forging temperatures, in Table XLII. It should be noted that these austenitic steels are susceptible to *weld decay*, and those interested in this aspect of the subject should carefully read the relevant notes in *The Structure of Steel.*

Many of the stainless steels have heat-resisting properties, particularly the austenitic steels. There are, however, a number of steels designed specifically for heat-resistance. Many of these are supplied as castings only and are not susceptible to heat-treatment. Of the remainder, a steel containing approximately

TABLE XLII

Steel No.	Composition	Begin Forging at	Finish Forging at
1	Chromium 18–20, nickel 8–9, carbon 0·15 (max.), silicon 0·5 (min.), manganese 0·4–0·8, copper 1·0–1·5.	1095°–1120° C.	Not less than 900° C.
2	Chromium 18–20, nickel 8–9, carbon 0·15 (max.), silicon 0·5 (min.), manganese 0·4–0·8.	1150°–1205° C.	do.
3	Chromium 18–20, nickel 8–9, silicon 0·5 (min.), manganese 0·4–0·8, tungsten 0·5–0·8, copper 0·5–0·7.	do.	do.
4	Chromium 18–20, nickel 8–9, carbon 0·15 (max.), silicon 0·5 (min.), manganese 0·4–0·8, molybdenum 3–4, copper 1·0–1·5.	do.	do.
5	Chromium 18–20, nickel 8–9, carbon 0·15 (max.), silicon 0·5 (min.), manganese 0·4–0·8, tungsten 0·5–0·8, copper 0·5–0·7, titanium 0·5–0·8.	1170°–1200° C.	do.
6	Chromium 12–13, nickel 12–13, carbon 0·15 (max.), silicon 0·5 (min.), manganese 0·4–0·8, copper 1–1·5.		

12 per cent chromium, 0·1 per cent carbon, 0·5 per cent manganese, 0·2 per cent silicon, will harden in air from 970°–995° C. An alloy with 17 per cent chromium, 0·1 per cent carbon, 0·5 per cent manganese, 0·3 per cent silicon, may respond slightly to hardening if heated to temperatures above 980° C. and allowed to cool in the air. A steel with 27 per cent chromium, 0·15 per cent carbon, 0·7 per cent manganese, 0·3 per cent silicon, cannot be heat-treated, but will take on an undesired brittleness if maintained for a protracted period between 425° and 550° C.

On the other hand, there are three heat-resisting steels of the austenitic type that can be heat-treated to a certain extent. The first of these contains, on the average, 20 per cent chromium, 25 per cent nickel, 0·25 per cent carbon, 0·6 per cent manganese, and 2·5 per cent silicon. This should be forged at 1120°–925° C., and can be completely softened at 1095°–1150° C., but cannot be hardened by heat-treatment. The softening temperature must not be prolonged once it has been reached, and cooling should be rapid, in water, oil, or free air. This steel is specially suitable for furnace doors, muffles, retorts, skids, tubes, etc., at temperatures up to 1150° C.

The second steel contains, on the average, 25 per cent chromium, 12 per cent nickel, 0·2 per cent carbon, 0·75 per cent silicon, and 1·0 per cent manganese. This steel should be preheated to 845°–870° C. for forging, and held at this temperature long enough for complete penetration of the heat to take place. Forging should be carried out at 1230°–1095° C., care being taken to ensure thorough soaking. Forging should not be carried on below 985° C. To soften this steel it should be heated to 1090°–1150° C., but not soaked at this temperature, and then allowed to cool in the furnace. This steel is suitable for oil burner parts, chemical plant rollers, skid rails, and other furnace parts.

The third steel contains, on average, 25 per cent chromium, 20 per cent nickel, 0·25 per cent carbon, 1·1 per cent silicon, and 0·6 per cent manganese. It should be preheated for forging to 925°–980° C. and soaked well at this temperature, forging being carried out at 1205°–1120° C., again soaking thoroughly. Forging must not be continued below 980° C. To soften the steel it should be heated to 1095°–1150° C., but not unduly soaked. This steel is designed for furnace parts, retorts and tubes at temperatures up to 1095° C.

CHAPTER XXVI

Heat-treatment of Alloy Steel Castings

We deal in this chapter with those steel castings only whose alloy content is below 5 per cent.

There is an extremely wide range of these, including a number of standard compositions and an even larger number of special compositions representing the whims of designers or the experience of particular manufacturers. We do not outline here the individual treatments for every type of alloy steel casting, but only the general principles of alloy casting heat-treatment, supplementing these by a table of representative and typical compositions and heat-treatments.

The actual operations to which the alloy castings will respond are the same as for carbon steel castings, namely, softening or annealing, normalizing, quenching, and tempering. Annealing alone, with no succeeding treatment, is rarely employed, because it shows no particular advantage, except that it makes the steel more suitable for machining. As a rule, when alloy steel castings are annealed, they are normalized or quenched and tempered afterwards.

Not every alloy steel casting should be quenched, and as a rule a choice will have to be made between normalizing and quenching-and-tempering, much depending on the purpose for which the castings are required, their composition, and the mechanical properties they should possess. Usually, an alloy steel casting is quenched and tempered in order to give it the maximum combination of hardness and toughness, but quenching should not be attempted if the form is highly complex or changes abruptly in section, as the result may be severe distortion or the formation of cracks. The point cannot be too forcibly made that the designer of castings should consult the steel founder, as the steel capable of giving, in cast form, the particular physical properties desired may demand a heat-treatment not consistent with a preconceived theoretical design. By slight modification of design and a little delay in producing the pattern, the price of the casting may often be greatly decreased and its quality improved. More important still, the speed of production and the time of delivery will be improved. For example, if the casting is required hard in a form not suitable for quenching, the steel founder may be able to suggest a composition capable of being hardened in the air.

The normalizing of alloy steel castings is usually carried out at slightly higher temperatures and the castings are held for a rather longer period at temperature than with carbon steel castings, because corresponding changes take place more slowly, or sluggishly, in alloy steels.

There can be either one or two normalizings, the principle being as already outlined in the chapter on carbon steel castings. Where a single normalizing treatment is given, the usual practice is to heat the castings in the furnace to a temperature between 845° and 925° C. according to the carbon percentage and allow them to cool in the air. An average time of heating is one hour per inch of section. Certain molybdenum steels may need heating to 950° C.

Where a double normalizing treatment is given, the purpose is to promote a thoroughly satisfactory grain structure, and the usual practice is to reheat the castings to a temperature approximately 10–25° above the critical range, maintaining the heat just long enough to give even heating. As a rule, from 30 to 60 min. after even temperature has been attained will be found adequate.

The quenching and tempering operation may either constitute a treatment in itself or may form a concluding link in the sequence annealing-normalizing-quenching. It is, on the whole, better for it to follow a previous treatment, because this will produce a more refined grain structure, a shorter soaking period being required to ensure uniform structure than when the casting is simply heated and quenched. The casting should be raised gradually and evenly to a temperature from 10–25° above the critical range, and this temperature maintained for a period sufficient for the heat to permeate its whole cross-section.

Where castings are quenched in water it is advisable that the bath temperature should not fall below 50°–65° C., particularly when the castings have a high carbon content.

Precautions will, in any event, be necessary to prevent the formation of cracks, particularly in castings of complex form or abrupt section change. It is advisable in such instances to withdraw the castings from the bath before they have cooled out (say at 200° C.) and transfer them to an already heated tempering furnace.

TABLE XLIII

		C	Si	Mn	Cr	Ni	Mo	Anneal	Normalize	Temper	Quench	Temper	Typical purposes for which used
1	Carbon Manganese	0·25–0·35	0·25–0·35	1·6–1·8	—	—	—	950° C.	890° C.	600° C.	850° C. Water	600–650°C.	For transmission gears and similar parts where toughness is desired combined with wear resistance.
2	Carbon Manganese Molybdenum	0·20–0·25	0·25–0·35	1·4–1·6	—	—	0·25–0·30	950° C.	890° C.	600° C.	850° C. Water	600–650° C.	For parts subject to severe shock and stress as in dredging and excavating machinery.
3	Carbon Manganese Molybdenum	0·25–0·35	0·25–0·35	1·4–1·6	—	—	0·25–0·30	950° C.	890° C.	600° C.	850° C. Water	600–650° C.	
4	Carbon Molybdenum	0·20–0·25	0·25–0·35	0·8–1·0	—	—	0·25–0·30	950° C.	809° C.	600° C.	—	—	For parts of superheaters and steam plant where high pressures are encountered, e.g. steam chests, turbine casings, etc.
5	Carbon Molybdenum	0·30–0·35	0·25–0·35	0·8–1·0	—	—	0·25–0·30	950° C.	890° C.	600° C.	—	—	
6	Carbon Chromium	0·50–0·55	0·35–0·45	0·8–1·0	0·65–0·75	—	—	920° C.	—	—	850° C.	600–650° C.	For wearing parts, such as liners, etc., for crushing and grinding plant, gear blanks, etc.
7	Carbon Chromium	0·7–0·8	0·35–0·45	0·6–0·8	1·8–2·0	—	—	920° C.	—	—	820° C. Oil	(*a*) 250° C. (*b*) 600–650° C.	For wearing parts of crushing, grinding and pulverizing plant giving high wear resistance and a considerable degree of toughness and for wearing parts of ball, tube and rod mills, wash mill harrows, etc., where high resistance to wear is required, but where less shock is encountered.
8	Carbon Chromium Molybdenum	0·65–0·75	0·35–0·45	0·6–0·8	0·8–1·0	—	0·25–0·30	920° C.	—	—	850° C. Oil	600–650° C.	
9	Carbon Chromium Molybdenum	0·40–0·45	0·30–0·40	0·6–0·8	1·4–1·7	—	0·4–0·5	950° C.	—	—	850° C. Oil	600–650° C.	
10	Nickel Chromium Molybdenum	0·40–0·45	0·25–0·35	0·4–0·6	0·7–1·0	2·25–2·75	0·4–0·5	950° C.	—	—	850° C. Oil	600–650° C.	For parts of lifting machinery, excavators, winches, gears and smaller parts where strength and toughness are desired.

Where the table shows both normalizing and quenching, these are alternative treatments.
The tempering range given after quenching indicates that the tempering may be between these limits to give the desired mechanical properties.

Quenching should always be followed by tempering, normalizing sometimes only, according to the kind of steel and the form of the part. As alloy steels are highly sensitive to heat-treatment, there is a wide range of tempering temperatures according to the mechanical properties desired. As a general rule, however, the castings should not be heated to a temperature in excess of 675° C., but may go as low as 175°–250° C. Table XLIII should be studied in this connection. The tempering temperatures should be maintained long enough for the heat to penetrate uniformly the thickest portion of the casting. For small and average-sized castings this is usually not more than two hours, but as much as four to 10 hours may be needed for big castings (those with cross-sections of 12 in. or above).

It commonly happens when the mould is broken open after cooling, or as a result of quenching, that a casting is found to have *pulled,* i.e. warped, to some extent, but it can be straightened without undue difficulty. This is done by heating it evenly to a temperature between 260° and 480° C., or the operation may be attempted, if conditions permit, during the cooling period after normalizing or the heating period for tempering.

Welding, oxy-acetylene cutting, and other processes in which heat is locally applied usually set up considerable local stresses and often harmful malformations of crystalline structure. For this reason, the castings should be stress-relieved or reheat-treated afterwards.

Table XLIII should be studied for specific treatments in condensed form.

CHAPTER XXVII

Heat-treatment of Die Steels

MANY die steels, of diverse compositions, are made by individual steel manufacturers, and it would be difficult, if not impossible, in a work of this type to give detailed heat-treatments for each and every one. All we can hope to do is to consider the principal groups of die steels—those whose purpose and basic compositions are broadly identical—and outline the main characteristics of satisfactory treatment.

OIL-HARDENING "STANDARD" DIE STEELS

The first, and probably the most widely used, group is that comprising the standard *non-distorting*, manganese-carbon and manganese-tungsten-chromium oil-hardening die steels, of which Edgar Allen K.9 is a typical example. Many of the steels, if not all, classed here as die steels can be used for many other types of tools, but this seldom affects the basic heat-treatment to any great extent, and if the general principles of heat-treatment are carefully followed, no difficulty should be experienced.

The oil-hardening die steels are generally employed because water-hardening "carbon" tool-steels are liable to distort, warp, shrink or crack during or as a result of the hardening process. The extreme accuracy of size and form required of steel dies makes it essential to minimize the risk of distortion, while the cost of making the dies means that if they crack, much time and expense are wasted. Table XLIV gives typical compositions of these steels of the oil-hardening type, with their condensed heat-treatments.

When heating these steels for forging, the temperature should be raised gradually to about 815° C., and then more rapidly to the forging temperature. It is better to avoid placing the cold steel in an already hot furnace, as this may possibly cause fracture. Too rapid heating is also dangerous for the same reason. The steel is usually supplied in the annealed condition, but even so, the risk of cracks from the causes given remains. Forging should not be begun until the heat has thoroughly permeated the material, and should not on any account be continued below the finishing temperatures given in the table. If the operations are still incomplete, the steel must be reheated.

TABLE XLIV

Steel No.	Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Normalize at ° C.	Anneal at ° C.	Preheat for Hardening at ° C.	Harden at ° C.	Temper at ° C.	Brinell No. after Hardening and Tempering
1	0·95–1·05 carbon, 0·8–1·0 manganese, 0·2–0·4 silicon, 0·3–0·5 tungsten, 0·7–0·8 chromium.	950–1000	700	800–820	730	650	780–800	200–250	—
2	0·9 carbon, 1·1 manganese, 0·5 tungsten, 0·5 chromium, 0·2 vanadium (optional), 0·3 silicon.	980–1060	870	850	775–790	650	790–815	165–250	680–685
3	0·9 carbon, 1·6 manganese, 0·3 silicon.	980–1040	870	800	760–775	650	780–800	165–250	—
4	1·15 carbon, 0·3 manganese, 1·6 tungsten, 0·5 chromium, 0·2 vanadium.	980–1065	870	900	790–800	650	855–885	175–300	—

Forging sets up strains and this renders normalizing essential. The steel should be well cooled after forging, and reheating for normalizing should not begin so long as any heat-glow—even the palest red—is seen. Heating should be gradual up to 815° C.

If the steel has to be re-annealed it should be heated gradually and evenly, and maintained at the annealing temperature long enough to ensure thorough soaking and the best possible structural condition.

It should be borne in mind that as these steels are intended to harden in oil, their composition is such that the same degree of softness as annealing produces in ordinary carbon tool steel is not possible. If correctly annealed, however, they should give a Brinell hardness of about 207 (Brinell hardness is fully explained in *The Structure of Steel*), which represents a steel capable of being readily machined. Any strains set up as a result of machining can be removed by a *sub-critical annealing* (annealing at a temperature below the lower critical point) at 650°–675° C. If heated above the lower critical point, the steel should be cooled slowly, not exceeding a maximum of 25° C. per hour down to 550° C.

This temperature is also a good preheating temperature in advance of hardening. Preheating is advantageous because it reduces the risk of warping or distortion due to volume changes. The steel should be brought up to 650° C. by gradual and even heating.

If the steels of Table XLIV are hardened at 760°–780° C., i.e. the lowest temperature that will yield adequate hardness, a slight contraction or expansion in length may be experienced, but this will generally be less than one thousandth of an inch for each inch. At somewhat higher hardening temperatures, the quenched steels may expand a little, but this again will be less than one thousandth of an inch for each inch of cross-section or length. It is worthy of note that the total volume of a quenched steel may be larger than the volume before quenching.

Steels Nos. 1, 2, and 4 should be held at the hardening temperature for at least 30 min., according to dimensions, so as to ensure the highest possible degree of hardness after quenching. If, however, freedom from distortion is more important than maximum hardness, soaking should be avoided. Steel No. 3 should not be soaked, and should be quenched as soon as the hardening temperature has been attained throughout the mass.

Too much stress cannot be laid on the necessity for *gradual* heating, particularly for dies of complicated form with sharp section-changes. If this precaution is neglected, warping will be inevitable.

The steel should not be quenched in dead cold or low-grade oil. A good quality, such as Houghton's No. 2, should be used, kept at a temperature between 40° and 50° C.

Tempering curves for a typical steel of this type are shown in Fig. 84. When these steels are tempered, reheating should follow immediately on quenching; the exact tempering temperature will depend on the type of die or tool being treated. If the temper is let down from a light (220° C.) to a dark straw colour (230° C.), or from a dark straw to a brown purple (265° C.) little hardness will be lost, but there will be a considerable gain in toughness.

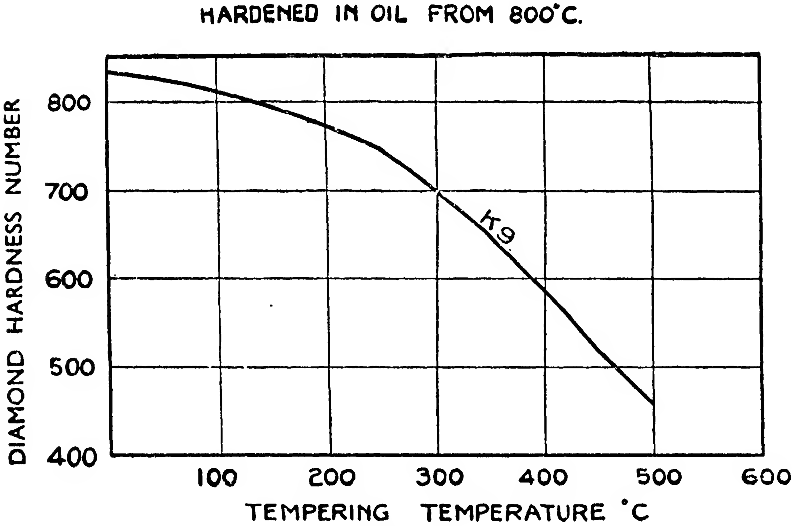


FIG. 84

As examples of tempering temperatures for different classes of tools and dies when made from these steels, one may mention threading dies (230°–245° C.), punches, drills, and cutting dies (230° C.), hollow cold nut-punches (245° C.).

A point often overlooked in hardening these steels is the temperature of the quenching bath after a long period of quenching. The oil is apt to rise in temperature unless carefully watched, and this may cause its ignition, or retard its cooling action considerably. Hence either the volume of oil in the bath must be such as to ensure that the oil will not heat up quickly, or there must be a reserve tank to which quenching operations can be transferred when the original tank is becoming overheated.

Decarburization of the surface (soft skin) during hardening must be avoided, as this may lead to spoiled dies. To prevent it, a furnace with atmosphere control, regulated to give only a slightly oxidizing atmosphere, is advisable.

The areas of the steel away from corners and edges must be properly hardened, which means that they must be brought effectively into contact with the quenching oil, preferably by some form of forced circulation.

HIGH CARBON-HIGH CHROMIUM STEEL

The standard die steels of oil-hardening type dealt with in the previous paragraphs are not always equal to the user's requirements when specially long runs or other severe service are required. In view of this, a range of die steels superior in properties to the previous range has been developed. These steels contain high percentages of expensive alloys, and as a result they cost more, but will withstand most exacting work, so that the difference between their cost and that of an ordinary die steel is saved many times. Steel No. 1 of Table XLV, for example, is suitable for intricate sections and also for punches for thin material. Dies for blanking, tin-making, coining, cutting, drawing, thread-rolling, and many other purposes, can be satisfactorily made from it, while it can also be used for plug and ring gauges, mandrels, press tools, and bushings. If correctly hardened, it will not warp or distort, and its cutting edges will last longer than those of standard die steels. It is designed for work on both hard and soft materials.

Steel No. 2 of Table XLV is suitable for dies, special shear blades, cold press work, etc., and has great hardness and wear resistance.

To obtain the best results from these complex steels, special care should be taken in forging. They are liable to become brittle if overheated or heated up too quickly. Hence they should be warmed gradually to 900° C. before any attempt is made to bring them to the forging heat.

The temperature should then be slowly increased, but in no

TABLE XLV

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Normalize at ° C.	Anneal at ° C.	Preheat for Hardening at ° C.	Harden at ° C.	Temper at ° C.	Brinell No. after Hardening and Tempering
1	1·5–1·8 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 12–13 chromium, 0·2–0·5 vanadium, 0·7–1·0 molybdenum.	1000–1100	870	950–980	780–800	750–800	950 in oil, 1050 in air blast, 950–980 in still air.	200–250	—
2	1·2–1·4 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 12–13 chromium, 2–3 cobalt, 1·0–1·5 molybdenum.	1000–1050	870	950–980	780–800	750–800	950 in oil, 1020–1050 in air blast.	200–250	—
3	2·1 carbon, 12·0 chromium, 0·2–0·4 silicon, 0·2–0·3 manganese, 0–1·0 vanadium (optional), 0–0·5 (max.) cobalt.	980–1040	870	—	870–900	815	970–995	205–540	228

circumstances should it be carried above 1100° C. It is advisable to soak the steel well at the forging heat before beginning work. Heavy blows at the outset should be avoided, light blows being preferred until the requisite degree of plasticity is attained. It is equally important not to carry on forging much below 870° C. If the forging operations have not been completed at this stage, reheating becomes necessary, and further reheatings until the whole of the work has been done. Too great a reduction of size should not be attempted at a single stroke. Higher temperatures are required for heavy sections, or extensive reductions, than for light sections or small reductions.

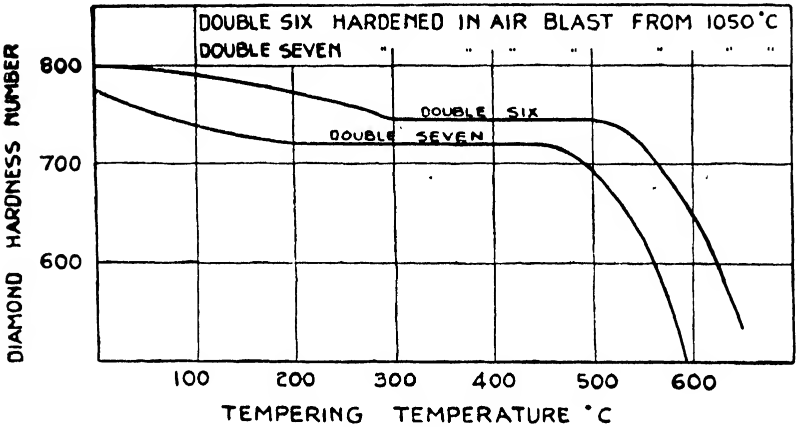


FIG. 85

Normalizing to relieve the strains set up in forging should be undertaken before the steel has completely cooled down from forging. Steel No. 3 should not be normalized, however, but buried in lime to ensure gradual cooling.

Steel No. 3, incidentally, is designed for maximum wear-resistance at the expense, to a certain extent, of machinability and toughness. In application it resembles Steels 1 and 2.

Annealing for machining should be carried out between 780° and 800° C. This temperature should be maintained for a period varying from two to four hours according to the section. A good rule is at least one hour per inch of section. The steel should then be allowed to cool down slowly in the furnace, the cooling rate not exceeding 25° C. per hour down to 540° C. The Brinell figure thereby obtained will be in the region of 225–230.

For hardening, the steels should be preheated very slowly between 750° and 800° C., then brought up to the hardening heat, held at this heat for one-quarter to three-quarters of an hour, according to size, and cooled in still air in a dry place. A good rule for soaking period is three times the period employed for identical dies or tools of carbon steel.

It should be noted that these steels are liable to decarburize on the surface (soft skin), so that a well-constructed furnace with full atmosphere control is highly desirable for their heating.

Tempering curves for two typical steels of this group are shown in Fig. 85. It is seldom worth while to temper below 200° C. as the steels will be inclined to exhibit brittleness. Gradual heating for tempering is essential if all danger of crack-formation is to be eliminated.

Hot Die Steels

The next large group of die steels are those primarily designed for pressing or squeezing dies, but not for drop-stamping dies. These resist the heat and shock met with in hot process work, and have been applied with great success to hot nut and bolt production, being used for nut dies, piercers, punches, cut-offs, gripper dies, and head-forming tools. They also resist tempering when brought into contact with hot metal. The hardness of the better qualities is not appreciably affected by reheating to temperatures below 450° C. Though they cost more than the standard oil-hardening die steels, they are more economical in certain instances, on which the manufacturer will usually advise, if consulted.

In this chapter no reference is made to carbon tool or high-speed steels, both of which are sometimes used for hot forging machine tools.

Some of these steels have also proved extremely satisfactory for hot shear blades, comparing favourably with the much more expensive high-speed steel for this purpose.

Naturally, the number of these steels is considerable, but the most representative types, many of which are American, are shown in Table XLVI, together with the condensed heat-treatment appropriate to each. The reader should bear in mind, however, that the treatments given refer to steels of the compositions shown only. Any extensive departure from these compositions involves an equally extensive variation in heat-treatment.

TABLE XLVI

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Normalize at ° C.	Anneal at ° C.	Preheat for Hardening to ° C.	Harden at ° C.	In	Temper at ° C.
1	0·25–0·35 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 9-10 tungsten, 3·0–3·5 chromium, 0·2–0·5 vanadium.	1100–1150	900	—	800	750–780	1100–1150	Air blast	600–700
2	1·0–1·1 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 3·5–4·5 chromium.	1100	900	—	750–770	830	1000-1050 850–900	Air blast Oil	450–660
3	0·6 carbon, 0·65 manganese, 0·75 chromium, 0·25 molybdenum.	1010–1050	850	870	760–790	—	870–900	Air blast	310–540
4	0·6 carbon, 4·0 chromium, 0·5 molybdenum.	1010–1050	870	—	790–810	760–710	880–980	Still air	310–600
5	0·35 carbon, 1·0 silicon, 5·0 chromium, 0·4 vanadium, 1·4 molybdenum.	1100–1150	900	—	815–845	815–845	980	Still air	540–650
6	0·5 carbon, 2·0 tungsten, 1·25 chromium, 0·25 vanadium.	1010–1050	850	—	790–810	—	900–950	Oil	175–345 for low temperature work, 540–675 for high temperature work
7	0·4 carbon, 0·6 manganese, 1·5 silicon, 7·5 chromium, 7·5 tungsten.	1100–1150	925	—	870–900	815–845	1150–1170 1120–1150	Oil Air	315 540

The highly alloyed steels of the group are usually supplied in the annealed condition. Where re-annealing has to be carried out, the steel should be heated gradually and evenly, following the standard rule of at least one hour per inch of section or thickness. The annealing temperature as specified in the table should be held for a period varying from two to four hours according to size, to ensure thorough soaking. Cooling in the furnace should then be carried out at a rate of not more than 25° C. per hour down to 540° C., after which the cooling rate can be increased if desired.

For forging, the steel should be brought gradually to 900° C. for Steel No. 1, 845° C. for Steels Nos. 2, 3, 4, 5, and 6, and to 870° C. for Steel No. 7.

Steel No. 3, which is normalized after forging, should be heated gradually for this treatment to 790° C., and held at this temperature for from a quarter of an hour to one hour according to dimensions. The steels not normalized after forging should be buried in lime to ensure gradual cooling down.

Those steels that need a preheating operation for hardening should be heated slowly and evenly, then transferred to the high temperature furnace. Steels Nos. 1 and 2 should then be heated rapidly to the hardening temperature, but the others slowly. Quenching should be carried out as soon as the steels are thoroughly and evenly heated. The hardening heat should be maintained for from 10 min. to half an hour for Steels Nos. 2, 3, 4, and 6, but Steels Nos. 1 and 7 should be quenched at once, without soaking. The best quenching medium for Steels Nos. 1, 2, and 3 is a low pressure dry air blast. The steels are allowed to grow quite cold before being later reheated slowly and evenly to the tempering temperature, which will vary with the type of tool. The tempering temperature is maintained for at least 1½ hours. per inch of thickness, after which the steel is allowed to cool in a dry place. Fig. 86 shows tempering curves for two typical steels.

The conditions under which the best results are obtained from these steels vary in different works, and the heats require adjustment within the limits stated above, according to local conditions. The steel manufacturers are usually glad to advise.

DIE-CASTING DIE STEELS

Modern practice uses highly alloyed steels for aluminium and other die-casting alloys. Table XLVII shows the most representative steels of this group, with their condensed heat-treatments.

TABLE XLVII

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Normalize at ° C.	Anneal at ° C.	Preheat at ° C.	Harden at ° C.	In	Temper at ° C.	Brinell No. when Hardened and Tempered
1	0·3–0·4 carbon, 1·0–1·4 silicon, 0·2–0·3 manganese, 4·0–5·5 tungsten, 4·5–5·5 chromium, 0·3–0·6 molybdenum.	950–1000	850	—	750	650	950	Oil	550	—
2	0·4–0·5 carbon, 0·2–0·9 silicon, 0·4–0·8 manganese, 1·5–2·0 chromium, 0·15–0·25 vanadium.	950–1000	850	—	730	—	850	Oil	500	—
3	0·45 carbon, 0·7 manganese, 0·8 chromium, 1·35 nickel.	1010–1060	850	870	760–790	—	810–840	Oil	260–425	—
4	0·3 carbon, 0·5 manganese, 1·2 chromium, 0·5 molybdenum, 1·2 chromium, 0·5 molybdenum, 1·2 aluminium.	1040–1150	870	—	—	—	Nitride	—	—	402–460
5	0·3 carbon, 0·9 silicon, 1·0 tungsten, 5·0 chromium, 0·25 vanadium, 1·0 molybdenum, 0·5 cobalt.	1100–1150	900	—	850–870	—	980–1010	Still air	540–590	402–460
6	0·3 carbon, 0·6 manganese, 0·9 silicon, 5·0 chromium, 0·25 vanadium, 1·0 molybdenum.	1100–1150	900	—	850–870	—	980–1010	Still air	540–590	402–460
7	0·35 carbon, 10·0 tungsten, 3·0 chromium, 0·5 vanadium.	1120–1180	900	—	870–900	810–840	1010–1170	Air or oil	540–670	402–460

The same caution in regard to variation in composition causing modification in heat-treatment temperature must be given here also. Steels Nos. 1, 2, 5, and 6 are designed primarily for aluminium and magnesium alloy die-casting dies, the first for long runs, the second for shorter runs. Steels Nos. 3 and 4 are used for lead, zinc, and tin alloys. Steel No. 7 is designed for copper alloys. There are, of course, many other less typical steels used, but space does not allow of their inclusion here.

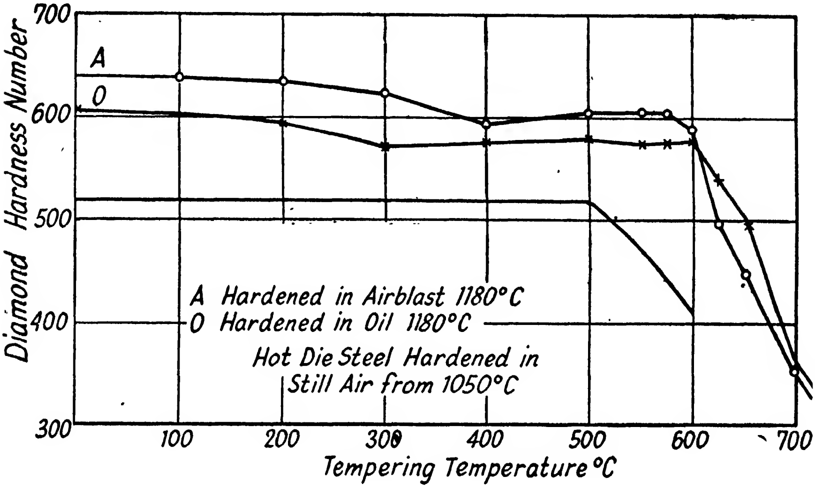


FIG. 86

There is little to add except that the general principles of heat-treatment should be carefully followed. The steels not requiring normalization after forging should be cooled off in lime, then annealed. Steel No. 4 is not annealed, but, if required to be softened for machining, is quenched in oil from about 950° C. and tempered at 675°–730° C., which yields a Brinell hardness of about 200–250.

Heating for hardening and tempering should be carried out even more slowly than with other steels of alloy type, to avoid any possible risk of distortion or cracking. An average heating time is 1½ hours per inch of maximum section, but even this may on occasion be too rapid.

Dies should be tempered immediately after quenching, but not loaded into a dead cold furnace, nor into one already at the tempering temperature. Preferably, the temperature of furnace and dies should be identical, since oil-quenched steels for these dies should not be left in the bath until cold, but withdrawn while still warm, the exact moment of withdrawal being mainly decided by experience. The tempering temperature should be held for two hours per inch of maximum section, and this must be regarded as a minimum.

CHAPTER XXVIII

Heat-treatment of High-speed Steels

CHAPTER XV giving the general principles of heat-treatment should be carefully read and thoroughly grasped as a preliminary to the notes given here. The first golden rule in heat-treating any high-speed tool steel is to warm the steel before it is put into either the fire or the furnace, and then to heat it up slowly, thoroughly, and evenly. If this simple hint is observed, there is virtually no risk of spoiling the steel. The reason for stressing this point is that high-speed steel is denser, i.e. about 10 per cent heavier, than ordinary steel, and its thermal conductivity lower. If the steel is denser, the heat will take longer to penetrate, so that if the tool is thrust straight into the fire or into a hot furnace, the outside is liable to expand more quickly than the inside, and a crack will develop either on the surface or inside the tool. If the crack is inside, the tool will look no different, even when hardened and ground, but as soon as it is put to work it will break, and the fractured surface will show the conchoidal or shell-like appearance so characteristic of careless heating.

Whether high-speed steel should be hardened in an air blast or quenched in oil depends on the convenience with which either can be carried out, and also on the mass of the tool to be hardened. If the tool is small, air-hardening is preferable. For heavy tool sections, however, oil-hardening will probably be more trustworthy, the cooling power of oil being more effective when a heavy mass is undergoing treatment.

There are three main types of high-speed steel: the cobalt steels, the tungsten steels, and the molybdenum steels.

COBALT HIGH-SPEED STEELS

In Table XLVIII are given the compositions and condensed heat-treatments of the most commonly used high-speed steels. These are specially designed for cutting the hardest and most difficult materials. It will be seen that, in addition to cobalt, they contain large proportions of tungsten, molybdenum, chromium, and vanadium.

The first operation is forging, which, after the careful warming and heating to 870° C. recommended, should be carried out at

TABLE XLVIII

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Anneal at ° C.	Preheat at ° C.	Harden at ° C.		In	Give Secondary Hardening Treatment at ° C.
						Atmosphere-controlled Furnace	"Open" Furnace		
1	0·75–0·85 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 20–22 tungsten, 4·5–5·5 chromium, 1·2–1·6 vanadium, 11–12 cobalt, 0·2–0·6 molybdenum.	1150–1200	980	Cool and then heat to 800–820	850	1300–1320	1330–1350	Air	580–600
2	0·75–0·85 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 18–20 tungsten, 4·5–5·5 chromium, 1·2–1·6 vanadium, 5–6 cobalt, 0·2–0·6 molybdenum.	1120–1175	950	Cool and then heat to 800–820	850	1300–1320	1320–1340	Air	580–600
3	0·75 carbon, 14 tungsten, 4·0 chromium, 2·0 vanadium, 0·5 molybdenum, 5·0 cobalt.	1120–1175	900	Cool and then heat to 800	820–870	1260–1280	1280–1300	Air or oil	540–550
4	0·8 carbon, 20·0 tungsten, 4·0 chromium, 2·0 vanadium, 0·6 molybdenum, 8·0 cobalt.	1150–1205	980	Cool and then heat to 800	820–870	1280–1300	1300–1320	Air or oil	550–580

1120°–1200° C. Forging should never be continued when the steel has cooled to a temperature below 900° C.

After forging, the steel should be reheated to 900°–950° C., cooled, reheated to 800°–820° C., and again cooled, to remove the strains set up by the mechanical working. Although the steel can be cooled in still air after forging, it is, on the whole, better to bury it in lime or mica to ensure gradual cooling, and thus prevent any possibility of crack-development.

To bring the steel to its softest condition, it should be slowly heated to 850° C., soaked for 1–4 hours, and allowed to cool slowly in the furnace. The heating is, if possible, carried out in a closed box or tube, packed with mica dust or sand containing about 1 per cent by weight of charcoal. This prevents decarburization. Cooling rate should not exceed 20° C. per hour.

Tools should be rough-ground to shape before being hardened, to remove any soft skin or scale. As different conditions prevail when tools are hardened in a blacksmith's hearth as compared with a gas-fired furnace, the methods advised for each are given separately. In the gas-fired furnace the temperature can be measured and held steady within fairly close limits. In such circumstances, tools hardened in a gas-fired furnace should be passed through the high temperature chamber on a time-limit basis.

In the blacksmith's hearth, however, the temperature cannot be measured, and varies considerably from zone to zone, so that when hardening by this method, the operator must withdraw the tools according to their visible condition. While broad outlines of the methods recommended are given below, the rest depends entirely on the hardener's own skill.

HARDENING IN THE BLACKSMITH'S HEARTH

Preheat the cutting edge of the tool slowly, evenly, and thoroughly to about 850° C. (a bright cherry-red) then raise the temperature of the tool evenly in the heart of the fire almost to the final temperature. Any dirt adhering to the tool should be cleaned off, and the tool itself then heated to the highest possible temperature, but short of actually burning it. This is by no means easy to judge accurately without pyrometric aid, but if the operator uses coloured glasses he can, by using the rake, comfortably watch the tool nose in the heart of the fire, and withdraw it at the right moment. The tool first becomes white hot, and soon afterwards the nose may bubble vigorously. Heating is continued until the bubbles grow sticky and merge into a mass extending all over the cutting edge. This usually takes place quickly. The tool is then held for a few seconds only to make the temperature thoroughly uniform, then withdrawn and placed in an air blast. The hardening temperature should be only just short of fusing. This practice of judging by the eye is only advocated for the blacksmith's hearth in the absence of a trustworthy pyrometer. It presents many dangers, and if not carried out with the utmost care, is liable to cause irreparable harm. *These instructions do not apply to the molybdenum high-speed steels now being used as substitutes.*

Burning the tool nose is never to be recommended, as this lowers its cutting efficiency, but the tool must be hot enough or, again, efficiency will be lost. It will be seen that the margin between success and failure is a very narrow one, hence the necessity for the highest degree of skill on the part of any operator using the blacksmith's hearth for the treatment of these steels.

HARDENING IN THE GAS-FIRED FURNACE

It is always safer to heat-treat cobalt high-speed steels in a gas-fired furnace. The preheating should be carried out in the low temperature chamber of the furnace slowly, evenly, and thoroughly to about 850° C. The tool should then be quickly transferred to the high temperature furnace or chamber, maintained at the temperatures given in Table XLIX. These temperatures are essential in order to obtain maximum cutting power. The

TABLE XLIX

Section in Inches	Time Seconds	In Furnace Maintained at ° C.		
		Steel No. 1	Steel No. 2	
3/8 sq. × 3	65	1330–1350	1320–1340	In Furnaces not Atmosphere-controlled.
7/16 ,, × 3	75	,,	,,	
1/2 ,, × 3	85	,,	,,	
5/8 ,, × 3	95	,,	,,	
3/4 ,, × 3	105	,,	,,	
7/8 ,, × 3	120	,,	,,	
6 × 3 × 1 Flat tyre-turning tools.	135	,,	,,	

tool must not be exposed to the higher temperature for too long a period or it will burn and be ruined. It is a good plan to check the time of heating by a stop watch. The operator will have to discover for himself the best time for any particular type or section of tool to remain in the furnace. Table XLIX shows advised times for small lathe tools or toolholder bits. These should serve as a rough guide. The dimensions of the furnace also influence the time required.

Where tools of considerable mass have to be hardened, it may be advisable to give them a double preheating, the first at 620°–700° C., the second at 870°–925° C. The steel should never be left at the actual hardening temperature for a soaking period, as this may lead to considerable decarburization as well as a deterioration due to coarsening of the grain structure, and even to the partial remelting of its constituents. If the latter occurs, the structure of the steel approximates to that of the original ingot, and the tool then becomes useless except as scrap for remelting, forging, etc.

QUENCHING

Tools made from the cobalt high-speed steels should for preference be quenched in an air blast, the air of which must be quite dry. If it contains the slightest moisture (as often happens with compressed air), great risk of cracking the tools is run. A fan-generated air blast should, therefore, be used. An alternative method is to cool the tools in whale oil, or one of the standard proprietary brands of good quality oil, but for straightforward lathe tools air is better, giving satisfactory cutting efficiency with less risk of cracking.

Whether the furnace is of the salt-bath or gas-muffle type is not important, so long as the heat is evenly distributed and the temperature carefully controlled. The working limits being relatively narrow, only carefully calibrated pyrometers should be used, and the end of the thermo-couple should be placed as near the tool nose as possible.

For drills, reamers, milling cutters, etc., this treatment for all classes of high-speed steel is specially recommended, as it not only confers increased cutting efficiency, but also relieves all hardening strains—an important matter with these tools. The chart, Fig. 87, shows the effect of the secondary hardening treatment on Steel No. 1 of Table XLVIII (and 1 of Table L). The rapid falling-off in hardness above 600° C. will be observed.

HARDENING MILLING CUTTERS OR OTHER COMPLICATED AND DELICATE TOOLS

All high-speed steels containing cobalt decarburize to some extent during heating for hardening, and the higher the cobalt content, the greater appears to be the degree of decarburization. Hence, it is essential to grind the working surfaces of the tool after hardening.

To protect the cutting edges of milling cutters, etc., made from these steels, the tools should be heated in a gas-furnace with a reducing flame, or, alternatively, in a salt bath. Painting with silica paint constitutes an additional means of protection.

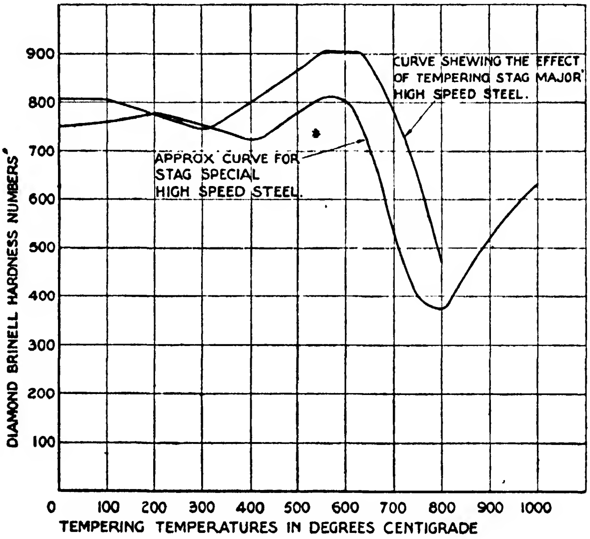


FIG. 87

Too rapid preheating must be avoided at all costs, to minimize strains set up by variation in the mass of complicated tools. For the same reason, lower hardening temperatures than those shown in Table XLVIII for lathe tools are advisable. The skilled judgment of the hardener is effective here, but the steel manufacturer will advise if any doubt exists.

HARDENING SPECIAL TOOLS

Design and facilities often decide whether special tools shall be hardened in the gas-fired furnace or in the blacksmith's hearth, but complex design or long cutting edges demand a gas-fired furnace if the best results are to be obtained.

TUNGSTEN HIGH-SPEED STEELS

These steels can be used for all types of cutting tools and for the machining of most materials. The general principles for hardening high-speed steels must be followed. Table L gives the three main steels of this group, with their condensed heat-treatments.

They should be forged at an orange colour, the temperature being raised slowly and evenly to 870° C., then more rapidly to forging heat, cooling down after forging being slow, in lime or mica, the object being to minimize the danger of cracking. The steel is then reheated slowly and evenly to 900°–950° C., allowed to cool in still air, reheated to 800°–820° C., and again cooled in still air. To put the steel into the softest condition, it is heated to 850° C. and cooled down in the furnace at a rate not exceeding 20° C. per hour to 540° C. Cast iron chips can be used to pack the closed box or tube in which the steel is annealed, to prevent decarburization. The steel is held for one to four hours at the annealing temperature.

Sometimes a further annealing at 650°–730° C. may be expedient after a tool has been machined, in order to relieve the strains set up by machining. In any event these steels must be annealed after forging, and the steel should be roughly ground afterwards to remove scale and soft skin in advance of hardening.

The hardening of these steels involves similar precautions to those for hardening cobalt high-speed steel, namely, a slow and even preheating to 850° C. in the low temperature chamber of the furnace, followed by quick transfer to the high temperature furnace, working to the temperatures given in Table L. These temperatures should be attained quickly, and the tool held at temperature for the period suggested in Table XLIX.

In hardening these steels in the blacksmith's hearth, the point to watch for is the bubbling of the nose when the steel is at a white heat. After this bubbling has extended all over the cutting edge, which usually takes place rapidly, the tool is withdrawn. It is then placed quickly in a fan-generated air blast to cool.

Secondary hardening treatment will be found beneficial. Fig. 87 shows the effect of this on Steel No. 1 of Table L. The rapid fall in hardness after 600° C. will again be observed.

TABLE L

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Anneal at ° C.	Preheat to ° C.	Harden at ° C.	In	Give Secondary Hardening Treatment at ° C.
1	0·7–0·8 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 18–20 tungsten, 4–5 chromium, 1·2–1·6 vanadium.	1100–1150	925	900–950, cool in still air and then heat to 800–820	850	1290–1330	Air	580–600
2	0·6–0·7 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 14–16 tungsten, 3·25–3·75 chromium, 0·25–0·75 vanadium.	1100–1150	925	do.	850	1250–1300	Air	580–600
3	0·8 carbon, 10·0 tungsten, 4·0 chromium, 2·0 vanadium, 0·7 molybdenum.	1120–1200	925	870–900	790–870	1260–1290	Air or Oil	540–620

It may, on occasion, be desired to straighten a tool that has warped slightly on being hardened. This should be done at once, before the tool's temperature has declined below 230° C. If the operation is carried out after the secondary hardening treatment, the steel must not be allowed to cool below 560°–580° C.

MOLYBDENUM HIGH-SPEED STEELS

With the spread of war to the Far East, sources of tungsten were lost, or, at least, access to them became more difficult. This led steel manufactures in Great Britain to turn their attention once more to the molybdenum high-speed steels so widely used in the United States of America, where native sources of tungsten are limited. It had long been known that molybdenum would replace about double its own weight of tungsten, but previous experiments carried out in Britain had not succeeded in producing steels that gave perfectly consistent results.

Under the stress of war, however, and with the aid of metallurgical experts, all giving their brains to the task, a range of molybdenum high-speed steels was developed, some of which have proved as good as, perhaps even better than, the corresponding tungsten high-speed steels they soon began to replace.

Table LI gives a list of the most commonly used English and American types of these steels with their compositions and condensed heat-treatments.

In general, these steels can be heat-treated similarly to the other high-speed steels (particularly the tungsten group), but the following points should be borne in mind. They are more susceptible to decarburization, are forged at lower temperatures, and need lower hardening and tempering temperatures than the tungsten high-speed steels to which they correspond.

The heating for forging is carried out slowly and evenly to 815° C., and then to the temperature, and a fair reduction should be carried out at each stroke. The upper limit of forging temperature must on no account be exceeded, and forging never be continued below 900° C. Owing to their susceptibility to decarburization, these steels must only be held in the furnace at the maximum forging temperature for the shortest possible time necessary to ensure adequate heat uniformity in the steel.

Cooling down after forging must be slow, preferably in ashes, lime, or mica, down to about 150° C., so as to avoid forging strains, causing stress cracks.

TABLE LI

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Anneal at ° C.	Preheat to ° C.	Harden at ° C.	In	Temper or "Secondary Harden" at ° C.
1	0·8 carbon, 4·0–5·5 molybdenum, 6·0 tungsten, 4·5 chromium, 1·35 vanadium.	1000–1100	900	820–840	820–870	1220–1240	Oil or Air	560 for 45 min. twice, or 560 for 90 min.
2	0·8 carbon, 1·5 tungsten, 4·0 chromium, 1·0 vanadium, 9·0 molybdenum.	1040–1095	900	845–870	760–815	1175–1230	Oil or Air	510–590
3	0·8 carbon, 4·0 chromium, 2·0 vanadium, 9·0 molybdenum.	1040–1095	900	845–870	760–815	1175–1230	Oil or Air	510–590
4	0·8 carbon, 1·5 tungsten, 4·0 chromium, 1·5 vanadium, 9·0 molybdenum, 5·0 cobalt.	1040–1095	900	845–870	760–815	1200–1230	Oil or Air	510–590

The steels are reheated after forging, to between 820° and 840° C., and for ordinary annealing the same procedure is followed as for the tungsten high-speed steels.

Where it has been customary to relieve machining strains, after machining particularly intricate tools of high-tungsten high-speed steel, the same course must be followed with the molybdenum high-speed steels, the temperature being between 650° and 730° C., with the same care as regards slow cooling.

The molybdenum high-speed steels need as careful preheating as the high-tungsten high-speed steels, and large sections must be carefully preheated to between 760° and 815° C. before being put into a hot furnace.

The general method for hardening molybdenum high-speed steels resembles that for high-tungsten high-speed steels, with recognition of the facts previously mentioned, that hardening temperatures are lower and care necessary to avoid decarburization. The temperatures are shown in Table LI.

SECONDARY HARDENING

The efficiency of practically all high-speed steels is improved by a secondary hardening treatment, and generally the higher the alloy content of the steel, the more it responds to this treatment. Some indication of the influence of secondary hardening (which may be likened to tempering) is given in Table LII.

TABLE LII

Hardening Temp. ° C.	C 0·79, Si 0·20, Mn 0·25, Cr 4·0, W 14·0, V 0·65				C 0·75, Si 9·29, Mn 0·20, Cr 4·2, W 18·0, V 1·0			
	Air-cooled		Secondary Hardened (575° C.)		Air-cooled		Secondary Hardened (575° C.)	
	Vickers	Rockwell	Vickers	Rockwell	Vickers	Rockwell	Vickers	Rockwell
1320	764	63·5	836	64·5	793	64·1	852	65·0
1328	760	62·9	831	64·6	780	63·4	864	65·2

For cobalt high-speed steels, the secondary hardening treatment should always be carried out, because it greatly increases the cutting efficiency and hardness of the tools.

For molybdenum steels the steel should not be allowed to cool down below 40° C. from the quenching temperature, and should be charged into an already heated furnace, held steady and under accurate pyrometric control at 560° C. After the tool nose has been thoroughly soaked at this temperature, it should be held for about half an hour, then laid on the floor to cool.

Owing to their susceptibility to decarburization, the tools must not be kept at the hardening heat longer than is necessary to ensure adequate heat uniformity of the steel. The exact heating time cannot be laid down, as this is affected by the type of furnace, the furnace temperature, and the size and shape of the tool to be hardened, in conjunction with the heating capacity of the furnace. *Coke fires or the blacksmith's hearth are not advised for these steels.* The surfaces of tool cutting edges should be rough ground or machined after annealing to remove any superficial flaws and to lessen the grinding required after hardening.

Quenching for hardening can be carried out in either oil or a strong, dry, fan-generated air blast.

Where it is necessary to straighten a tool after it has been hardened, this must be done immediately after hardening, while there is still considerable residual heat in the tool, and before it has cooled down to room temperature.

Tempering is carried out *immediately* after hardening at 560° C. for a period of 45 min. and the tool then cooled in still air. Retempering for a further 45 min. at 560° C. is suggested, but is, in any event, advisable for tools subject to shock. Alternatively, a single temper at 560° C. for 90 min. gives equally good results, although perhaps not in every instance.

Tools with sharp corners or marked variations in section, or of large area, must never be given a drastic oil quench. If oil is used, however, the tool should always be removed at red heat (590° C.) and allowed to cool in air. *Blind holes* (holes which do not penetrate right through a tool) should always be plugged with clay or asbestos.

Single point cutting tools should be hardened at the higher end of the hardening range.

Tools used in intermittent cutting, or subject to chatter, should be hardened at about the middle of the hardening temperature range, and this applies equally to drills, countersinks, taps, milling cutters, reamers, broaches, form tools, etc.

These molybdenum steels will take any special surface treatment normally applied to high-tungsten high-speed steels, including the cyaniding treatment.

CHAPTER XXIX

Heat-treatment of Alloy Chisel Steels

TABLE LIII gives a survey of the most commonly used alloy chisel steels, with their condensed heat-treatments. The importance of proper heat-treatment must be stressed, because without it these steels will not make up tools capable of withstanding the severe fatigue stresses they are called upon to meet, particularly when used in pneumatic machines, and capable also of retaining a keen cutting edge.

Steel No. 1 is specially designed for dressing alloy steels and hard and tough materials. It hardens in oil and needs little or no tempering, so that its manipulation is easy. Many steel makers advocate no tempering of this steel, but the authors are not wholly convinced that this is ideal practice, even with the so-called non-tempering chisel steels. Chisels made from this steel retain a keen cutting edge with excellent wear-resistance, while their cutting efficiency and the speed with which they remove material make them highly economical. The steel is usually supplied ready annealed, but if re-annealing is necessary, should be heated to and thoroughly soaked at 730° C., then allowed to cool at a rate not exceeding 25° C. per hour down to about 600° C. Forging should be carried out with rapid but light blows, and care taken not to continue forging much below 900° C. Heating for forging should be slow up to 790° C. Cooling should be slow, in ashes, lime, or mica. If the chisel shows thumbnail cracks, more or less following the contour of the intended cutting edge, it is a sign that forging was carried out with the steel at too low a temperature.

The type of work for which the chisel is intended will largely govern its hardening temperature. To some extent, the higher this temperature, the harder the cutting edge, but for general work 900° C. should not be exceeded. Heating for hardening should be slow up to 760° C., and the steel should be maintained at temperature for 10–30 min. Tempering is not absolutely essential for chisels, but although reheating is advised, should the same steel be used, as it sometimes is, for dies, the tempering temperature should be 200°–230° C. for cold dies and 500°–550° C. for hot dies.

TABLE LIII

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Normalize at ° C.	Anneal at ° C.	Harden at ° C.	In	Temper at ° C.
1	0·4–0·5 carbon, 0·2–0·4 silicon, 0·2–0·4 manganese, 1·8–2·0 tungsten, 1·7–1·9 chromium, 0·15–0·25 vanadium.	1000–1050	850	—	730	900–950	Oil	150–200 preferable, though not absolutely necessary. 200–230 for cold dies. 500–550 for hot dies.
2	0·35–0·45 carbon, 0·2–0·4 silicon, 0·2–0·4 manganese, 2·5–3·0 nickel.	950–1000	870	850 Air cool	700	800–850 Cutting edge only	Thin oil	Tempering not essential, but advisable at 150–200
3	0·3–0·45 carbon, 0·2–0·4 silicon, 0·2–0·4 manganese, 1·9–2·1 tungsten.	950–1000	870	870	730	900	Oil	
4	0·5 carbon, 0·8 chromium, 0·2 vanadium.	980–1095	870	900	775–790	775–790		
5	0·6 carbon, 0·5 chromium.	1040–1150	870	870	775–790	790–815	Brine or water	175–290
6	0·5 carbon, 0·4 manganese, 1·0 silicon, 0·5 molybdenum.	980–1065	870	870	790–815	855–915	Brine or water	175–370
7	0·35–0·40 carbon, 0·5 manganese, 3·0–3·5 nickel, 0·5–1·0 chromium.	1000–1100	850	840 Slow cool	680	800–820	Oil	200–250
8	0·35–0·45 carbon, 0·5 manganese, 2·5–3·0 nickel, 0·5–1·0 chromium, 0·4–0·6 molybdenum.	1100–1200	870	—	680	800–820	Oil	200

Steels 7 and 8 have been found to give excellent results in practice. Both steels should be softened (annealed) at 680° C. before being hardened, and only the cutting edge of the chisel should be hardened and tempered. Both steels work-harden to a greater extent than Steel No. 2.

***Note.* With all chisels, a final Vickers hardness value between 550 and 650 should be aimed at.**

When the steel is made into pneumatic chisels a special treatment becomes necessary to avoid breakages at the shank. The entire chisel is heated to 850°–870° C. and quenched in oil. The whole chisel is then tempered at 500° C. This strengthens the shank and gives a Brinell hardness number of 415–388. The cutting edge is next hardened in the usual way by heating it to 900° C. and quenching in oil. No further tempering will then be needed.

Steel No. 2 is a high quality nickel steel often needing only a single treatment. Tempering is not absolutely necessary, but reheating to 150°–200° C. is advised. The chisels made from this steel stand up admirably to their work. The same steel is adaptable to many other tools, such as sates, drifts, riveting tools, etc., after similar treatment.

This steel is much more resistant than a high quality carbon tool steel to shock. An interesting point is that the tool edge of a chisel manufactured from it can be made sharp again, when blunted, by touching it up with a sharp file. Work-hardening (see *The Structure of Steel*) sets in in this steel when it is subjected to percussion, and this makes the head of the chisel less likely to splay out under the blows of the hammer. This property of work-hardening is also of importance in connection with the cutting edge. On a first grinding, the results may not be so satisfactory as those after the edge has been reground—the reason being that the edge possesses additional hardness after the first work has been put upon it, even though it may have been blunted.

Toughness is another quality possessed by tools made from this steel, which are also extremely long-lasting.

A normalizing operation should follow the forging of the steel to relieve forging strains. Heating should be slow up to 850° C., and should be maintained for 15–16 min. After having cooled in air, the chisel should have its cutting edge heated to the temperature given in Table LIII, and oil of an extremely thin type should be used for quenching. Little or no tempering is necessary, but if re-annealing is desired, this can be carried out by heating to 730° C. and allowing to cool slowly.

A point worthy of note is that if decarburized skin is carefully removed from the surface of alloy steel chisels after heat-treatment, and any tool marks ground out, the chisels will be in a better condition to withstand fatigue stresses, and failures will be fewer in consequence. Heating should in all instances be slow and even, to about 790° C. for forging and annealing, and to 760° C. or thereabouts for hardening. The period at temperature should be from a quarter of an hour to one hour for normalizing, and from one hour to four hours for annealing. The soaking time at the hardening temperature will vary. For Steels Nos. 1, 2, and 6 it will be from 10 to 30 min. For Steel No. 4 from 20 to 30 min; for Steel No. 5 for 10 min., and for Steels Nos. 7 and 8, for 5 to 10 min. (cutting edge only).

CHAPTER XXX

Heat-treatment of Some Special-purpose Tool and Other Steels

THE number of purposes for which special tool steels have been developed is legion, and to give the detailed heat-treatments recommended for every such steel would require a book double or treble the size of the present. Nevertheless, the reader confronted with a particular heat-treatment problem is entitled to expect guidance, and as nothing is more irritating than to draw blank in a work of reference, the present chapter is devoted to the heat-treatment of a number of widely different steels, each of which fulfils a special function or set of functions. There may very well be, and in many instances are, numerous other steels of varying compositions fulfilling identical functions. Our object here, however, is not to be all-embracing, but to choose from each group of purposes a typical steel not previously discussed and detail its heat-treatment. Some of the alternative steels may already have been dealt with in earlier chapters, since many tool steels fulfil numerous functions. Others are peculiar to individual manufacturers, and the reader would do better to apply to these makers for detailed advice.

Table LIV gives a list of the steels dealt with in this chapter, with their average compositions, condensed heat-treatments, and their particular functions. The following notes merely amplify the data given in the table.

Steel No. 1 is a water-hardening steel which is less expensive than high-speed steel, but contains tungsten, though not enough for it to rank as a high-speed steel proper. Its chief properties are hardness, fine grain structure, and the ability under certain conditions (i.e. where the service is not so severe as to generate great heat at the tool nose) to keep a keen cutting edge. It is designed for the best finishing work, where the output is not large enough to call for a high-speed steel or tungsten-carbide tool, and where the type of work is not too arduous. It will give excellent results on chilled iron and hard materials generally, and is specially useful for brass working. It is also suitable for tools used in grooving or fluting chilled iron flour rolls, but is given a special temper for this purpose. Hence, if it is required for fluting

TABLE LIV

Steel No.	Typical Composition per Cent	Begin Forging at ° C.	Finish Forging at ° C.	Normalize at ° C.	Anneal at ° C.	Preheat to ° C.	Harden at ° C.	In	Temper at ° C.	Function
1	1·1–1·4 carbon, 0·2–0·4 silicon, 0·2–0·3 manganese, 3·5–4·0 tungsten, 0·25–0·75 chromium.	950–1000	760–790	—	730	—	820–840	Water	150–200	Finishing work, and for brass, fluting chilled iron rolls.
2	0·25–0·35 carbon, 0·2–0·4 silicon, 0·4–0·8 manganese, 1·0–1·11 chromium, 0·15–0·25 vanadium.	1050 (max.)	850	—	730	—	840–860	Water	200 for 1½–2 hr.	Pneumatic rivet snaps, etc.
3	1·5 carbon, 12·0 chromium, 0·75 molybdenum.	980–1065	980	—	870–900	815	925–980	Oil	200–540 for 2½ hrs. min.	Thread-rolling dies.
4	0·6 carbon, 0·6 manganese, 0·9 chromium, 0·7 molybdenum, 1·75 nickel.	1010–1065	845	870	760–775	—	815–840	Oil	315–595	Forging hammer die blocks.
5	0·35 carbon, 10·0 tungsten, 3·0 chromium, 0·5 vanadium.	1120–1175	900	—	870–900	815–845	1010–1175	Air or oil	540–675	Die inserts.
6	0·6 carbon, 0·6 manganese, 1·0 chromium, 0·5 molybdenum, 1·5 nickel.	1010–1065	845	800	760–775	—	840–860	Oil	315–540	Solid shear blades.
7	0·5 carbon, 0·8 chromium, 0·2 vanadium.	980–1095	815	800	775–790	—	775–790 900–950	Oil ,,	150–290 230–315	Hot rivet sets.
8	1·15 carbon, 0·3 manganese, 1·6 tungsten, 0·5 chromium, 0·2 vanadium.	980–1065	870	900	780–800	—	840–860	Oil	175–290	Taps and thread-cutting tools.
9	0·4–0·45 carbon, 0·2–0·3 silicon, 0·4–0·8 manganese, 1·0–1·1 chromium, 0·15–0·3 vanadium.	1050	850	—	730	—	850	Oil	200	Plastic moulds.
10	1·0–1·3 carbon, 12·0–14·0 manganese, 0·2–0·4 silicon.	950–1000	760–790	—	—	—	Toughen 950–1000	Water	—	Wearing parts of machinery for crushing and grinding, etc.
11	0·35–0·45 carbon, 0·2–0·3 silicon, 0·4–0·8 manganese, 0·95–1·15 chromium, 0·15–0·3 vanadium.	1050	850	—	730	—	Harden 800 ½ in. up point only	Water	—	Coalcutter picks.

these rolls, the fact should be stated. It is usually supplied in the annealed condition. For forging, it should be heated to a bright red (away from the blast, if a smith's hearth is used), i.e. to about 950°–1000° C., then forged and set aside to cool. It should not be hammered after it has cooled below a dull red—760°–790° C. The cutting edge only should then be reheated to 820°–840° C. and cooled in lukewarm water. Tempering should be carried out at 150°–200° C. Precautions against too rapid or irregular heating are necessary, to prevent cracking.

If re-annealing is desired, the steel should be heated to 730° C., thoroughly soaked, and then allowed to cool slowly.

Steel No. 2 is designed for rivet snaps used in conjunction with pneumatic hammers, and for other tools subjected to a succession of rapid blows. Being specially tough, it withstands fatigue due to the rapid blows, and has sufficient hardness to maintain efficiency. It has also been used for nosing shells, making shrapnel discs, etc., for hot nut-piercers and heavy duty lathe-centres.

Supplied annealed, it should, if intended for rivet snaps, be quenched as a whole snap in water from a temperature of 840°–860° C. and afterwards tempered at 200° C. for one and a half to two hours. This treatment should give a Brinell hardness number of 477–444. For re-annealing, if desired, the steel should be heated to and thoroughly soaked at 730° C.

Steel No. 3 is a high carbon, high chromium steel designed for thread-rolling dies. This steel should be heated slowly for forging to 870° C. Forging should begin at 980°–1065° C. according to the cross-section, but not continued after the steel has cooled down to 980° C. Cooling from the forging operation should be gradual, the die being buried in ashes, lime, or mica. No normalizing operation is necessary. Annealing is carried out by heating at the rate of one hour per inch of thickness for a period of one to four hours according to mass, at 870°–900° C.

Dies made from this steel need to be machined after annealing, so as to eliminate all traces of soft skin and other superficial blemishes that would be harmful. To relieve the stresses set up by machining, a special stress-relief treatment consisting of heating up to 595°–650° C. will prevent warping of the teeth when later heat-treated.

Heating for hardening should always be extremely slow, and a preheating to 815° C. is specially beneficial. An atmosphere controlled furnace is particularly recommended because it eliminates the formation of soft skins. The hardening temperature range is 925°–980° C., and the steel should be held at the hardening heat for from a quarter to three-quarters of an hour. Quenching in oil follows.

Heating for tempering must also be slow, the temperature range being 200°–540° C. Of great importance is the period of temperature maintenance, which must be prolonged, a minimum of two and a half hours being advisable, longer if possible.

Steel No. 4 is a nickel-chromium-molybdenum steel largely used for forging hammer die blocks and other purposes, but not for *die inserts.* (Die inserts are small pieces of steel inserted in a die block to raise its strength or decrease the wear at given points of the impression. They are usually of costlier steel than the main mass and greatly lengthen die life.) To forge this steel it is essential to heat it gradually and evenly to 790° C., and then more rapidly to 1010°–1065° C., at which temperature forging may be carried out, but should on no account be continued below 845° C. A normalizing treatment is necessary after forging, to unify forging strains. For this, the steel is heated slowly to 790° C., raised more quickly to 870° C., and held at this temperature for a quarter of an hour to an hour, according to its section.

Annealing requires gradual and even heating to 760°–775° C. for a period of one to four hours, and cooling from the annealing temperature should not be allowed to proceed faster than 20° C. per hour down to 550° C.

It is most important not to place dead-cold blocks into the furnace. They should be warmed first, and the furnace not raised to a temperature over 260° C. The time required to heat the steel for hardening follows the general rule given previously, i.e. one hour per inch of section. The hardening temperature should be maintained to ensure complete penetration of heat. A good average time at this temperature is 25 min. per inch of section.

It is important in quenching that the whole mass of steel should be covered by the quenching oil, and it is a great advantage if some form of oil circulation is adopted to ensure thorough dispersal of the heat, while the quantity of oil in the tank should be large enough to avoid any possibility of too sharp a temperature increase. The steel should not be withdrawn from the oil before the temperature has declined to about 230° C.

Tempering can be carried out on a hot plate or in a salt bath, but a furnace is best. Neither bath nor furnace should be heated above 200° C. for the furnace and 150° C. for the bath before the tools are introduced. Similar heating and soaking times as for hardening will prove satisfactory.

As far as possible, this steel should be heated in a furnace with controlled atmosphere. Where this is impracticable, the face of the block carrying the die impression should be packed with charcoal or spent pitch coke as shown in Fig. 88.

Steel No. 5 is an alloy steel for die inserts. It should be heated slowly for forging to 845° C. Forging should be begun at 1120°–1175° C., but must not be carried on when the steel has cooled much below 900° C. Cooling from forging should be slow, in ashes, lime, or mica. Annealing is carried out at 870°–900° C. for one to four hours, according to section. For this operation the steel should be heated for one hour per inch of section, and not be allowed to cool down at a rate faster than 25° C. per hour down to 550° C. This steel should not be normalized.

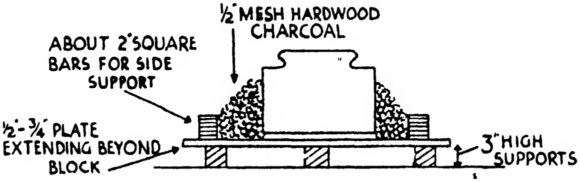


FIG. 88

If this steel is air-hardened, a fan-generated blast should be employed to ensure absence of moisture. Preheating for hardening is almost essential, and the steel is then raised quickly to the hardening temperature, but not soaked.

Steel No. 6 is an alloy steel for solid shear blades. It should be heated gradually and evenly to about 800° C. Forging should begin at 1010°–1065° C., but should not be carried on below about 845° C. Slow cooling in ashes, lime, or mica after forging is recommended. The steel will need a normalizing treatment after forging, and should be heated up gradually to 800° C. and held at this temperature for a quarter of an hour to an hour, according to mass. For annealing, gradual and even heating to 760°–775° C. and maintenance at the proper temperature for one to four hours are required, followed by slow cooling in the furnace at the usual desirable rate of 25° C. per hour down to 550° C.

Preheating for hardening is not necessary, but heating should be slow and even to 840°–860° C., followed by oil quenching. If the blades are long and weighty, some agitation of the quenching medium is desirable, and the blade cutting-edges should be undermost. During the quenching operation the blade should then be reversed in the bath. This will reduce the liability to distortion. Tempering is carried out within the range 315°–540° C. The steel should be held at the tempering temperature for at least two hours. The actual tempering temperature is governed by the degree of hardness required in the blade and the type of material it is required to cut.

Steel No. 7 is a chromium-vanadium steel for pneumatic rivet sets designed to work on hot material. Heating for forging must be slow and even up to 800° C. Forging is begun at 980°–1095° C., but must not be continued below 815° C. A normalizing treatment should follow forging, the steel being heated slowly to 800° C., and held at this temperature for a quarter of an hour to one hour. For annealing, the steel is heated evenly to 775°–790° C. and held for one to four hours, cooling down at the usual rate as given for Steel No. 6.

To harden the steel, it must be heated gradually and evenly. Two different treatments can be used. The first is to heat the steel to 775°–790° C., hold for a quarter of an hour, then quench in oil. The second is to quench from 900°–950° C. in oil. In the first treatment the tempering range is 150°–290° C., and in the second 230°–315° C.

When immersing the sets in the quenching bath, they should be fully covered by the oil, and particular attention should be paid to ensuring that oil passes continuously into and out of the cup-shaped depression of the tool.

Steel No. 8 is a special alloy tool steel designed for taps and similar tools intended for the cutting of threads. Forging demands slow heating to 815° C. The forging operation begins at 980°–1065° C., but must not be carried on much below 870° C. A normalizing treatment should follow forging, the steel being heated gradually to 800° C. and then more quickly to 900° C. To anneal the steel, heating should be slow and even up to 780°–800° C., the heat being held for one to four hours, after which slow cooling at the standard rate in the furnace should follow, unless a salt or lead bath has been used for heating, in which case the steel should be cooled in ashes, lime, mica, or infusorial earth. The use of the lead or salt bath for heating this steel involves a rather higher hardening temperature, but to balance this, rather less time at heat than for furnace-heated steel, while an addition of about 10° C. should be made to the hardening temperature given in Table LIV, and below. The steel should not be cold when placed in the bath.

Heating for hardening should be slow and even, and the steel should be oil-quenched at 840°–860° C.

In general, a controlled atmosphere furnace is preferable to either the lead or the salt bath, but care should be taken to see that the furnace atmosphere is rich in carbon monoxide, with minimum moisture and carbon dioxide. If the semi-muffle type of furnace is employed, there should be an effective gas-curtain or surplus of gas, and soaking at the hardening temperature should be avoided.

The tempering temperature range is 175°–290° C. As a rule only the cutting portion of the tap is hardened, the shank being left in a tougher and less hard condition, but if the shank has also been hardened, it will be too brittle and will need tempering to remove this brittleness.

Steel No. 9 is a chromium vanadium steel used for plastic moulds. It may be employed either for hobbing or for direct-cut moulds. When annealed it has a Brinell hardness of less than 156. After hobbing it should be heated to 850° C. and quenched in oil. Tempering should be carried out immediately the steel is cool, at 200° C., for one hour.

Steel No. 10 is the well-known austenitic manganese steel used for wearing parts of crushing and grinding machinery, railway and tramway special trackwork, dredger pins, buckets, links, lips and bushes, etc. Before this steel is forged it must be heated thoroughly to the centre. Then the heat may be raised gradually, frequently turning the piece in the fire (if the smith's hearth is used) to a uniform yellow colour (1050° C.). The steel should not be forged while at a dull red. When it has been forged it should be reheated to a uniform light orange (1000° C.), plunged into cold water, and kept moving. This toughens it. It is worse than useless to plunge this steel into the water at any temperature below that producing a light orange colour.

Steel No. 11 is an alloy steel specially designed for high quality coal-cutter picks. For forging, it is heated slowly and evenly to 1050° C., forged to shape, and allowed to cool slowly.

Forging should not be continued below 850° C. To harden picks made from this steel, the point or points should be very slowly heated. They should then be quenched in cold water for a distance of ½ in. up the point from a temperature of 800° C. (a cherry-red heat), keeping the pick in motion to avoid *straight-line hardening* (too sharp a line of division between the hardened and unhardened parts), as this would lead to premature fracture in service.

It must be repeated that this collection of miscellaneous steels does not attempt to be comprehensive. A typical steel of each class (with the exception of Steel No. 10) has been chosen, but many other types of steels may be used for the same purposes, some of them dealt with earlier in different categories (e.g. die steels, high-speed steels, stainless steels, etc.). Moreover, the steels shown in Table LIV must not be regarded as necessarily the best for their particular functions. They are typical steels, and no more is claimed for them than this.

CHAPTER XXXI

Spheroidizing Ball-bearing Steels and Austempering

We have left to a late stage in our exposition two minor but very interesting forms of heat-treatment. The first of these, *spheroidizing*, is of extreme importance in connection with certain high carbon steels. It comprises heating steel to a temperature and for a period long enough to cause that constituent known as cementite (see *The Structure of Steel*), when existing either "free" or together with ferrite in the form of pearlite, to form microscopic balls or "spheroids."

When this happens to the full, the hardness of a carbon steel is reduced, but its machinability greatly increased, so that spheroidizing is in effect a form of annealing. When the steel is heated just below the lower critical point, the operation is, indeed, often described as *sub-critical annealing.* This type of structure can be obtained by heating a *hyper-eutectoid pearlitic* steel (one whose structure consists of cementite and pearlite alone—see *The Structure of Steel*) to a temperature just below the Ac_1 point, or alternatively at or very slightly above Ac_1; but in this instance the heating period must be shorter, and the results are less sure.

The point of greatest importance is the heating period, which, if inadequate, will not produce the desired structural condition. For these high carbon steels temperatures between 680° and 700° C. are generally employed.

One of the principal advantages of spheroidizing is that it facilitates the machining of high carbon tool steels, thereby greatly reducing labour cost and tool life. At the same time, however, the very fact that the cementite (or carbide) exists in the form of microscopic spheroids means far less danger of cracking and distortion or warping when the tool is afterwards hardened by quenching in oil or water. Moreover, the tool when ultimately hardened is uniform in properties.

Spheroidizing of the cementite is a matter of paramount importance in the fabrication and heat-treatment of the high carbon, high-chromium steels used so extensively in the manufacture of *ball-bearings and ball-races.* The composition limits for this steel are generally as follows: Carbon 0·9–1·1; silicon less than 0·3; manganese 0·4–0·6; chromium 1·1–1·5 per cent.

To spheroidize and soften this steel adequately for machining, one has the choice of two alternative treatments: (*a*) prolonged soaking at 800° C., followed by slow cooling in the furnace to little more than atmospheric temperature; or (*b*) soaking at 820° C., followed by cooling down to 650° C. at a rate not exceeding 20° C. per hour. Treatment (*a*) takes about 36 hours, whereas treatment (*b*) takes from 12–18 hours, depending on the section of the bars being treated.

After either of these treatments, the Brinell hardness should not exceed 229.

To harden this steel, it may be quenched in water from 780°–800° C., or quenched in oil from 820°–840° C., followed in each instance by tempering at 130°–180° C. Diamond hardness values between 800 and 900 may then be expected.

The remarks already made have had particular reference to the high carbon steels containing an excess of cementite, and it is the spheroidizing of this free carbide that is so necessary in order to avoid hardening cracks. There are other instances, however, where spheroidizing of steel of much lower carbon content is carried out for an entirely different purpose, as, for instance, in certain steels intended for *cold pressings*, e.g. in the manufacture of aircraft and automobile parts, such as brake-drums, etc. In such instances, the deformation by cold pressing is severe, and spheroidizing becomes a preliminary process in order thoroughly to soften the steel. Some idea of the influence of different treatments on the properties of a typical cold-pressing steel used for such purposes is given in Table LV.

TABLE LV

Carbon	Silicon	Manganese	Condition	Typical Tests	
				Tensile Strength tons/sq. in.	Elongation per cent in 4 in.
0·25–0·35	0·2 max.	0·4–0·7	Normalized 880° C.	31·5	28
			Annealed 880° C.	30·0	30
			Spheroidized 680° C.	25·5	33

The usual spheroidizing temperature for this class of work, as indicated, is about 680° C., a treatment that "balls-up" the carbide of the pearlite.

AUSTEMPERING

Austempering is, in some respects, not unlike the *patenting process* applied to steel wire. It comprises raising the temperature of a steel until its structural condition is completely *austenitic*, i.e. well above its upper critical point (see *The Structure of Steel*), and then immersing it in a molten lead or salt bath heated to and rigorously maintained at a chosen temperature, which cools it quickly to this temperature, but is above the temperature at which the austenite in the steel normally changes to hard martensite when quenched in oil or water at ordinary temperatures. The bath temperature is maintained, in short, below the change point of the steel, but still higher than that at which martensite forms under more drastic quenching conditions. The austenite is not retained, of course, but is gradually tempered, hence the term *austempering*, yielding a structural state comparable with, but perhaps finer than, that obtained by the more orthodox hardening and tempering treatments. The result is a tougher steel for a specific hardness than can be obtained by the normal method of hardening followed by tempering.

It is claimed, quite legitimately, that austempering minimizes cracking and distortion during heat-treatment.

It should be noted that there is a limit for the carbon steels to the effectiveness of austempering. This is because the cooling rate must not exceed extremely narrow limits in either direction, and is only effective in producing the required structural condition over a distance or depth of about $\frac{1}{4}$ in. from the surface of the steel. This means that austempering of carbon steels more than $\frac{1}{2}$ in. thick will not be complete. It is probable that alloy steels rather thicker than this can be austempered, but research has not yet sufficiently investigated this field for certainty to be established.

The heat maintenance period is of vital importance, because it is necessary to ensure that none of the original (austenitic) structure remains unaltered and liable, as the steel cools, to turn into martensite. No hard and fast rule can be laid down, since the precise period depends entirely on the type of steel and the degree of hardness desired. It may vary from twenty minutes to several hours.

Austempering appears to be most beneficial in steels with carbon contents ranging from 0·5 to 1·2 per cent. Some alloy steels cannot be effectively treated by this method because to transform their structure to the condition (pearlitic) in which martensite is avoided would involve a cooling temperature maintenance period so long as to be wholly uneconomical.

The exact temperature to which the steel should be heated is again variable with the carbon percentage, but will be largely coincidental with the hardening temperatures for carbon steels given in earlier sections. Variable, too, is the carefully chosen constant temperature of the salt or lead bath. The full range appears to be from 180°–400° C., the lower end of the range corresponding to the lower carbon percentages.

Austempering is hardly a heat-treatment process of major importance yet, because of the limitations of cross-section imposed upon it. Steel shovels appear to constitute one of the most familiar applications, but some attempts are also being made to apply it to steels for case-hardening, because it may enable steels with higher carbon percentages to be used that would otherwise not be tough enough to withstand the stresses resulting from the ordinary heat-treatment. Experiments have also suggested a potential application of the process to springs of small cross-section.

CHAPTER XXXII

Case-carburizing (Case-hardening)

CASE-HARDENING (perhaps better termed case-carburizing) is one of the oldest of all heat-treatment processes. It is designed to give to steel parts called upon to withstand wear, shock, and fatigue an exceptionally hard surface or *case* combined with a tough *core* or interior. The operation proper comprises two distinct processes. First, the steel is heated to a specific temperature in either a liquid, a solid, or a gas rich in carbon, and, secondly, the parts thus dealt with must be separately heat-treated. The first stage raises the carbon content of the steel's surface by permeating the outer layers with particles of additional carbon. The second gives the necessary hardness to this carbon-rich surface, while rendering the interior or core tough.

This chapter does not deal with the mechanism of carburization (dealt with in *The Structure of Steel*), nor with its advantages, which are assumed to be well known, but is confined to the methods adopted. In ordinary commercial practice there are three different methods: (*a*) pack-hardening, (*b*) gas carburizing, (*c*) liquid carburizing. We shall deal with these in succession.

PACK-HARDENING

This comprises packing the articles to be treated in a box or tube containing some powder rich in carbon. The box or tube is fitted with a lid, which is usually sealed (*luted*) with clay or some other suitable material in order to exclude air. This method is probably the most commonly used, as it is certainly the most simple. The steel parts can be dealt with either in batches or continuously. The carburizing powder, whatever its composition, supports those parts in which heat readily produces distortion. Moreover, the steel cools down with desirable slowness in the box or tube, again with a beneficial effect in reducing distortion.

On the other hand there are drawbacks, mostly economic. The method absorbs considerable time, since the heating period is prolonged. while much labour expense is incurred in packing and unpacking the boxes or tubes.

The choice of carburizing compound or powder demands careful thought. Many different mixtures have been used, consisting of such materials as charcoal, charred leather, crushed bone or horn, potassium ferro-cyanide (or yellow prussiate of potash, as it is often called) and barium carbonate. Charred leather contains nitrogenous matter in addition to carbon and is a satisfactory carburizing medium, but better results are obtained by mixing about 60 per cent of wood charcoal with 40 per cent of barium carbonate. Many commercial compounds, however, use only about 20 per cent of some alkaline or metallic carbonate with a binder such as oil, tar, or molasses. To this mixture is also added about 20 per cent of powdered coke, to act as a heat conductor and thus render temperatures in the box more even.

A good case-hardening compound should not diminish appreciably in volume during the operations, and should be practically free from sulphur and phosphorus.

There is an inevitable loss of the carbonate, due to the absorption of carbon into the steel and the effect of heat, causing shrinkage, so that whatever mixture is employed, it should not be used twice unless a certain proportion of new or unused material is mixed with it. This proportion should not be less than 15–20 per cent, and may often need to be as high as 25 per cent, but the exact figure varies according to the skill and care of the operator, the design of the container, and the kind of bond or binder used.

Cost greatly affects the choice of a carburizing compound. Many of those mentioned above are too expensive for regular commercial use. Others are too dilatory in their action, needing inordinately long heating periods. Other factors affecting choice are (*a*) handling methods, which may be either economical or wasteful of carburizing compounds; (*b*) design of the carburizing container, which, if faulty, may expose the compound to the harmful action of the air while under heat; (*c*) the form of quenching method used, which, if direct, may cause a certain amount of the compound to be lost by burning.

Before being placed in the boxes, the parts to be carburized should be thoroughly cleaned by removing dirt, scale, or grease, in order to prevent the formation of "hard" and "soft" spots on the surfaces of the finished articles.

It may be that certain areas of the finished section are required soft. In such circumstances, assuming enough metal is left on the part before it is carburized, the carburized layer may be removed from this area by machining before the final heat-treatment is carried out. Alternatively, the areas in question may be protected from the carburizing action by coating them with films of copper, either electrically deposited or simply wiped with an acid solution of copper sulphate. Copper deposits 0·003–0·004 in. thick are perfectly adequate for this purpose. Thicker deposits flake off and defeat the object. The copper films formed prevent the steel from absorbing carbon over these areas. Fire-clay is also used protectively, while there are several proprietary paints available for identical purposes. This subject is dealt with in greater detail at the end of this chapter.

The packing of the box is most important. The empty container is first given a layer of compound from ½–1 in. deep, the thinner layer being for the lighter work. It is a mistake to use too much compound, because this will greatly prolong the heating period, the compound being a bad conductor of heat, and as little as will give the desired result should be employed. The exact quantity is governed by the form of the container and the parts being carburized. Distorted tubes or boxes need more compound on the top to allow for possible burning away, with consequent exposure of the parts.

The carburizing containers are largely made to-day from one or other of the heat-resisting steels or alloys containing nickel and chromium. These are often made as castings, though sheets are obtainable. In general, castings have advantages over containers built up by welding from heat-resisting sheet. In the first place they cost less, and can be made with thinner walls, which means a shorter heating period and a consequent saving in heating cost. Moreover, being all in one piece, there is less likelihood of failure than with a welded container, which, if the welding has not been expertly done, may fail in service.

Many case-hardening boxes are still made from ordinary rolled carbon steel or steel castings, but their use is largely confined to those firms who carburize but rarely, or have to deal with articles of great bulk or symmetrical form, when they may prove less expensive per case-hardened piece than the heat-resisting alloy containers. On the whole, tubes or cylindrical containers are preferable to square or rectangular boxes because they give more even heating, there being no corners to heat up more rapidly than the sides, with a consequent quicker heating up of the work in the corners than of that in the middle. Sometimes separate tubes inside boxes are used.

After the articles have been packed in the box, which is best done with the longest dimension vertical—a point of importance when case-hardening long, slender parts—they are heated to temperatures between 900° and 950° C. according to the chemical composition of the steel. It may be asked why the steel must be heated to so high a temperature. The reason is that iron is allotropic (i.e. capable of existing in several quite different forms —as is carbon: cf. coal, the diamond, and the "blacklead" in a pencil), and exists in different forms over different temperature ranges. Without going, as we have said, into the mechanism of carburization, we may briefly say that heat increases the ability of the outer layers of the steel to absorb carbon, just as heat increases the ability of tea to dissolve sugar, and the allotropic form in which iron exists at these high temperatures is that necessary for the maximum carbon absorption rate. In good practice the rate of absorption of carbon by the outside layers and diffusion towards the interior largely balance each other. The carbon content of the case is, therefore, usually about 0·85 per cent, the interior or core remaining virtually unchanged.

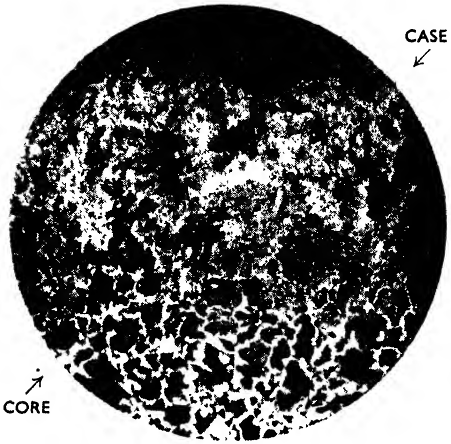


Fig. 89

After being carburized, the articles are slowly cooled in the boxes, and typical microstructures of case and core are shown in Fig. 89. Fig. 90 shows the structure of the case at a much higher magnification.

In a properly carburized part the higher carbon case should always gradually merge into the unchanged core, because if there is a sharp line of demarcation between them, the defect known as *exfoliation*, *peeling*, or *flaking* may occur during later heat-treatment.

Even so, however, carburized parts may be regarded, for all practical purposes, as composed of two steels, the case containing about 0·85 per cent carbon, and the unchanged core containing, for example, 0·15 per cent carbon. In view of this wide difference in carbon contents, two heat-treatments are required to produce the most satisfactory results.

(*By courtesy of Messrs. Blackie & Son, Ltd.*)
FIG. 90

The first treatment aims, therefore, to refine the relatively coarse structure of the core. The steel is heated to a temperature just above its *upper critical point* and then quenched in water. For those steels of inherently coarse grain the most suitable temperature is 870°–900° C., though with fine-grained steels, a properly designed furnace, and accurate temperature control, even higher temperatures (say 920°–940° C.) can be employed with little or no detriment.

As a general rule, however, the lower temperatures are used mainly to minimize distortion, while the nickel case-hardening steels also demand lower temperatures. The best average carburizing temperature for these nickel steels lies within the range 885°–920° C. Some extremely small or thin articles, where a heavy carburized case must be carefully avoided, have to be carburized at still lower temperatures, say 845° C. A good average minimum case depth for normal pack carburizing is 0·025 in.

The first heat-treatment outlined leaves the steel with a refined core structure, but low ductility and resistance to impact. Moreover, the case, though hard, will have an exceedingly coarse structure and be extremely brittle as a result. The second treatment, therefore, comprises reheating the parts to what is really a correct hardening temperature for the case. This temperature is between 760° and 780° C., and results not only in a refinement of the structure of the case, but also in that of the core, as shown in Fig. 91. The case is now properly hardened and the necessary toughness induced in the core. A useful and commonly applied test for case-hardened material is the fracture test. After proper heat-treatment the case has a fine-grained, "silky" appearance, and the core a fibrous fracture indicative of toughness, as illustrated in Fig. 92.

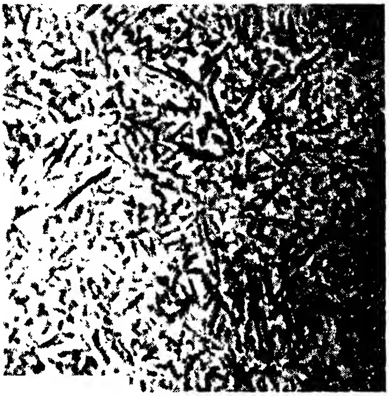


FIG. 91A. MICROSTRUCTURE OF "CORE" AFTER "FIRST" QUENCHING FROM 870°–900° C.

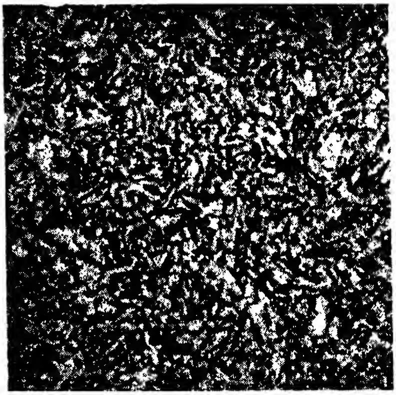


FIG. 91B. MICROSTRUCTURE OF "CORE" AFTER "DOUBLE" QUENCHING TREATMENT

Sometimes, with the primary object of reducing expense, a single heat-treatment is carried out. This may be a quenching direct from the carburizing temperature, or a reheating to about 900° C. followed by quenching, or a reheating to and quenching from about 830° C.

The first of these three alternative treatments results in an overheated case having a coarse structure and a core both brittle and lacking in shock resistance. This practice has little to recommend it, and should only be used for purposes requiring maximum surface hardness at the expense of other properties.

Reheating the carburized parts to about 830° C. followed by quenching gives somewhat better results, but the microstructures of both case and core are coarser than is desirable. In consequence, the core does not possess maximum resistance to shock, and the parts should not be used as components where this property is of primary importance.

The choice of carburizing furnace is of importance, and above all the attempt must be made to keep the carburizing temperature within ± 5° C., with even heating throughout within 10° C. In general it is better for the furnace to be capable of being charged from ground level, particularly where the boxes or tubes are big and heavy, and where a good deal of direct quenching from the case-hardened temperature is done. Oil-fired furnaces are not recommended because of difficulty in preventing temperature variability.

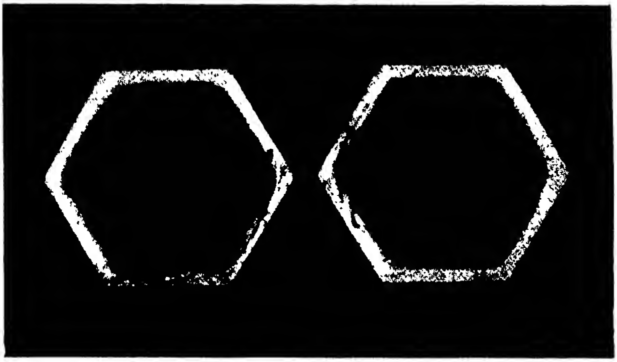


FIG. 92. SHOWING FRACTURES OF PROPERLY HEAT-TREATED CASE-HARDENED BARS

A continuous pusher furnace is advantageous for high output, and where moderate case-depth together with minimum heating period are adequate. In this connection careful design of the containers or boxes can play an important part, as can attention to the use of case-hardening compound, case-hardening temperature, and heating period. The principal advantages of the continuous pusher furnace are greater economy in fuel, longer life of boxes, more even heating, and more uniform case depth.

Hitherto we have dealt with ordinary plain carbon case-hardening steels. The principal alloy introduced into the alloy case-hardening steels is nickel, with or without varying proportions of chromium. The most popular nickel case-hardening steels contain about 3–3½ per cent nickel, although 5 per cent nickel case-hardening steels are used for special purposes, where particularly high core-strengths are required, as in certain parts of internal combustion engines, such as gears, etc.

Nickel raises the tensile strength of the core without seriously affecting ductility and resistance to impact. It also hinders coarsening of the grains during the carburizing period. After being carburized, the core of a nickel case-hardening steel is not nearly so coarse as that of a corresponding carbon steel, so that the usual preliminary quenching for core refinement may often be dispensed with and a single quenching from 760°–780° C. suffice to yield the necessary properties. This is illustrated by the following data—

TABLE LVI

CARBON 0·14 PER CENT, NICKEL 3·33 PER CENT

Treatment	Yield Pt. Tons per Sq. In.	Ultimate Tensile Strength Tons per Sq. In.	Elongation per Cent in 2 in.	Redn. Area per Cent	Izod Impact Ft.-lb.
Oil-quenched 850° C. Oil-quenched 760° C.	24·4	36·6	37·0	67·8	94, 90, 90
Oil-quenched 760° C.	23·9	35·5	35·0	63·7	90, 90, 88

Nickel case-hardening steels may be either oil- or water-quenched, according to the strength of core required.

Nickel-chromium steels are used when particularly high core strengths are needed. Chromium improves the tensile strength without seriously affecting ductility and impact resistance. One of its most beneficial effects, however, is a marked improvement in the wear-resisting properties of the case.

Chromium-nickel case-hardening steels are not nearly so susceptible to the *mass effect* on heat-treatment as either plain carbon or plain nickel steels, a factor of importance when large sections are being treated. Moreover, since they may be satisfactorily oil-quenched, distortion during heat-treatment is minimized, so that they are particularly suitable for parts of intricate and varying section. The carbon contents of these steels are of the utmost importance, and it is vital that they should not exceed 0·18 per cent.

With practically all case-hardening steels "double quenching" generally yields better results than single quenching.

Tempering of all case-hardened parts at temperatures between 100° and 200° C. is always desirable, but becomes absolutely imperative with the nickel-chromium steels after the final quenching. Tempering at such low temperatures has little or no influence on the properties of either case or core, but relieves quenching strains and thus prevents belated distortion or even cracking.

A typical heat-treatment for a 3½ per cent nickel steel is: carburize at 900°–920° C.; quench from 860° C. in water or oil; harden by quenching at 760°–780° C. in water. For a 5 per cent nickel case-hardening steel a typical treatment is: carburize at 880°–900° C.; refine at 850° C.; requench at 750–770° C. in water, or from 800°–820° C. in oil.

For a 2 per cent nickel case-hardening steel a typical treatment is: carburize at 900°–950° C.; refine at 880° C.; requench at 760°–780° C.

For a 3·0–3·75 per cent nickel, 0·8–1·1 per cent chromium case-hardening steel, a typical treatment is: carburize at 900°–920° C.; refine at 860° C. and cool in air, oil, or water; harden at 770° C. and quench in oil or water. A single quench at 770°–790° C. in oil is suitable for small and intricate parts.

For a 4·0–4·5 per cent nickel, 1·0–1·6 per cent chromium case-hardening steel, a typical treatment is: carburize at 880°–900° C.; refine at 840° C., and cool in air or quench in oil; harden at 760° C. and quench in oil; temper at 180°–200° C. The refining and hardening operations may, as with other alloy case-hardening steels, be combined and a single oil quench from 770°–790° C. be substituted, followed by tempering at 180°–200° C. This latter treatment will suit parts of sections liable to distort.

GAS CARBURIZING

In this form of carburizing, the steel's outer layers obtain the carbon that gives them case-hardness not from a surrounding mass of solid carbonaceous matter which gives off a gas when heated, but from a carbon-containing gas already made and introduced into a furnace chamber in which the parts are placed.

This gas, whatever its exact composition, is one that breaks up at the carburizing temperature into its component parts and yields the necessary carburizing gas.

These carburizing gases include carbon monoxide (CO), methane (CH_4), ethane (C_2H_6) and propane (C_3H_8), but town gas, acetylene, and petroleum vapour have also been used. In general, however, simple hydrocarbon gases of the first four types are either too slow or too quick in their carburizing action for effective commercial use, and it is usual to use mixtures of gases. By controlling the composition of these gases, the time of heating, the carburizing temperature, and the speed with which the gas is caused to flow through the chamber, it becomes possible to control, to virtually any desired degree, the composition of the case and the extent to which it shades off into the core structure. Some users of this method take the additional trouble to modify, as necessary, the composition of the gas during the actual heating period, in order to secure a closer control of these factors.

The principal commercial drawback to gas carburizing is the high first cost of the equipment required, while for economical operation, high production from a large unit is essential. Moreover, the close control usually demanded calls for a considerable degree of skilled supervision. If these conditions are achieved, however, the process is extremely economical, particularly if automatic quenching is adopted.

The gases added to the *hydrocarbon* (compound of hydrogen and carbon) carburizing gases to form a good carburizing mixture are termed *diluents,* i.e. they dilute the gases rich in hydrogen and carbon in order to regulate the speed with which carbon is absorbed by the steel, and so control the composition of the case. These diluents are gases of *decarburizing* character, such as carbon dioxide (CO_2) and water vapour (H_2O), or *neutral* gases, such as nitrogen (N_2). The decarburizing diluents are largely produced by the hydrocarbon gas and air undergoing combustion in a separate gas generating chamber or in the furnace chamber into which the mixture of air and gas is introduced. The neutral diluents are as a rule separately generated by passing a burnt mixture of gas and air, or of air alone, through a layer of hot charcoal. This results in the liberation of carbon monoxide and nitrogen. Sometimes, as when natural gas is the carburizing hydrocarbon, the used gas left in the furnace chamber after it has parted with its carbon serves as a diluent of the new gas as it enters the furnace chamber.

The type of furnace used for gas carburizing may be either for batches or for continuous production. Batch furnaces may be gas-fired or electrically heated, and comprise a horizontal or vertical retort. The horizontal retort may be either fixed or rotary. Fixed horizontal furnaces are usually gas-fired.

The horizontal rotary retort furnace inevitably causes the parts being case-hardened to knock up against one another, almost as in a *rumbler* or cylindrical revolving barrel designed for the cleaning of small parts by common impact of their surfaces. Hence only the more robust articles should be introduced into a retort of this type. The rotary retort is of simple design, there being no shelves or other appurtenances, and in consequence is relatively deep. Moreover, soot particles are not allowed, by reason of the constant movement, to settle on the parts and inhibit the carburizing action of the gas.

The horizontal stationary retort necessitates the use of trays and similar fixtures. It must be charged with care to avoid injury to the retort from the too sudden and clumsy dumping into it of a great weight of unheated parts.

The vertical retort is being increasingly used because of the even case it gives when correctly operated. It is sometimes, though not invariably, combined with a means of mechanically stirring the gas inside the retort. The object of this is to improve case uniformity by cutting out the speed of gas intake, a factor that may adversely affect this.

The continuous furnace is of the pusher tray type, the parts being placed on trays or similar fixtures. They cost less to run than continuous pack carburizing furnaces so long as they are kept running to nearly maximum capacity. Anything short of this raises the carburizing cost per part considerably.

LIQUID CARBURIZING

This is a development whose progress has been considerable of recent years, and in numerous shops it is eliminating the older method of *cyaniding*, with which we shall deal in a later chapter. It is designed to give a fairly thin case at medium temperatures, but if "cases" thicker than approximately 0·03 in. are needed, a different process should be adopted. Liquid carburizing is well suited to continuous working and automatic quenching. It is also highly economical, the principal cost being that of the salt employed.

Liquid carburizing depends upon what is termed an *activated* bath. This means that the liquid bath itself, originally of neutral (non-carburizing) composition, has an addition made to it to render it active and carburizing. There are numerous different bath compositions, and among the ingredients employed are calcium cyanamide, plus *polymerized* hydrocyanic acid, or sodium or potassium cyanide, to which are added a salt or salts designed to control the disintegration of the cyanides. These salts include fluorides or special substances known as *catalysts*, because they are able to cause a chemical change in the material into which they are introduced without changing themselves. (Incidentally, a polymerized hydrocyanic acid is one whose molecules have united with themselves, without the elimination of any simple atom or molecule, to form another compound whose molecules are individually heavier.) As a rule, when sodium or potassium cyanide, plus a catalyst or salt, is used, it is obtained ready for use in lump or powdered form.

Liquid carburizing, as indicated, is not an economical method for obtaining cases of considerable depth, because heating costs become excessive, and the cost of carburizing pot replacement is also high per ton carburized. The best operating temperature lies between 815° and 900° C., but the higher end of the range is usually employed for all but the very thinnest cases.

The type of furnace used is the metal pot, which may be a carbon steel casting, a heat-resisting steel casting, or made from welded sheet steel. Heating of the pot may be by gas-, electrical-, or oil-firing.

The heating time largely depends on the depth of case desired, longer heating being required for deeper case. For a case of maximum economical depth, e.g. 0·03 in., at least three to three and a half hours will be required. For a very thin case, 0·01 in. thick, from 45 min. to an hour will suffice. The operator should bear in mind, however, that the average heating period may be modified by the mass of the article being carburized, the kind of furnace employed, and the weight of the total charge. Heavy charges need longer to bring to temperature, and consequently more carburizing time is required for case-formation.

A few common causes of failure in case-hardening are discussed in the following lines, such causes as are not specifically due to heat-treatment being excluded.

The failure of a case-hardened steel part is not always due to causes common to all steels, e.g. non-metallic inclusions, rokes, unsuitable compositions, bad grinding, etc. A case-hardened steel is in reality a composite steel whose heat-treatment is complex, and whose failure may be due to either a *defective case* or a *defective core.* Common defects are *soft spots* on the surface of the hardened case. The following are possible causes—

(*a*) The presence of dirt or scale on the surface during treatment, resulting in non-carburizing, or in decreased intensity of hardening during quenching.

(*b*) Insufficient time allowed for carburizing, particularly when allied with careless packing in the carburizing medium, may yield a thin case of varying thickness. In extreme instances, the case may then be so thin in parts that the normal grinding allowance, i.e. the allowance made in deciding the case depth to ensure that grinding off for finishing will not reduce that depth below the desired minimum, completely removes it.

(*c*) Excessive grinding may not only cause soft spots by removing the case altogether at particular points, but may also cause a general lack of hardness due to the conversion, as a result of the heat generated, of the surface layers into structures known to lack hardness. The heat generated, in short, reheat-treats the case and softens it. This trouble is usually the result of using the wrong type of grinding wheel, glazing of the wheel, and an inadequate supply of coolant.

(*d*) Isolated soft spots may be caused by *parts being in contact in the reheating furnaces,* or even by *tong marks.*

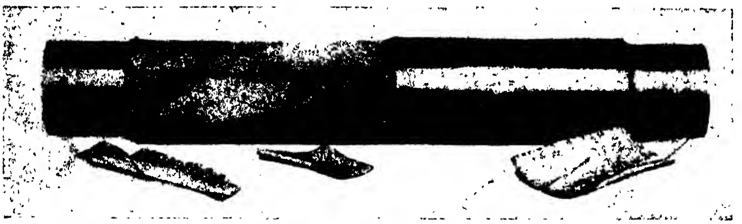
(*e*) With an incorrect *furnace atmosphere,* soaking for too long a period at either of the quenching temperatures may decarburize the skin to such a depth that the decarburized layer is not removed by normal grinding.

(*f*) When *the second reheating temperature is too low,* the case is not so effectively hardened. It is, perhaps, for this reason that the temperature in British Standard Specification S.14 is specified as 780° C. rather than 760°–770° C. If so, it is merely to allow for inexperience in the hardener, and not because of any fault in the steel.

(*g*) *Original steel defects.* Inclusions of non-metallic material or *phosphide ghosts* on the surface may cause soft spots because of their *inability* to absorb carbon during carburization.

(*h*) *Ineffective quenching.* The water or oil used as the quenching bath must be clean and cold, and either the bath or the parts must be agitated during quenching. Otherwise, bubbles of vapour are formed that cling to the surface and retard the cooling speed, forming spots not efficiently hardened. Parts having re-entrant angles need particular care in this respect.

Flaking, *peeling*, or *exfoliation* of the case has been a common source of trouble (see Fig. 93). In these defects, the outside skin cracks and peels off. The two main causes of peeling are: (*a*) a too sharp line of demarcation between case and core in respect of carbon content. This is usually due to the use of an unsuitable carburizing compound; (*b*) carburizing at too high a temperature for a short period of time. This bad treatment may also cause the formation of cracks during grinding.



(*By courtesy of the Bureau of Information on Nickel, The Mond Nickel Co., Ltd.*)
FIG. 93

Flaking is more likely to occur when the articles are given a single rather than a double quenching treatment. It will, however, always be minimized by tempering at about 200° C. after the final quenching. Flaking or peeling may also be accompanied sometimes by the formation of soft spots.

Brittle cores may be caused by quenching at incorrect temperatures or by carburizing the steel, particularly if the parts are of thin section, for too long a period. Even when the steel is correctly carburized, too low a first quenching temperature or too high a second quenching temperature may lead to the production of a core lacking the required shock-resisting properties.

Inefficient carburizing. The use of poor carburizing mixtures may lead to several difficulties, e.g. too low a carbon content for the case, too sharp a line of demarcation between case and core, thus giving rise to flaking and even difficulties in machining.

It may be of value to take a specific part such as presents difficulties in case-hardening, and outline not only the procedure employed, and the trouble likely to be experienced, but also some (but not all) of the types of case-hardening steels used. *Spline shafts* constitute a good example, and the following notes refer specifically to these. A spline shaft, for those not familiar with the terms of the automobile industry, is a shaft along whose length run *feathers* or serrations forming an integral part of the shaft. Over these serrations slides the main shaft. Sometimes the spline shaft meshes, by means of its serrations, with gears. It may have its serrations formed by cutting out of recesses or keyways, or these serrations may stand up "proud," so to speak, above the surface. In either instance, a spline shaft is long (seldom less than 1 ft.) and slender (say a minimum of 1½ in. in diameter), and has an irregular surface, presenting a by no means easy case-hardening problem.

We will not deal here with the importance of its design as affecting success in case-hardening. The general principles of design in relation to heat-treatment are dealt with in an earlier chapter. Here we confine ourselves solely to the difficulties and requirements of the case-hardening process as applied to it.

The most probable difficulty is warping. Where the shafts are machined in advance of case-hardening to an extent involving the generation of considerable heat, stresses may be set up liable to cause eventual distortion. In these circumstances it will be as well to give the shafts a normalizing or annealing treatment as soon as possible after the completion of machining operations. Spline shafts constitute an instance in which the single rather than the double quench may be expedient to prevent warping. The risk of warping is greater when the spline shaft is keywayed in an unbalanced manner, i.e. the keyways are placed at unequal distances.

Table LVII shows a characteristic but not exhaustive list of carburizing steels suitable for spline shafts, with their condensed carburizing and heat-treatments. (*It should be borne in mind that there are also non-carburizing oil and water-hardening steels used for these shafts.*)

Normalizing of these steels, where necessary, involves heating up to a temperature between 900° and 950° C. If it is desired to facilitate machining operations to the maximum, a temperature about 25° C. higher than the carburizing temperature will be found

TABLE LVI

Typical Compositions, Heat-treatments, and Mechanical Properties

Steel No.	Composition per Cent	Carburize at ° C. and Cool in Box	Reheat to ° C. and Quench in Oil	Reheat to ° C.	Quench in	For Single Treatment Only Reheat to ° C.	For Single or Double Treatment Quench in	Temper at ° C.	Tensile Strength Tons/sq. in.	Elongation per Cent in 2 in.	Izod Impact Ft.-lb.
1	0·2 carbon, 0·75 manganese, 0·2 silicon.	920–950	880–900 (may also be quenched in water)	760–780	Water	780–800	Water	175–200	34·6	34·0	75, 80, 78
2	0·15 carbon, 0·40 manganese, 3·5 nickel, 0·25 silicon.	900–920	860 (may also be quenched in water)	760–780	Water	760–800	Oil	175–200	52·3	22·5	55, 60, 58
3	0·2 carbon, 0·45 manganese, 3·5 nickel.	900–920	840	745–760	—	760–800	Oil	175–200	54·6	19·5	45, 48, 50
4	0·15 carbon, 0·30 manganese, 5·0 nickel, 0·25 silicon.	880–900	850	750–770 800–820	Water Oil	740–760	Oil	175–200	73·5 71·4	18·0 17·0	32, 35, 32 32, 37, 35
5	0·15 carbon, 0·45 manganese, 1·25 nickel, 0·6 chromium.	900–930	850	760–775	—	760–780	Oil	175–225	47·5	25·0	50, 52, 55
6	0·2 carbon, 0·45 manganese, 1·26 nickel, 0·6 chromium.	890–920	845	760–775	—	760–770	Oil	150–250	53·2	17·5	45, 48, 46
7	0·17 (max.) carbon, 0·45 manganese, 4·25 nickel, 1·5 chromium.	880–900	840	750–760	—	760–770	Oil	180–200	85·6	17·0	38, 40, 36
8	0·15 carbon, 0·45 manganese, 3·0 nickel, 0·8 chromium.	900–920	860	765–775	—	780–800	Oil	150–200	68·3	16·0	34, 38, 44
9	0·15 carbon, 0·55 manganese, 1·8 nickel, 0·25 molybdenum.	890–910	860–880	755–775	Oil	770–790	Oil	150–200	54·5	19·5	47, 45, 51
10	0·2 carbon, 0·55 manganese, 1·8 nickel, 0·25 molybdenum.	880–900	850–860	750–760	Oil	760–780	Oil	150–200	57·3	18·0	46, 40, 42

effective. Soaking at this temperature should be minimized to avoid oxidation of the surface, and slow cooling is desirable. Care must also be exercised in the annealing operation so as to avoid distortion.

The general principles of carburizing will apply quite successfully to spline shafts, but for preference they should be placed vertically in the tube or box, where this is feasible without sacrifice of even heating. Where vertical position involves uneven heating, it may be wiser to place the shafts horizontally and risk the necessity of a straightening operation later.

Owing to the great risk that these long slender parts will distort, it is, as already stated, quite usual to dispense with the double quench and use a single quench only, lower case-carburizing temperatures combined with higher reheating temperatures being used. Much distortion can be avoided by suitable choice of steel, but this subject lies outside the scope of the present work.

Vertical suspension of the shafts from the furnace roof for hardening is an advantage, particularly if quenching without removal of the shafts can be carried out in the same position. The necessity of straightening slightly warped shafts can often be prevented by allowing a good margin of case for finish grinding, and quenching in a suitable fixture on the concluding heat, which means that the shafts come out so straight that the final grinding does all that is necessary to make them dead true.

If heated horizontally, the shafts should be laid on equally-spaced supports, particularly if the furnace is of the continuous type, but as a rule a measure of straightening will be needed.

The exact tempering temperature will, of course, depend on the degree of hardness required. The upper end of the range will give the lower hardness. In general, the tempering temperature should never be below 150° C. for any of the steels in Table LVII.

LOCAL CARBURIZING

This chapter would not be complete without reference to those instances in which a part has to be locally carburized, i.e. where not all the external surfaces are required to have a hard case, and where, in fact, it may be advantageous that certain areas shall be left soft, or in their normal structural condition. This means that some method must be adopted to prevent the carburizing action from taking place at these points. There are many different ways, not all of which can be summarized here. We have dealt earlier with those most commonly used.

The method of leaving extra metal on the area desired soft instead of machining it off when machining operations are in progress is an efficient means when it is desired to preserve the original condition of sharp angles or threaded portions. The surplus metal is, of course, machined off *after* carburizing, care being taken to eliminate the entire case at these points, so that the softer layers are exposed, which is what is required. This method is not economical for high production and is usually confined to tools.

Copper plating to a depth of at least 0·0003 in. is, of course, the commonest method, the plating being deposited electrolytically, but it is only economical where the output justifies the cost of putting down the requisite equipment. The reader should note that copper plating is not effective with *every* carburizing compound, as with some it can be penetrated by the carbon, which thus reaches the underlying metal. The reason is that some of these compounds contain energizers that attack the plating itself and destroy it.

There is no special feature about the electro-plating operation itself. A suitable bath is made up by dissolving 8 oz. copper-potassium-cyanide in a gallon of water. A solution of this type will have a free cyanide content of about $1\frac{1}{2}$–$1\frac{3}{4}$ oz. per gallon, and will need to be replenished from time to time. The cyanide copper solution is generally heated to 45–50° C., using an electrical pressure of $2\frac{1}{2}$ volts and an electrode distance of 9 in., which gives a current density of between 8 and 10 amp. per sq. ft.

Where the part has keyways cut in it, or other recesses, as in dies, etc., the requisite local copper plating of these recesses may be achieved by either plating the whole article and afterwards grinding or machining off the plating from everywhere except the recess, or by protecting all the surfaces to be carburized with a suitable japan lacquer, so that the recessed areas alone will receive the copper. If the second method is chosen, the article must be properly cleansed so as to remove all greasy or oily matter. The japan is then brushed on to the surfaces concerned and the part afterwards inserted into a suitable furnace at 175°–200° C. This sets or bakes the lacquer. The part is then thoroughly cleaned by immersion in a suitable solution, washed, plunged into a dilute solution of hydrochloric acid, and once more well rinsed. If these precautions are not taken, the result will be unsatisfactory. For example, certain substances, e.g. white lead, cause the copper to spread over areas that should be carburized. Plating then follows. Sometimes a different type of *lacquer* is painted on instead of a *japan* lacquer. When the parts are carburized, the heat destroys the japan or lacquer, so that no barrier to carburization exists except where the recesses are copper-plated.

Where the output required does not justify the installation of an electro-plating equipment, other means of copper-plating may be employed, and will be effective so long as the carburization is not protracted. The usual method is to dip the parts in a commercial copper dipping solution, but where such a solution is not available a suitable one can be made with 20 per cent copper sulphate, 2 per cent sulphuric acid, and the balance water. The parts should be cleansed before immersion, and the maximum dipping period is 10 sec., since a longer period will produce a heavier coating that will flake off. The solution can be brushed on if the form of the part does not lend itself to dipping.

Another way of obtaining protection by the use of copper is only suitable for tapped holes, piston pins, shaft extremities, etc. The method comprises masking these areas with a tube, bar, bush, or disc of pure copper fitted over or into the area concerned, but not so tightly that later removal is difficult. This method must be regarded as a half-measure, since it does not afford complete protection, but does result in a much softer and thinner-cased local area than would otherwise be obtained.

The method of protection by fireclay or some other cement has two distinct modes of application. In the one, the areas required uncarburized are coated, and in the other it is the areas to be carburized that are coated. In the first application, which is principally designed for tapped holes, gear bores, etc., these are stopped up with a fireclay cement comprising 64 per cent fireclay, 33 per cent sodium silicate, and 3 per cent water. Sometimes a small addition of sand is made to counteract any diminution of volume of the cement when heated. This cement is tapped out after the case-hardening operation is finished. Such a cement is not suitable for outside areas, and it is better to use one of the commercial preparations specially intended for this work when it is desired to protect external surfaces by this method.

In the second application, the parts that have to be hard are coated with a carbonaceous cement, and this constitutes the carburizing mixture, which, when heated, produces the hardened case on all those surfaces to which it has been applied, leaving the uncovered areas in their original condition. There will, however, be intermediate areas neither fully hard nor fully soft.

Another method not hitherto mentioned is to pack the parts to be left soft in sand so that only the exposed areas are carburized. Here again the carburized areas will not be sharply separated from the rest, but will merge into them by degrees because the carburizing gases permeate the topmost layers of the sand. This method has many drawbacks and risks, and is not widely employed.

It should be noted that where gas carburizing is employed, local carburization presents somewhat greater difficulties than when a solid compound is used.

CHAPTER XXXIII

Cyaniding

Cyaniding is a case-hardening, i.e. a surface-hardening, process in which a cyanide salt—almost invariably sodium cyanide, which is cheaper and better than the alternative, potassium cyanide—is employed. Sometimes the powdered cyanide is sprinkled on the object at a temperature high enough to melt the salt; but in efficient modern practice the part to be dealt with is immersed in a bath of molten cyanide to which other salts, e.g. sodium, potassium, calcium, and barium chlorides, are added in order to lower the melting temperature of the cyanide salt.

Both carbon and nitrogen penetrate into the outer layers of the steel, with the result that after a quenching process the case acquires a high degree of hardness. It should also be borne in mind that a cyanide bath need not be used exclusively for case-hardening, but can also be used (as it often is) for heating or reheating steels for hardening purposes with a view to minimizing the possibility of forming soft skins, and thus ensuring a satisfactory surface.

The composition of the sodium cyanide bath is largely dependent on the kind of work the bath is called on to perform. Most case-hardening is carried out with a "solution" concentration of 45 per cent of sodium cyanide, but a 30 per cent "solution" may be used because of its cheapness and stability for high outputs. It should be noted that these solutions are of sodium cyanide in the other salts, and not in water. The bath must, of course, be kept up to strength, as the constituents it contains volatilize and decompose at high temperatures. For this purpose it is replenished from time to time with quantities of a higher strength solution containing 75 per cent of sodium cyanide. This is because most of the other ingredients of the bath are more inert and do not volatilize, so that it is only the cyanide content that must be replaced. The powdered form has the highest strength of all (96–98 per cent). Failure to replenish the bath means that the parts will have soft skins and be liable to be covered with oxidation scale. Ordinary losses of the bath solution caused by drips, etc., from withdrawn parts are replaced as necessary by a further addition, not of the highest strength but of the same basic mixture of salts.

Cyaniding is, in short, an effective means, within limits, of rapidly and cheaply giving to parts a hard, thin, wear-resistant case. It is not so effective when a deep case is required. For example, a mild carbon steel immersed for one hour at 845° C. will have a depth of case of approximately 0·01 in. At the end of three hours the case depth will only be 0·018 in. If heated for three hours at 870° C., the case depth will not be more than 0·065 in. Nor does a cyanide case contain, as a rule, so high a percentage of carbon as can be obtained by the normal case-carburizing process described in the previous chapter.

As a general rule, therefore, cyanide immersions for case-hardening purposes seldom last longer than 30–60 min. In a mild steel of the same type as that mentioned above, the percentage of carbon in the case at the end of 60 min. immersion at 845° C. was found to be about 0·62 per cent. After three hours it was about 0·64 per cent, and after three hours at 870° C. 0·65 per cent. In the main, lower cyaniding temperatures result in a higher carbon percentage and deeper case depth of the parts.

It must be noted that both the mass of the part being treated and the cyanide concentration of the solution affect the results obtained. For example, a part ¼ in. in section cyanided at 815° C. for half an hour may have a case depth of 0·0058 in. As against this, one with 3 in. section may have a case depth of only 0·004 in. It can therefore be laid down that, in general, the larger the part, the thinner the case for identical time and temperature of treatment.

A 75 per cent sodium cyanide bath used for case-hardening a part 1 in. in diameter at 815° C. with half an hour's immersion produced a case depth of 0·007 in. A 30 per cent solution produced a case depth of 0·006. A 15 per cent solution produced a case depth of 0·005 in. It thus seems evident that the weaker the solution, the thinner the case, though the difference is not extreme.

We must now consider whether the quality of the steel has any effect on the results obtained by cyaniding. In general it may be said that it has not, so far, at all events, as depth of case is concerned when normal cyaniding procedure is followed. The alloy steels of the nickel and nickel-chromium type present a slight difference in that they show a less abrupt transition from case to core, but as against this, they have a rather lower percentage of carbon in the case. Most case-hardening steels suitable for the processes outlined in the previous chapter can be cyanided, so that it is not necessary to devote space here to the enumeration of suitable cyaniding steels.

Cyaniding is used to-day only for special reasons, e.g. where a high rate of output is required, where low cost is of maximum importance, or where the type of case produced by the process conforms more nearly to what is required than an ordinary carburized case.

Usually the best cyaniding temperature is just about the upper critical point of the core, the usual range being 800°–850° C., and after the period of immersion is over, quenching should follow immediately without giving the steel time to cool. This treatment will give a good hard case combined with a tough core possessing good grain structure.

The quenching medium will be governed by the type of steel, which in its turn will depend upon the purpose the parts are required to fulfil. Either oil or water may be used. Mineral oil will be found better than blended or organic oils because it does not combine with the alkali of the bath to form a saponaceous (soapy) residue liable to lower the quenching efficiency of the bath and to interfere with the circulating or piping systems. Quenching water should be circulated to ensure uniform cooling and to minimize distortion. For spline shafts and similar long, thin articles, it is better to use "still" quenching water. *Quenching water for cyaniding should never be warmed.*

Considerable economies can be effected in cyaniding by care in the choice of the container or pot, and in its use. Lower cyaniding temperatures mean longer-lived pots, and pot-life appears to be greatly lengthened by automatic, as distinct from manual, furnace-operation. Most commercial cyaniding plants employ pots made of pressed steel, which are low in first cost, offer excellent resistance to the cyanide, and are unlikely to fail as a result of heterogeneity of composition or structure. There is, however, an increasing tendency to use cast pots of either carbon steel or heat-resisting alloy. It is essential, however, that these should be properly cast in the foundry and of suitable composition. The greater first cost of the cast pots is recompensed by the longer life obtained from them.

The design of the pot will also make a vast difference to the length of service life obtained from it. Badly applied heat is, of course, always deleterious to metal, and badly applied high temperatures extremely so. Hence, heat should be kept away as far as possible from the bottom of the pot. It is safe to say that electrically-heated cyaniding pots where the heat is externally applied last longer than those heated by any other means.

Attention must be paid to the thorough sealing of the pot so that there is no leakage of cyanide into the heating chamber. Cyanide is a deadly poison if breathed as a fume, and may be dangerous if, as a result of contact, it enters the blood-stream through skin abrasions or cuts. Most up-to-date cyaniding furnaces are efficiently sealed by means of special arrangements, but where the furnace does not possess its own seal, the best sealing method is to cover the furnace top with a ring of dry powdered fireclay on which the flange of the pot rests when placed in position.

The latest development in cyanide furnaces is the electric type operated by A.C. current, in which electrodes are introduced into the bath of molten cyanide. Electrodes are simply conductors of current. The cyanide of the bath is resistant to the progress of the current through it from the electrode, and this resistance generates the heat required. The pot is fully insulated, and the electrical effect creates some motion of the molten salt, so that heating is more uniform. Advocates of the new furnace argue that it provides lower working cost, a more even temperature over the entire bath, higher output, a more uniform case, and better operating conditions for the workers.

CHAPTER XXXIV

Nitriding

Nitriding, *nitrarding*, or *nitrogen-hardening* is a process by which, as in carburizing, a hardened outer case is given to a finished steel part. There are, however, important differences to be borne in mind. In the first place the hardening agent is not a carbonaceous compound, a hydrocarbon gas, or a cyanide salt, but a nitrogenous gas, usually *dissociated* (split up) ammonia, to whose action the hot steel is subjected for an adequate period. The second great difference, that constituting the principal economic justification for the process, is that after subjection to this gas, the parts do not have to be heat-treated, because the nitriding temperature does not affect the properties of the steel apart from the skin. This considerably minimizes distortion. The third great difference is in the steels used, which are of different composition from those suitable for case-carburizing.

In *The Structure of Steel* we have outlined the mechanism of nitriding, and it is not proposed to dwell on that in the present work. It is sufficient to indicate that the hardness of the case is due to the combination of elements (essentially nitrogen) in the nitriding gas with the alloying-elements in the outer layers of the steel to form nitrides, which give exceptional hardness to the case, shading off gradually into the softer unchanged core structure. This case is seldom deeper than 0·002 in. The actual depth depends on the nitriding time (see page 329).

Assuming that a steel to be nitrided is free from residual stresses, e.g. those set up as a result of machining or preliminary heat-treating operations, the nitriding process will not cause it to distort or warp to any noteworthy degree. This is because of the relatively low temperature employed and the absence of a later quenching operation. As a rule nitriding steels are supplied in the stress-relieved condition ready for immediate nitriding. Exception must be made of parts to be forged, which generally need a stress-relieving treatment after forging and before nitriding. Most nitriding steels are forged within the temperature range 1050°–1200° C.

To prepare a steel for nitriding, all traces of soft (decarburized) skin must be eliminated by machining or grinding. The stresses set up by these operations are relieved by heating to 650°–700° C., the temperature being maintained for one to four hours according to size. Finish grinding or machining takes place after this reheating. Forgings are made from the steel in this softened or annealed state, machined to rough limits, then reheated to 890°–910° C., quenched in oil, and tempered at 600°–700° C., and finally finish-machined or ground. To prevent any possibility of distortion where its occurrence would be dangerous, the steel is given a stabilizing treatment by heating to 550° C. between rough and final machining in advance of nitriding, and maintained at this temperature for two to six hours according to size.

In the nitriding process proper the dissociated or split-up ammonia gas is caused to act upon the parts when these are at a temperature between 500° and 650° C. In practice, however, this range is narrowed down to 510–540° C. The furnace used may be fired by gas or oil, or be electrically heated. A semi-continuous nitriding furnace of electrical type is shown in Fig. 46, and the reader is referred to the description of it contained on p. 97.

The container used demands careful choice. Ordinary mild steel is useless because it slowly picks up nitrogen from the gas and becomes dangerously brittle. Enamelled iron or steel is good so long as the enamel remains intact, but this condition is short-lived for reasons that will be imagined, and the use of these materials cannot be recommended.

Chromium-nickel heat-resisting alloy containers of the 80/12 or 20/25 type are advised, the figures representing the respective percentages of these elements in the order named. The container must be well sealed.

Care must be taken to remove any soft skin before nitriding, so as to prevent a condition of the case that will result in cracking and flaking off, and also to minimize enlargement of the parts, a measure of which is always found in nitrided articles. The extent of this enlargement is regular and calculable for each steel, and a suitable allowance is made for its removal by finish machining, grinding, etc. The enlargement may amount on average to 0·003 in. on a part one inch diameter nitrided for 80 hours at 500° C. The extent of this enlargement is partly affected by the depth of the nitrided case.

In this connection there is a point of importance affecting design. Where an article has angles or corners, the result of the uniform enlargement of the piece is to produce at these angles or corners a structural condition in which the steel has a hardened case rich in nitrides, but with little or no backing of tough core material. The result is that at the slightest provocation these corners will snip off. Hence, it is always advantageous to avoid sharp angles and corners on parts designed for nitriding and to radius or round (i.e. fillet) these off wherever possible.

In Table LVIII the principal nitriding steels are summarized. These are special alloy steels. Their ordinary heat-treatments are given in condensed form. Which steel is used is largely decided by the purpose for which the parts are intended, the mechanical properties of the core, and the degree of hardness of the case. A characteristic case-hardness range for nitrided steels is 600–1100 diamond (Vickers or Firth).

It is not feasible to resoften finished nitrided parts in order to change their form, because a fresh nitriding would not restore the original case hardness. On the other hand, it may sometimes be desired to straighten a nitrided part. This may, where the deviation is extremely slight, be carried out while the steel is cold; rather greater amounts of straightening call for a reheating of the steel to 650° C.

The depth of the case is largely governed by the steel and the temperature and duration of nitriding. The usual nitriding period for a steel similar to No. 2 of Table LVIII is 50–100 hrs. which gives a depth of case between 0·01 and 0·03 in. (0·25–0·75 mm.).

As with case-carburized parts, localized nitriding may be desired. This necessitates different methods from those used for carburized parts. The best method is to *tin* the parts required soft with a thin coating of solder (80 per cent lead, 20 per cent tin). The flux used is made by adding excess of zinc to a mixture of 500 c.c. hydrochloric acid, 250 c.c. water, and 15 g. ammonium chloride. The zinc is added to this mixture until all chemical action ceases. All parts thus treated must be thoroughly cleansed and free from rust or oxidation.

If only one end of a part needs to be left soft, it should be cleaned, fluxed, and dipped in the solder to the desired depth, carefully brushing off with a *carding brush* (one made from wire carding, i.e. wire bristles mounted on a pad of fabric) any superfluous solder.

If the middle of a part has to be left soft, the extremities are coated with a fire-resisting synthetic resin varnish. The entire

TABLE LVIII

TYPICAL COMPOSITIONS, HEAT-TREATMENTS AND MECHANICAL PROPERTIES

Steel No.	Composition per Cent	Harden at ° C.	In	Temper at ° C.	Nitride at ° C.	Diamond Brinell Range of Case	Tensile Strength tons per sq. in.	Elongation per Cent in 2 in.	Izod Impact ft.-lb.
1	0·2 carbon, 0·25 silicon, 0·5 manganese, 0·25 nickel, 3·0 chromium, 0·4 molybdenum, 1·1 aluminium.	900	Oil	650 for 2 hr. Air cool	500	800–900	50·5	22	103
2	0·4 carbon, 0·25 silicon, 0·55 manganese, 0·25 nickel (max.), 1·6 chromium, 0·25 molybdenum, 1·05 aluminium.	900	Oil	650–700	500	1050–1100	56·5	23	85
3	0·3 carbon, 0·6 manganese, 0·55 nickel, 1·10 chromium, 1·05 molybdenum.	870	Oil	660–680	500	600–650	57·0	25	100
4	0·25 carbon, 0·55 manganese, 0·25 nickel, 3·20 chromium, 0·5 molybdenum, 0·25 vanadium.	900	Oil	600–650	500	800–900	61·0	21	90
5	0·4 carbon, 0·2 silicon, 0·5 manganese, 0·25 nickel, 1·95 chromium, 0·3 molybdenum, 0·15 vanadium.	Normalize 920 Harden 900	Oil	650–680	500	750–800	66·5	20	63
6	0·35 carbon, 0·25 silicon (max.), 0·5 manganese (max.), 0·3 nickel (max.), 3·25 chromium, 0·35 molybdenum.	900	Oil	600–650	500	800–900	66·0	18	85

piece is then fluxed and immersed in the solder to the extent required. The carding brush is next employed to eliminate superfluous solder and the varnish, after which the part is ready to be nitrided.

Recesses and keyways can be protectively soldered by means of the soldering iron.

Tin plating to a depth of about 0·0007 in. or nickel plating to 0·0005 in. is also an effective means of localizing the nitriding action. Another method sometimes used is to paint the parts with a mixture of tin oxide and glycerine or pure tin oxide and shellac, but this is not a certain protective agent. A paste of finely divided lead and tin, properly bonded, may also be employed.

CHAPTER XXXV

Surface-hardening by Oxy-fuel Flame

In earlier chapters on case-hardening, nitriding, etc., we have shown the technical importance of producing a hardened case, or surface, sometimes on the whole and sometimes on chosen portions of a steel part. It must not be assumed, however, that the processes earlier described are the only ones capable of achieving surface hardness. There are others, of which the "Shorter," "Shorterizing," or *flame-hardening* process described in this chapter is one of the most important.

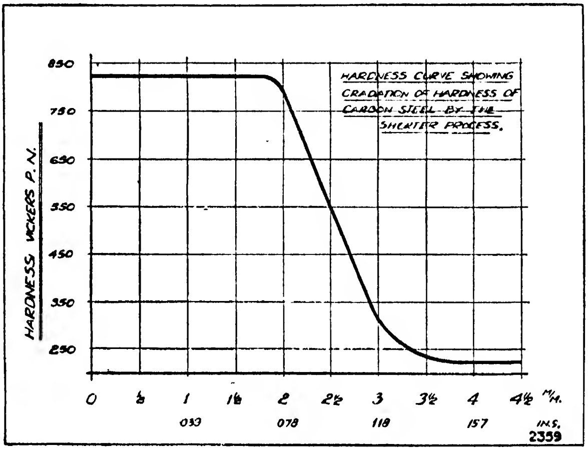


Fig. 94. Depth of Hardness Curve on Carbon Steel

In brief, it consists of locally heating the part, or parts, to be treated by an oxy-acetylene or other oxy-fuel blowpipe, quickly followed by quenching with water or other coolant, through specially designed water jets. Some 15 years ago Mr. A. E. Shorter developed the principle on a mechanized basis in order to ensure accuracy and commercial economy.

The case or hardened skin produced by the Shorter process may range from a thin film or layer (say 0·0125 in.) to about ¼ in. The governing factors are the method of application and the character of the steel. The normal depth is, however, standardized for convenience at 0·1–0·125 in. as shown in Fig. 94. The more highly alloyed steels give greater depth of hardness than the carbon steels because the alloying elements make the quenching more effective, and the hardness falls off less abruptly.

It is important that the reader should bear in mind the essen, tial distinction between "Shorterizing" and the case-hardening-nitriding, and cyaniding processes earlier explained. In the latter group, the chemical composition of the surface layers of the steel is changed. In Shorterizing it is not.

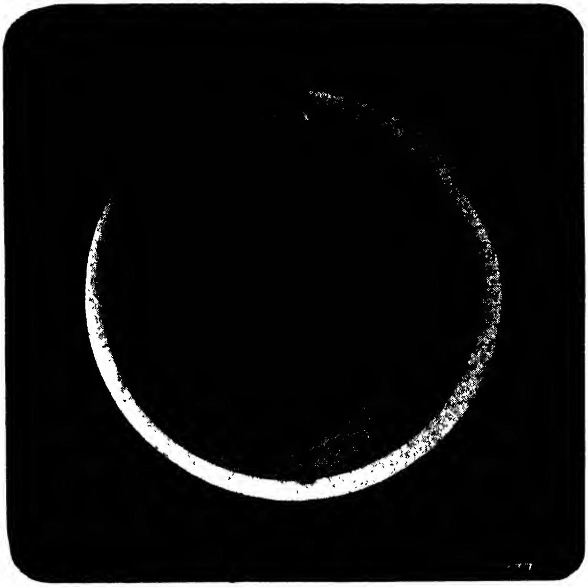


Fig. 95. Core Section

Various methods have been used for the heating and quenching of the surface to be hardened. Extremely large crankshafts and camshafts made in one piece are to-day usually treated by what is termed the progressive system (see (*a*), (*b*), and (*c*) below), smaller or medium-sized shafts by the controlled consecutive system (see (*d*) below). These we shall deal with in due course.

There are, in all, four different methods—

(*a*) The work remains stationary, and the burner and quenching jets move in relation to it (Fig. 96).

(*b*) The burner and the quenching apparatus remain stationary, and the work travels past them (Fig. 97).

(*c*) The burner and the quenching tackle move longitudinally while the work revolves (Fig. 98).

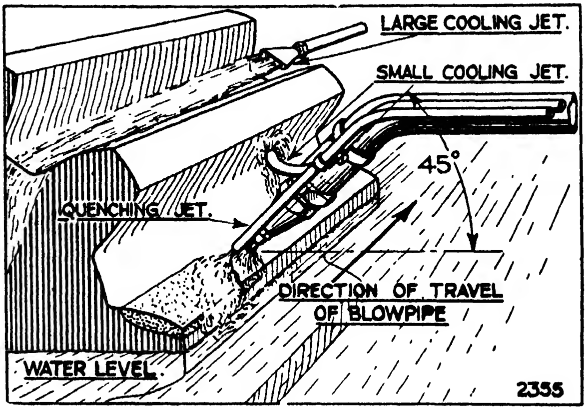


Fig. 96. Job Stationary; Burner and Quench in Motion

(*d*) The rapidly revolving part is first subjected to heat, after which the blowpipe is withdrawn or extinguished, and the quenching treatment applied (see Fig. 99).

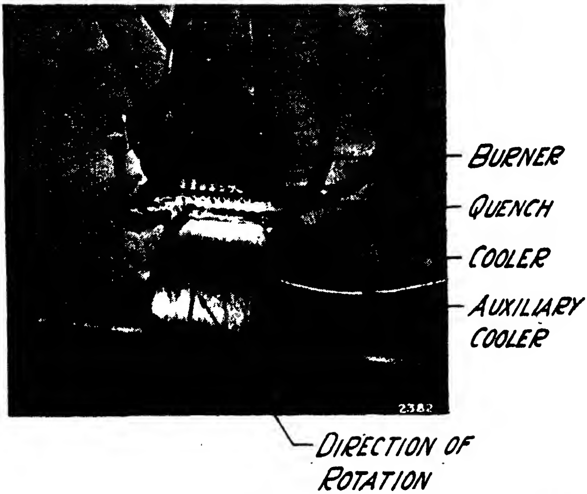


Fig. 97. Burner and Quench Stationary; Job in Motion

The work is mounted between *centres* (pivotal points) and set in motion, as for a turning operation. The blowpipe is carried at one end of a cross slide and the quenching apparatus at the other, so that a simple motion at right angles to the treated part brings either flame or water jets into action. This may be automatically controlled.

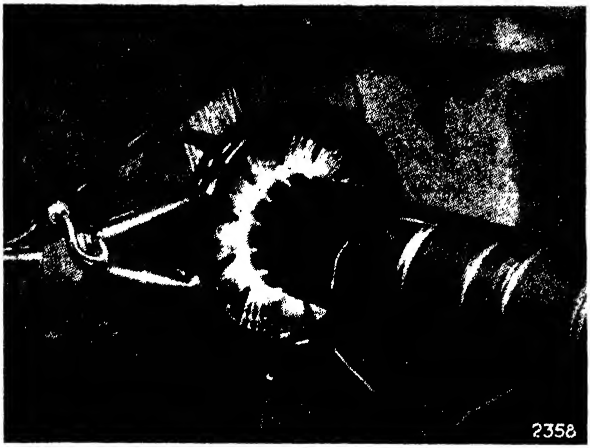


Fig. 98. Burner, Quench, and Job in Motion

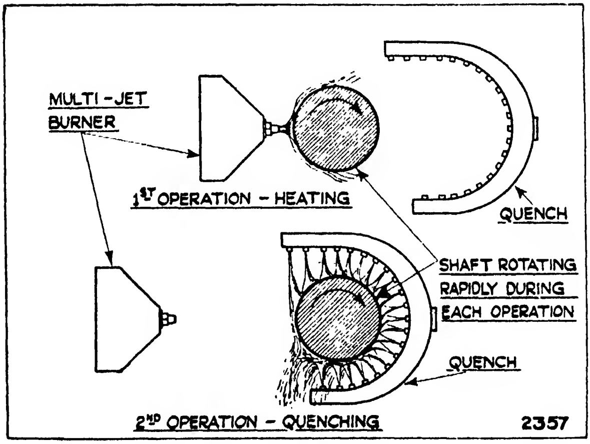


Fig. 99. Hardening in Consecutive Operations

The machines in (*a*), (*b*), and (*c*) methods are "progressive"; those for (*d*) are "consecutive." In the progressive systems the heating and quenching operations are combined, i.e. the quenching follows behind the burner, moving at an identical rate and in an identical direction. The rate of heating is regulated by the burner size and the speed of traverse, i.e. the speed at which the burner and quenching tackle move across the work, or vice versa. The effectiveness of the quenching (i.e. whether it is more or less drastic, as may be required) is regulated by the distance at which the jets follow the burner and the volume of coolant they provide. In the consecutive systems, the heating and quenching are separate and consecutive operations. The heating rate is controlled by the burner size and the speed with which the work revolves. The quenching intensity is regulated by the period that elapses between the burner withdrawal and the bringing into play of the quenching apparatus. This process is known as the Shorter Double Duro process and has been widely applied to the hardening of crankshaft surfaces.

The steels used for Shorterizing range from 0·3 to 0·6 per cent carbon, but other carbon and alloy steels can also be treated in this way. In Table LIX a list of typical flame-hardening steels is given, with their diamond and Brinell hardness numbers after treatment. High carbon steels can be "Shorterized," but surface cracks may develop unless great care is taken.

In connection with the alloy steels, it should be noted that while molybdenum is not an indispensable constituent, its addition is advised as rendering the steel more suitable for flame-hardening and giving improved physical properties. Shorterizing is not recommended where steels are already in a heat-treated condition that will give a tensile strength for the core of 60–65 tons per sq. in.

Before parts are flame-hardened, they *must be stress-relieved* by some form of normalizing, annealing, or hardening-cum-full tempering treatment. The hardening-cum-full-tempering is better if the parts are likely to undergo considerable shock in service. The reason is that it provides a good, robust backing to the hardened face. The treatment adopted will depend on the quality of steel, and in this connection earlier chapters should be studied. There is no specific limit to the size of part that can be flame-hardened, while flat, circular, or irregular forms can all be success fully treated. The Shorter process is not so effective and economical when a hardened case is required on a large number of small parts as the standard case-hardening processes, but finds its advantage in the surface-hardening of parts too large for ordinary furnaces, or of those in which it is vital to prevent distortion, often inevitable with the older methods. Shorterizing produces

TABLE LIX

Steel No.	Composition per Cent	Diamond Hardness No.	Brinell Hardness No.
1	0·30–0·35 carbon, 0·5–0·8 manganese.	300–400	300–400
2	0·35–0·4 carbon, 0·5–0·8 manganese.	400–500	390–465
3	0·4–0·45 carbon, 0·5–0·8 manganese.	500–650	465–570
4	0·45–0·5 carbon, 0·5–0·8 manganese.	650–700	570–600
5	0·5–0·55 carbon, 0·4–0·8 manganese.	700–800	600–660
6	0·55–0·6 carbon, 0·4–0·8 manganese.	800–850	660–680
7	0·5–0·6 carbon, 0·4–0·8 manganese.	700–850	600–680
8	0·35–0·5 carbon, 1·6–1·9 manganese, 0·3–0·4 molybdenum (optional).	650–750	570–630
9	0·35–0·45 carbon, 0·5–0·8 manganese, 1·0–1·5 chromium, 0·3–0·4 molybdenum (optional).	550–800	500–660
10	0·35–0·45 carbon, 1·2 manganese (max.), 1·0 nickel (max.).	550–700	500–600
11	0·25–0·35 carbon, 0·35–0·75 manganese, 2·75–3·0 nickel, 0·3 chromium (max.).	470–550	440–500
12	0·35–0·45 carbon, 0·5–0·8 manganese, 3·25–3·75 nickel, 0·3 max.	550–700	500–600
13	0·25–0·35 carbon, 0·45–0·7 manganese, 3·0–3·75 nickel, 0·5–1·6 chromium, 0·25 molybdenum (optional).	500–700	465–600
14	0·32 carbon, 0·56 manganese, 2·56 nickel, 0·72 chromium, 0·42 molybdenum.	650	570

virtually no distortion. This is because the high calorific or heat value of the oxy-fuel flame produces the required temperature so quickly that the core of the steel remains comparatively cool. The flame is closely followed by the quenching medium, so that at any given moment in the hardening sequence, only a small proportion of the total mass of the part is heated, the rest remaining cool, and therefore unstressed. Mass distortion is thus virtually non-existent, being often less, as tests have proved, than the original manufacturing inaccuracies. Such distortion as occurs in certain instances is usually caused by the heating and quenching of one side only of a thin part, and this can easily be counteracted by heating the reverse side or by use of a water bath, i.e. by heating the reverse side in a *hot* water bath.

Over and above its economic justification, Shorterizing has certain advantages. In the first place it gives the surface the high degree of hardness desired, yet leaves the core as it was at the outset. Thus it becomes feasible to heat-treat the core so as to make it as tough and ductile as possible, and afterwards to produce by flame-hardening the hard case without in any way weakening the core, which will resist any crushing effect likely to be imposed upon it in use.

The hardness given by the process is not inferior to, and is sometimes greater than, that given by the older processes. The hardness persists over approximately 80 per cent of the hardened area's depth, and the case is not sharply separated from the core, but merges gradually into it, so that there is little danger that the case will splinter off or flake.

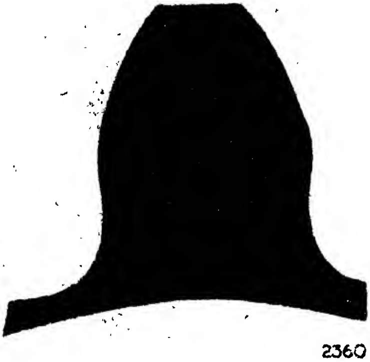


FIG. 100. SHORTER-HARDENED GEAR TOOTH

Gear teeth have their flanks treated so as to give a surface wear resistance on the rolling faces or flanks of the teeth, as shown in Fig. 100. The centre core and root are not affected adversely by the hardening, so that gear blanks can be heat-treated to give maximum ductility according to the quality of the steel employed. The hardness of the tooth flanks will also be governed by the grade of steel, hardness being largely dependent on its carbon content.

Thus, it is clear that essential requirements in Shorterizing are: (*a*) a stress-relieving treatment beforehand, or (*b*) where maximum core strength is needed, a suitable advance heat-treatment designed to give the necessary physical properties for core strength; (*c*) choice of a steel that, when flame-hardened, will give sufficient hardness to resist wear; (*d*) avoidance of any decarburization, scale, or surface defects such as pits, seams, blowholes, etc., on the surfaces to be hardened; (*e*) a tempering or stress-relieving treatment carried out as soon as possible after the quenching of the flame-hardened part. This is done by heating the part in an ordinary heat-treating furnace or an oil bath at 175–205° C. This will get rid of any residual quenching stresses, but the temperature is too low to cause any softening of the case. Cooling in the open air or in the furnace should follow; (*f*) burning or over-heating of the steel must be avoided at all costs. These faults may be caused by bringing the flame too near to the part or prolonging unduly the heating period.

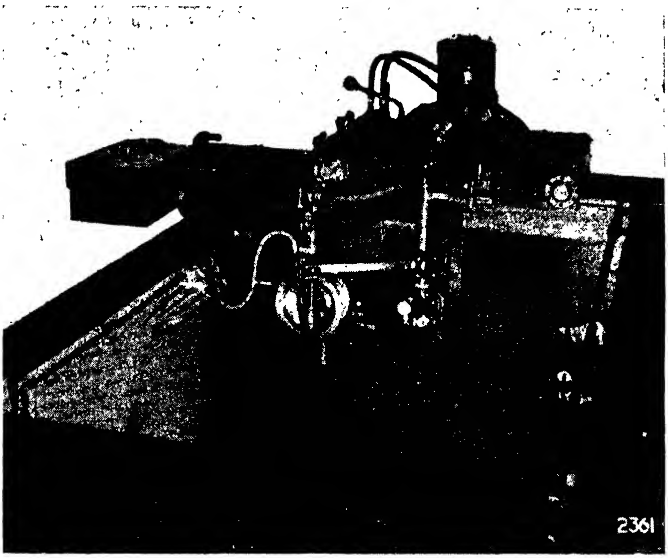


FIG. 101. SHORTER TYPE G.2 MACHINE OPERATING HEAD MOUNTED ON CROSS CARRIAGE OVER TANK AND TRACK, SHOWING SPECIAL HEADSTOCK ARRANGEMENT FOR TURNING CYLINDRICAL WORK

The types of parts to which Shorterizing has been successfully applied include gearing, brake drums, tyres, axles, cams, straightening and bending rolls, shafts, crankshafts, and journals.

For oil engine crankshafts of heavy type, each pin and journal is treated separately. For light shafts several are heated simultaneously. When the heat is applied, any temporary increase in length of the shaft, due to expansion, is automatically accommodated by a compensation device in the machine, so that distortion is avoided. In the design of the machine, provision is made for choosing a speed in accordance with the dimensions of the crankshaft concerned, to attain the required heat input in the proper period. Owing to the speedy heating, the penetration depth is about 5 per cent and the toughness of the core of the previously heat-treated shaft is unaffected.

Space does not allow of a detailed description of each type of flame-hardening machine manufactured, but Figs. 101 to 105 show representative examples. The heating torches are usually water-cooled and have multi-flame tips, which will maintain flames of great stability close to the surface of the work. The tips themselves are varied to suit the character and form of the work. In progressive flame-hardening the tips are formed in one piece with the water-quenching jets that follow them. These jets both quench the heated steel and keep the tips cool. In the consecutive process the tips are cooled internally and the quenching is done

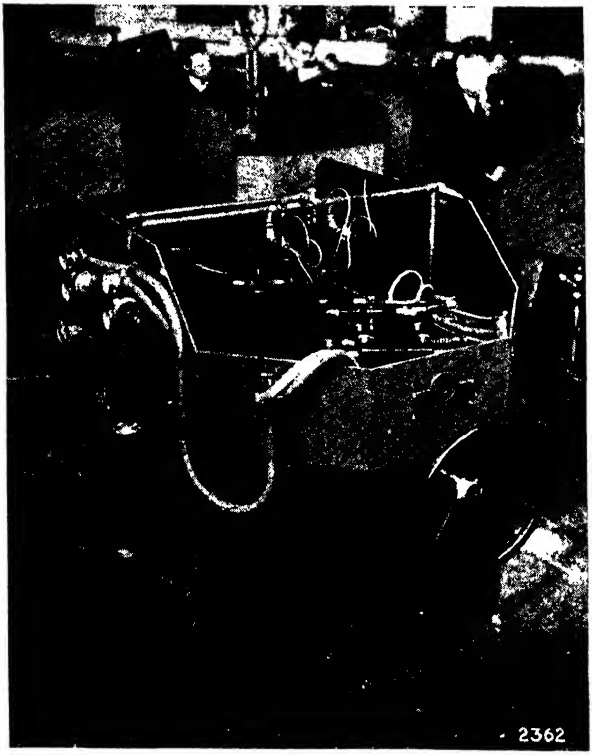


FIG. 102. SHORTER TYPE J.2 SPECIAL MACHINE FOR HARDENING SPROCKETS

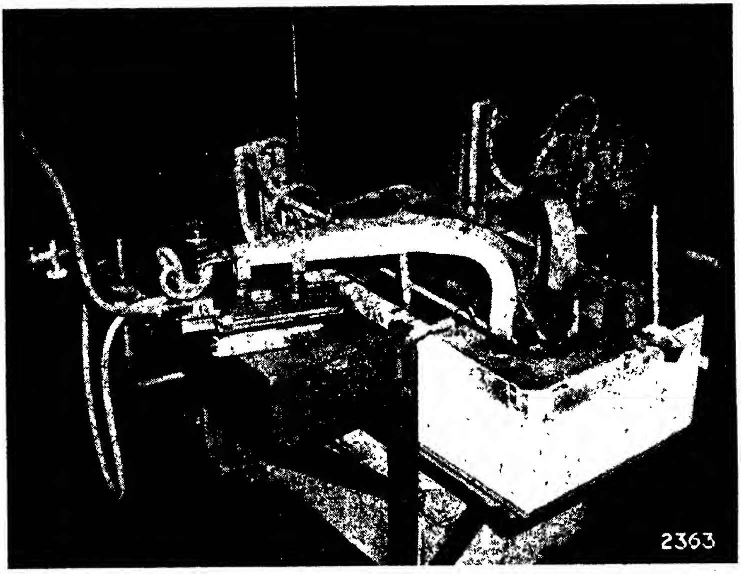


FIG. 103. SHORTER TYPE S.1 MACHINE

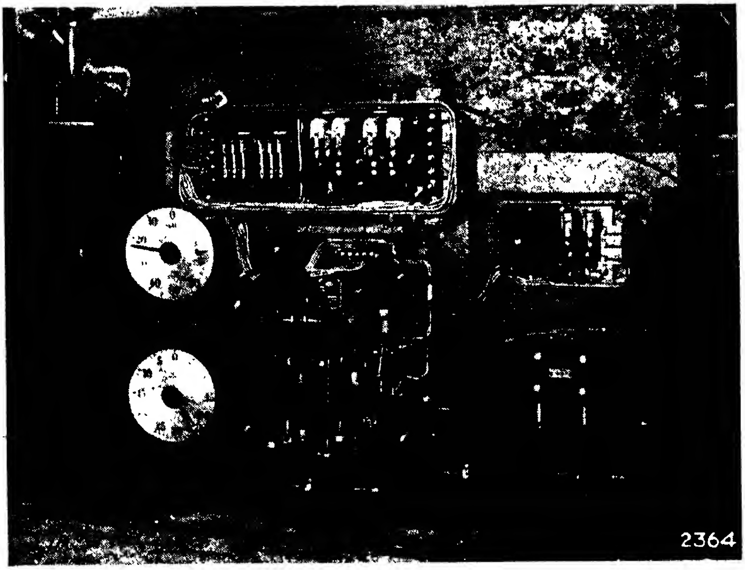


FIG. 104. SHORTER W.2 CAMSHAFT MACHINE

by separate jets or jets, located in the tip, that only operate after the flame has been extinguished.

Gears can be flame-hardened either by applying the flame to each tooth flank alternately or by *straddle* hardening, in which the burner head is so designed as to allow two flames to impinge simultaneously on both flanks, thus effecting a considerable economy in time and minimizing distortion, since uneven or one-sided heating of the teeth is obviated. The gas pressures must be carefully watched in hardening gear teeth. Inadequate pressure will not give the desired case hardness. Excessive pressure will upset the flames.

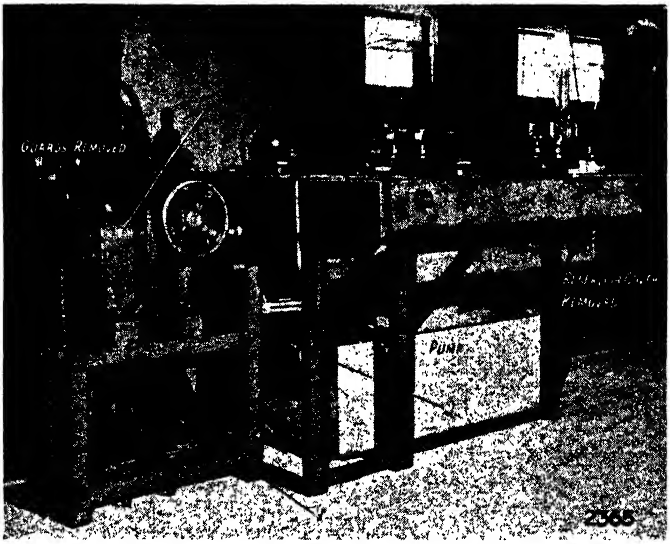


FIG. 105. SHORTER TYPE S.1 MACHINE

In the latest Shorter camshaft hardening machines, the duration of the heating process is set by an electrical timing and clock mechanism, adjustable to any desired length of heat-application period. This applies also to the quenching water or coolant. With unskilled labour, the process can be applied to from 30–50 camshafts per hour, once the machine is set for the type concerned. The procedure is fully mechanized, which greatly increases speed of production, and gives both accuracy and consistency of temperature control.

In the timing clock and mechanism, the shaft is slipped quickly

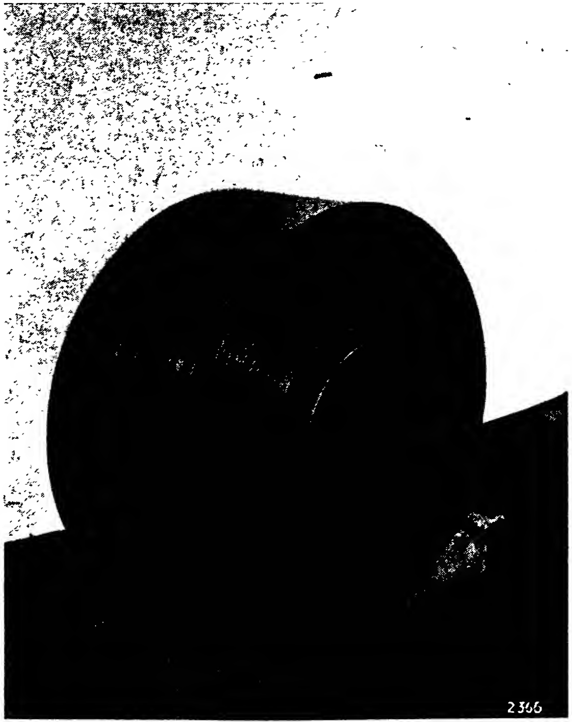


Fig. 106. Shorterized Brake Drum

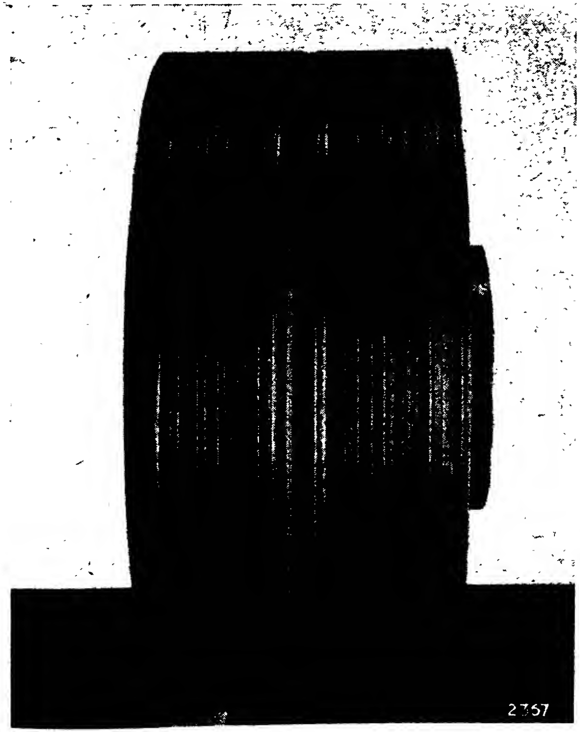


Fig. 107. Shorterized Brake Drum

into the machine, and a burner and quenching unit are provided for each cam on pressing the button. The top clock brings on the gases and ticks off the time accordingly. Inserted in the top clock is a pause clock, which can be set to give an accurately timed pause before the coolant is applied, if necessary. The lower clock ticks off at a predetermined quenching time.

The Shorter automatic machine for hardening the faces of front wheel drive shafts is operated with the two blow-pipe and quenching units arranged and located to suit the surface of the shaft to be hardened. It is fully automatic. The operator has only to lay the shaft in the tank and press a button, and the control is mechanical, thus producing accurate and uniform surface hardening as precise as is necessary for the work for which the machine was constructed.

Figs. 106 and 107 show a steel works brake drum treated in two widths, leaving a soft belt between the hardened bands. After the normal life had been more than doubled, the drum was photographed, and shows the wear on the centre soft belt as compared with that on the Shorterized surfaces. These drums are now treated in one width up to 12 in. wide.

CHAPTER XXXVI

Surface-hardening by Induced Heat

In the making of steels by the high frequency induction process, eddy currents are induced in a mass of steel to be melted, and the heat generated by the metal's resistance to the passage of the current serves to melt the mass. In the induction hardening process the same principle is largely relied upon to achieve the surface-hardening of a steel crankshaft.

It will be necessary to explain as simply as possible a rather complex electrical process, if the reader is to grasp completely all that is involved. Steel is, of course, a molecular substance, i.e. one composed of molecules. Each of these molecules can be regarded, for our purpose, as a tiny magnet. So long as the steel is not magnetized by any one of the magnetizing processes known, all these millions of tiny magnets will lie anyhow, like a crowd sleeping on Blackpool sands. If, however, a magnetic current of electricity is passed through the steel, it will have the effect—with whose cause we are not here concerned—of giving a definite uniform direction to the molecules so that they all lie in the same direction as the current, just as in a sandstorm the Arabs all turn their backs to the wind and face in the direction of its progress.

An electric current can be of two kinds, alternating or direct. In a direct current the flow of electricity is always in the same direction. In an alternating current, the flow is rhythmically or periodically reversed, like a train that plies between two stations on the one line. When a current alternates, the molecules of steel (our millions of tiny magnets) reluctantly change their direction or position with each alternation. This is termed *changing their polarity*. A comparable effect can be seen if a magnet is passed in one steady direction near a mass of iron filings and the direction then reversed. Such changes are said to be *induced*, and the process is known as *induction*.

The point to be remembered next is that these periodical molecular regroupings or changes of polarity of the steel molecules cause a certain amount of energy to be lost as a result of molecular friction, which is dissipated in the form of heat. This loss of energy in the form of heat is termed *hysteresis loss*, hysteresis being the motion (lagging behind) of the change of direction of the molecules (i.e. of the *magnetic induction*) when the magnetizing current's force is varied. The alternating current's direction may be changed or alternated swiftly, i.e. as often, perhaps, as 4000 times a second or even more. It is then known as a *high frequency current*, because of the high frequency of the current's reversals of direction. When such high frequency currents are used, it will be appreciated that a considerable amount of energy will be given out or dissipated in the form of heat, and it is this heat on which high frequency induction hardening partly depends.

The amount of heat thus given out is a variable governed by the kind of steel, the resistance its molecules offer to the passage of the current (i.e. its *permeability*, the ease or otherwise with which the induction increases or decreases) and the temperature of the steel. The effect of a rise in the temperature of the steel is to lessen the amount of heat generated. It is almost as if the changes of direction or polarity have become easier for the molecules, and less energy is used in making them change. Eventually, with rising temperature, the heat generated (or hysteresis loss) falls to zero, after which no further heating of the steel is possible by this method. In short the molecules practically lose their magnetism and cease to make the changes of polarity at all.

The heat produced by hysteresis loss will not suffice to produce the full structural changes required in surface-hardening. Some additional method of heating is therefore necessary, and this is achieved by *eddy currents*. Described as simply as possible, these are secondary electrical currents caused by the presence nearby of a primary current, which sets up an area of local electrical disturbance known as a *magnetic field*. A simple analogy is the drawing of a stick through a bath of water. The stick's passage causes eddies and whirlpools in the water behind it. Similarly the passage of a powerful electrical current sets up eddy currents in steel placed within the sphere of its influence, i.e. in the same *magnetic field*. The resistance of the molecules to the passage of these eddy currents generates heat, and this heat is again a variable governed by the strength of the current and the magnetic resistance of the steel. If the electrical voltage or pressure of the current is constant, the heating effect will be greater as the electrical resistance rises.

The electrical resistance is itself governed by the composition of the steel, the size of the grains, the heat-treatment to which the steel has been previously subjected, and the temperature. The eddy current loss (i.e. the heat dissipated, corresponding to hysteresis loss in the previous paragraph) is also variable according to the strength of the magnetic field (i.e. the force and area of influence of the primary current) and the frequency of rate of alternation of the current.

The total resistance of the steel increases greatly with increase in temperature, so that the effect of the eddy currents greatly increases as the temperature rises to the critical temperature of the steel. Thus, when the high frequency current is applied for longer and longer periods of time, the above-described action penetrates successively inward, layer by layer, from the outermost surface to a final depth controlled by a combined factor made up of the time and the frequency chosen.

The use of high frequency current for heating has a further influence on the steel known as *skin effect*. This means that the heating is confined to the *outer surface* of the piece subjected to the high frequency field. Skin effect is tied up mathematically with both eddy current and hysteresis losses. Let us consider this phenomenon. A material that will allow an electrical current to pass more or less readily through it is known as a *conductor*. The resistance of that conductor to the passage of electricity is known as the *real* or *ohmic resistance*. The specific resistance is greater for alternating than for direct current. This is because a conductor carrying A.C. (alternating) current generates an *alternating counter-flux* or current which in turn generates a *voltage* or electrical pressure of current in the conductor. This voltage establishes currents that oppose the main current at the centre, and help it at the outside of the conductor. The result is that more current is carried on the outside than in the interior. The higher the frequency, i.e. the greater the number of alternations in a given period, the greater is this skin effect.

The combined hysteresis and eddy current losses on the surface of the steel are at a maximum at the beginning of the heating cycle because the steel is cool, and these losses gradually decrease as the critical temperature is approached. If the high frequency current is kept on after the critical temperature has been reached at the surface, it serves only to heat the inner layers, because these are still magnetic and of lower electrical resistance. The time of application of the electrical power, assuming that the frequency and strength of the magnetic field are constant, determines the depth to which the heat will penetrate. The temperature of the shallow-heated area is actually slightly above the critical range of the steel, since the inherent reactions of the steel limit the temperature to which it can be raised.

A formula has been developed by which to calculate the depth

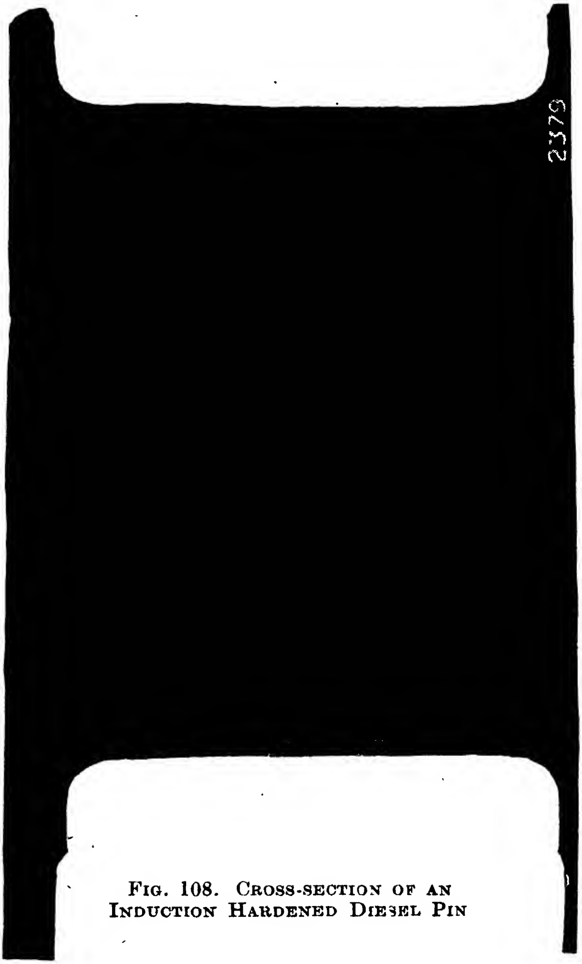


Fig. 108. Cross-section of an Induction Hardened Diesel Pin

of heat penetration, but it is complicated, because the factors it involves, e.g. eddy current, hysteresis, and skin effect, are always changing as the temperature changes. Moreover, the hot layers of metal are gradually altering the *magnetic couple* or effective air-gap between the *inductor* or inducing current and the steel by becoming non-magnetic as time goes on. We shall not, therefore, burden the reader with this formula here.

In the foregoing, we have attempted a simple explanation of induction heating. This explanation is open to criticism by experts, but it is hoped that it will give the non-technical reader at least some idea of the principles upon which induction heating is based.

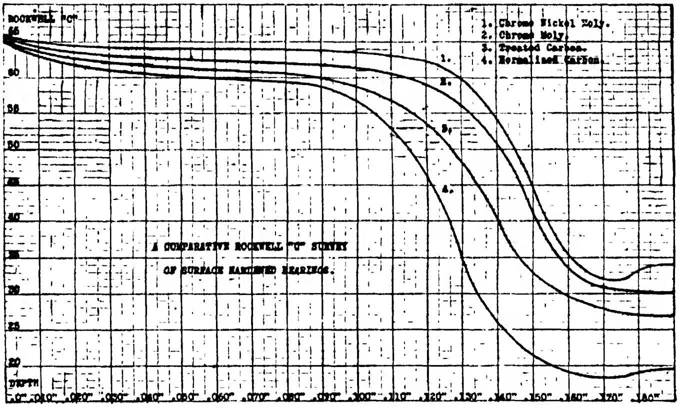


FIG. 109

In the Tocco process (derived from the initial letters of each word of the name of the originators of the process—The Ohio Crankshaft Company of Cleveland—the steel is heated extremely rapidly on the surface to just above the critical temperature, to a pre-determined depth, and then quenched. In locally hardening crankshafts, for which the process was originally designed, care has to be taken to control both temperature and time, and thus depth, while at the same time preventing the heating of adjacent parts.

The rapidity of the process enables it to be classed as a production process. It reduces the time for surface-hardening from hours to seconds, and is controlled to such fine limits as one-tenth of a second. The rapid heating and cooling produce a fine hard grain structure (essentially martensitic). Owing to the rapidity of the process, no surface decarburization occurs, nor do the grains enlarge or "grow." There is no real sharp line of demarcation between case and core, and the original structure of both the core and the fillets remains unchanged.

Care must be exercised in the choice of steel. A plain carbon steel (0·5 per cent carbon) is highly suitable. If an alloy steel is required for a particular part or purpose, one containing 0·4 per cent molybdenum will give a surface hardness comparable with that of the carbon steel. Many other steels can be successfully hardened by this process, but the two mentioned above are probably the most suitable.

Fine grained steels are advisable, as they give greater depth-control and less liability to cracking. Steel for this process should also be "clean," i.e. free from included non-metallic particles or *inclusions*, and previously heat-treated to give a structure (sorbitic) that will produce a good tough core, which is later not sharply differentiated from the surface layers, and so liable to cause flaking off of the hardened case. Where design will permit, normalizing only, before hardening, can be carried out, but it is preferable, in this instance, to cool the crankshaft quickly in the air, since by so doing a structure is obtained having a grain size comparable with that of a heat-treated steel.

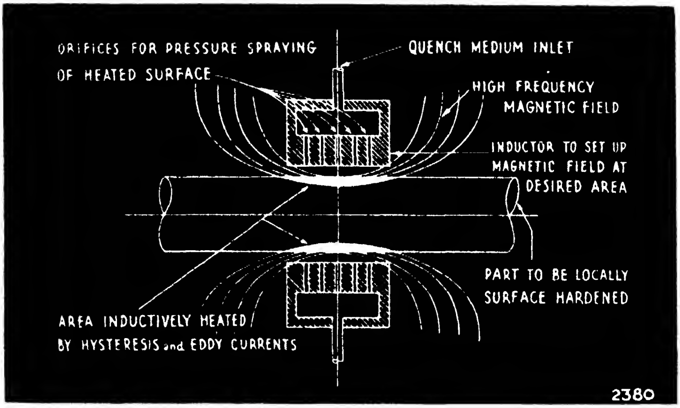


FIG. 110. SCHEMATIC DIAGRAM OF TOCCO INDUCTION BLOCK AND MAGNETIC FIELD HEATING A BAR

There is naturally no distortion with this process. The steels recommended for it are less expensive and also easier to machine than the alloy case-hardening and nitriding steels. Cracking due to grinding is now almost unknown.

In addition to crankshafts, camshafts have also been hardened by the Tocco process, as well as the cams, gears, and eccentrics of camshafts. Other parts to which the process has been applied include valve rocker shafts, tappets, track rollers, and axle shafts.

Fig. 111. Tocco Tunnel Line, Control Board, and Drawing Ovens for Hardening Large Size Crankshafts

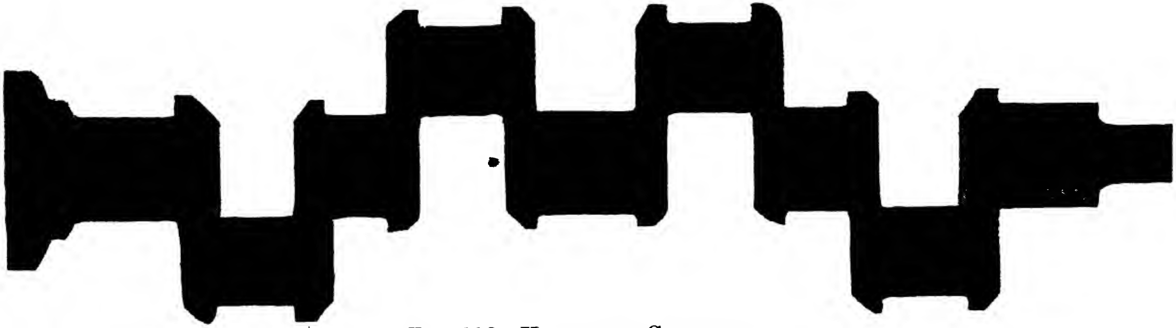


Fig. 112. Hardened Crankshaft

The length of time required to reach the hardening temperature is ascertained by a stop-watch and by taking sections from test pieces. These are examined, and according to the depth of penetration the time is adjusted, if necessary, so that the actual depth of heating is about ⅛ in. The hardening temperature is about 750–760° C. for the 0·5 per cent carbon steel and 790–800° C. for the chromium-molybdenum steel.

Preheating of the shafts is only carried out as a precautionary measure, and it is not necessary to preheat any part of the shaft again during the period in which it is being hardened, because the quench is not sufficiently prolonged to remove all the heat from the shaft, and distortion is thus eliminated.

The case-hardness produced compares most favourably with that produced by case-hardening and, in many instances, with that produced by nitriding. The general hardness figure for a Tocco hardened shaft is 58–62 Rockwell C., about 600–650 Brinell. The hardness along the entire bearing surface is quite uniform except at the ends, where it declines rapidly owing to the change in structure, which is, in reality, the bond between the case and the unhardened portion of the shaft.

Before the crankshafts are hardened, they are preheated for about two hours at a low temperature to take away the chill. They are then placed on a small truck or bogie and passed to the hardening plant, where *inductor blocks* made from special high conductivity copper are connected up to a transformer. Water jackets are attached to the top and bottom of each block, and these fit over special recesses cut in the back of the blocks. In this recess, numerous small holes are drilled, so that when the time comes the crankshaft can be quenched by pressure jets which drive the water through the block without its being necessary to take the block away. This saves time. Automatic or hand control can be employed.

The inductor block surrounds the bearing surface to be hardened, but does not touch it, an air gap being maintained by small lava or porcelain studs fitted in the block. The current is then switched on and the operation proceeds. The exact mechanism involved need not detain us. The plant is usually operated by five men, and a sixth operates the oil tempering tank constituting the final stage of the process. The pins of the crankshaft are usually hardened before the bearings. At the end of the hardening operation, the crankshafts are suspended in the oil tank, so as to remove any hardening stresses. The average time for hardening a bearing is 5–6 seconds, and about double that time for quenching.

The particular advantage of this process in hardening crankshafts is that it does not necessitate the heating of the entire crankshaft in order to harden only the bearing areas. Moreover, the cost of specially protecting areas to be left soft is eliminated, distortion is minimized, and the time required is cut down to seconds as compared with hours by such processes as case-hardening. Overheating does not occur, and it is perfectly possible to establish an inherent heating control. It is claimed that a five to tenfold increase in mileage has been obtained from Tocco hardened bearings, between regrinds, owing to the reduction of wear on the shaft.

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