HARDENING, TEMPERING, AND ANNEALING

Heat Treatment Of Standard Steels

Heat-Treating Definitions.—This glossary of heat-treating terms has been adopted by the American Foundrymen's Association, the American Society for Metals, the American Society for Testing and Materials, and the Society of Automotive Engineers. Since it is not intended to be a specification but is strictly a set of definitions, temperatures have purposely been omitted.

Aging: Describes a time–temperature-dependent change in the properties of certain alloys. Except for strain aging and age softening, it is the result of precipitation from a solid solution of one or more compounds whose solubility decreases with decreasing temperature. For each alloy susceptible to aging, there is a unique range of time–temperature combinations to which it will respond.

Annealing: A term denoting a treatment, consisting of heating to and holding at a suitable temperature followed by cooling at a suitable rate, used primarily to soften but also to simultaneously produce desired changes in other properties or in microstructure. The purpose of such changes may be, but is not confined to, improvement of machinability; facilitation of cold working; improvement of mechanical or electrical properties; or increase in stability of dimensions. The time–temperature cycles used vary widely both in maximum temperature attained and in cooling rate employed, depending on the composition of the material, its condition, and the results desired. When applicable, the following more specific process names should be used: Black Annealing, Blue Annealing, Box Annealing, Bright Annealing, Cycle Annealing, Flame Annealing, Full Annealing, Graphitizing, Intermediate Annealing, Isothermal Annealing, Process Annealing, Quench Annealing, and Spheroidizing. When the term is used without qualification, full annealing is implied. When applied only for the relief of stress, the process is properly called stress relieving.

Black Annealing: Box annealing or pot annealing, used mainly for sheet, strip, or wire.

Blue Annealing: Heating hot-rolled sheet in an open furnace to a temperature within the transformation range and then cooling in air, to soften the metal. The formation of a bluish oxide on the surface is incidental.

Box Annealing: Annealing in a sealed container under conditions that minimize oxidation. In box annealing, the charge is usually heated slowly to a temperature below the transformation range, but sometimes above or within it, and is then cooled slowly; this process is also called "close annealing" or "pot annealing."

Bright Annealing: Annealing in a protective medium to prevent discoloration of the bright surface.

Cycle Annealing: An annealing process employing a predetermined and closely controlled time–temperature cycle to produce specific properties or microstructure.

Flame Annealing: Annealing in which the heat is applied directly by a flame.

Full Annealing: Austenitizing and then cooling at a rate such that the hardness of the product approaches a minimum.

Graphitizing: Annealing in such a way that some or all of the carbon is precipitated as graphite.

Intermediate Annealing: Annealing at one or more stages during manufacture and before final thermal treatment.

Isothermal Annealing: Austenitizing and then cooling to and holding at a temperature at which austenite transforms to a relatively soft ferrite-carbide aggregate.

Process Annealing: An imprecise term used to denote various treatments that improve workability. For the term to be meaningful, the condition of the material and the time–temperature cycle used must be stated.

Quench Annealing: Annealing an austenitic alloy by *Solution Heat Treatment*.

Spheroidizing: Heating and cooling in a cycle designed to produce a spheroidal or globular form of carbide.

Austempering: Quenching from a temperature above the transformation range, in a medium having a rate of heat abstraction high enough to prevent the formation of high-temperature transformation products, and then holding the alloy, until transformation is complete, at a temperature below that of pearlite formation and above that of martensite formation.

Austenitizing: Forming austenite by heating into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing). When used without qualification, the term implies complete austenitizing.

Baking: Heating to a low temperature in order to remove entrained gases.

Bluing: A treatment of the surface of iron-base alloys, usually in the form of sheet or strip, on which, by the action of air or steam at a suitable temperature, a thin blue oxide film is formed on the initially scale-free surface, as a means of improving appearance and resistance to corrosion. This term is also used to denote a heat treatment of springs after fabrication, to reduce the internal stress created by coiling and forming.

Carbon Potential: A measure of the ability of an environment containing active carbon to alter or maintain, under prescribed conditions, the carbon content of the steel exposed to it. In any particular environment, the carbon level attained will depend on such factors as temperature, time, and steel composition.

Carbon Restoration: Replacing the carbon lost in the surface layer from previous processing by carburizing this layer to substantially the original carbon level.

Carbonitriding: A case-hardening process in which a suitable ferrous material is heated above the lower transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen by the surface and, by diffusion, create a concentration gradient. The process is completed by cooling at a rate that produces the desired properties in the workpiece.

Carburizing: A process in which carbon is introduced into a solid iron-base alloy by heating above the transformation temperature range while in contact with a carbonaceous material that may be a solid, liquid, or gas. Carburizing is frequently followed by quenching to produce a hardened case.

Case: 1) The surface layer of an iron-base alloy that has been suitably altered in composition and can be made substantially harder than the interior or core by a process of case hardening; and 2) the term case is also used to designate the hardened surface layer of a piece of steel that is large enough to have a distinctly softer core or center.

Cementation: The process of introducing elements into the outer layer of metal objects by means of high-temperature diffusion.

Cold Treatment: Exposing to suitable subzero temperatures for the purpose of obtaining desired conditions or properties, such as dimensional or microstructural stability. When the treatment involves the transformation of retained austenite, it is usually followed by a tempering treatment.

Conditioning Heat Treatment: A preliminary heat treatment used to prepare a material for a desired reaction to a subsequent heat treatment. For the term to be meaningful, the treatment used must be specified.

Controlled Cooling: A term used to describe a process by which a steel object is cooled from an elevated temperature, usually from the final hot-forming operation in a predetermined manner of cooling to avoid hardening, cracking, or internal damage.

Core: 1) The interior portion of an iron-base alloy that after case hardening is substantially softer than the surface layer or case; and 2) the term core is also used to designate the relatively soft central portion of certain hardened tool steels.

Critical Range or Critical Temperature Range: Synonymous with *Transformation Range*, which is preferred.

Cyaniding: A process of case hardening an iron-base alloy by the simultaneous absorption of carbon and nitrogen by heating in a cyanide salt. Cyaniding is usually followed by quenching to produce a hard case.

Decarburization: The loss of carbon from the surface of an iron-base alloy as the result of heating in a medium that reacts with the carbon.

Drawing: Drawing, or drawing the temper, is synonymous with *Tempering*, which is preferable.

Eutectic Alloy: The alloy composition that freezes at constant temperature similar to a pure metal. The lowest melting (or freezing) combination of two or more metals. The alloy structure (homogeneous) of two or more solid phases formed from the liquid eutectically.

Hardenability: In a ferrous alloy, the property that determines the depth and distribution of hardness induced by quenching.

Hardening: Any process of increasing hardness of metal by suitable treatment, usually involving heating and cooling. See also *Aging*.

Hardening, Case: A process of surface hardening involving a change in the composition of the outer layer of an iron-base alloy followed by appropriate thermal treatment. Typical case-hardening processes are *Carburizing*, *Cyaniding*, *Carbonitriding*, and *Nitriding*.

Hardening, Flame: A process of heating the surface layer of an iron-base alloy above the transformation temperature range by means of a high-temperature flame, followed by quenching.

Hardening, Precipitation: A process of hardening an alloy in which a constituent precipitates from a supersaturated solid solution. See also *Aging*.

Hardening, Secondary: An increase in hardness following the normal softening that occurs during the tempering of certain alloy steels.

Heating, Differential: A heating process by which the temperature is made to vary throughout the object being heated so that on cooling, different portions may have such different physical properties as may be desired.

Heating, Induction: A process of local heating by electrical induction.

Heat Treatment: A combination of heating and cooling operations applied to a metal or alloy in the solid state to obtain desired conditions or properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.

Heat Treatment, Solution: A treatment in which an alloy is heated to a suitable temperature and held at this temperature for a sufficient length of time to allow a desired constituent to enter into solid solution, followed by rapid cooling to hold the constituent in solution. The material is then in a supersaturated, unstable state, and may subsequently exhibit *Age Hardening*.

Homogenizing: A high-temperature heat-treatment process intended to eliminate or to decrease chemical segregation by diffusion.

Isothermal Transformation: A change in phase at constant temperature.

Malleablizing: A process of annealing white cast iron in which the combined carbon is wholly or in part transformed to graphitic or free carbon and, in some cases, part of the carbon is removed completely. See *Temper Carbon*.

Maraging: A precipitation hardening treatment applied to a special group of iron-base alloys to precipitate one or more intermetallic compounds in a matrix of essentially carbon-free martensite.

Martempering: A hardening procedure in which an austenitized ferrous workpiece is quenched into an appropriate medium whose temperature is maintained substantially at the M_s of the workpiece, held in the medium until its temperature is uniform throughout but not long enough to permit bainite to form, and then cooled in air. The treatment is followed by tempering.

Nitriding: A process of case hardening in which an iron-base alloy of special composition is heated in an atmosphere of ammonia or in contact with nitrogenous material. Surface hardening is produced by the absorption of nitrogen without quenching.

Normalizing: A process in which an iron-base alloy is heated to a temperature above the transformation range and subsequently cooled in still air at room temperature.

Overheated: A metal is said to have been overheated if, after exposure to an unduly high temperature, it develops an undesirably coarse grain structure but is not permanently damaged. The structure damaged by overheating can be corrected by suitable heat treatment or by mechanical work or by a combination of the two. In this respect it differs from a Burnt structure.

Patenting: A process of heat treatment applied to medium- or high-carbon steel in wire making prior to the wire drawing or between drafts. It consists in heating to a temperature above the transformation range, followed by cooling to a temperature below that range in air or in a bath of molten lead or salt maintained at a temperature appropriate to the carbon content of the steel and the properties required of the finished product.

Preheating: Heating to an appropriate temperature immediately prior to austenitizing when hardening high-hardenability constructional steels, many of the tool steels, and heavy sections.

Quenching: Rapid cooling. When applicable, the following more specific terms should be used: Direct Quenching, Fog Quenching, Hot Quenching, Interrupted Quenching, Selective Quenching, Slack Quenching, Spray Quenching, and Time Quenching.

Direct Quenching: Quenching carburized parts directly from the carburizing operation.

Fog Quenching: Quenching in a mist.

Hot Quenching: An imprecise term used to cover a variety of quenching procedures in which a quenching medium is maintained at a prescribed temperature above 160 degrees F (71 degrees C).

Interrupted Quenching: A quenching procedure in which the workpiece is removed from the first quench at a temperature substantially higher than that of the quenchant and is then subjected to a second quenching system having a different cooling rate than the first.

Selective Quenching: Quenching only certain portions of a workpiece.

Slack Quenching: The incomplete hardening of steel due to quenching from the austenitizing temperature at a rate slower than the critical cooling rate for the particular steel, resulting in the formation of one or more transformation products in addition to martensite.

Spray Quenching: Quenching in a spray of liquid.

Time Quenching: Interrupted quenching in which the duration of holding in the quenching medium is controlled.

Soaking: Prolonged heating of a metal at a selected temperature.

Stabilizing Treatment: A treatment applied to stabilize the dimensions of a workpiece or the structure of a material such as 1) before finishing to final dimensions, heating a workpiece to or somewhat beyond its operating temperature and then cooling to room temperature a sufficient number of times to ensure stability of dimensions in service; 2) transforming retained austenite in those materials that retain substantial amounts when quench hardened (see cold treatment); and 3) heating a solution-treated austenitic stainless steel that contains controlled amounts of titanium or niobium plus tantalum to a temperature below the solution heat-treating temperature to cause precipitation of finely divided, uniformly distributed carbides of those elements, thereby substantially reducing the amount of carbon available for the formation of chromium carbides in the grain boundaries on subsequent exposure to temperatures in the sensitizing range.

Stress Relieving: A process to reduce internal residual stresses in a metal object by heating the object to a suitable temperature and holding for a proper time at that temperature. This treatment may be applied to relieve stresses induced by casting, quenching, normalizing, machining, cold working, or welding.

Temper Carbon: The free or graphitic carbon that comes out of solution usually in the form of rounded nodules in the structure during *Graphitizing* or *Malleablizing*.

Tempering: Heating a quench-hardened or normalized ferrous alloy to a temperature below the transformation range to produce desired changes in properties.

Double Tempering: A treatment in which quench hardened steel is given two complete tempering cycles at substantially the same temperature for the purpose of ensuring completion of the tempering reaction and promoting stability of the resulting microstructure.

Snap Temper: A precautionary interim stress-relieving treatment applied to high hardenability steels immediately after quenching to prevent cracking because of delay in tempering them at the prescribed higher temperature.

Temper Brittleness: Brittleness that results when certain steels are held within, or are cooled slowly through, a certain range of temperatures below the transformation range. The brittleness is revealed by notched-bar impact tests at or below room temperature.

Transformation Ranges or Transformation Temperature Ranges: Those ranges of temperature within which austenite forms during heating and transforms during cooling. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting temperatures of the ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling.

Transformation Temperature: The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for iron and steels:

Ac_{cm} = In hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed during heating

Ac_1 = The temperature at which austenite begins to form during heating

Ac_3 = The temperature at which transformation of ferrite to austenite is completed during heating

Ac_4 = The temperature at which austenite transforms to delta ferrite during heating

$Ae_1, Ae_3, Ae_{cm}, Ae_4$ = The temperatures of phase changes at equilibrium

Ar_{cm} = In hypereutectoid steel, the temperature at which precipitation of cementite starts during cooling

Ar_1 = The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling

Ar_3 = The temperature at which austenite begins to transform to ferrite during cooling

Ar_4 = The temperature at which delta ferrite transforms to austenite during cooling

M_s = The temperature at which transformation of austenite to martensite starts during cooling

M_f = The temperature, during cooling, at which transformation of austenite to martensite is substantially completed

All these changes except the formation of martensite occur at lower temperatures during cooling than during heating, and depend on the rate of change of temperature.

Structure of Fully Annealed Carbon Steel.—In carbon steel that has been fully annealed, there are normally present, apart from such impurities as phosphorus and sulfur, two constituents: the element iron in a form metallurgically known as *ferrite* and the chemical compound iron carbide in the form metallurgically known as *cementite*. This latter constituent consists of 6.67 per cent carbon and 93.33 per cent iron. A certain proportion of these two constituents will be present as a mechanical mixture. This mechanical mixture, the amount of which depends on the carbon content of the steel, consists of alternate bands or layers of ferrite and cementite. Under the microscope, the matrix frequently has the appearance of mother-of-pearl and hence has been named *pearlite*. Pearlite contains about 0.85 per cent carbon and 99.15 per cent iron, neglecting impurities. A fully annealed steel containing 0.85 per cent carbon would consist entirely of pearlite. Such a steel is known as *eutectoid* steel and has a laminated structure characteristic of a eutectic alloy. Steel that has less than 0.85 per cent carbon (*hypoeutectoid* steel) has an excess of ferrite above that required to mix with the cementite present to form pearlite; hence, both ferrite and pearlite are present in the fully annealed state. Steel having a carbon content greater than 0.85 per cent (*hypereutectoid* steel) has an excess of cementite over that required to mix with the ferrite to form pearlite; hence, both cementite and pearlite are present in the fully annealed state. The structural constitution of carbon steel in terms of ferrite, cementite, pearlite and austenite for different carbon contents and at different temperatures is shown by the accompanying figure, *Phase Diagram of Carbon Steel*.

Effect of Heating Fully Annealed Carbon Steel.—When carbon steel in the fully annealed state is heated above the lower critical point, which is some temperature in the range of 1335 to 1355 degrees F (depending on the carbon content), the alternate bands or layers of ferrite and cementite that make up the pearlite begin to merge into each other. This process continues until the pearlite is thoroughly "dissolved," forming what is known as *austenite*. If the temperature of the steel continues to rise and there is present, in addition to the pearlite, any excess ferrite or cementite, this also will begin to dissolve into the austenite until finally only austenite will be present. The temperature at which the excess ferrite or cementite is completely dissolved in the austenite is called the *upper critical point*. This temperature varies with the carbon content of the steel much more widely than the lower critical point (see Fig. 1).

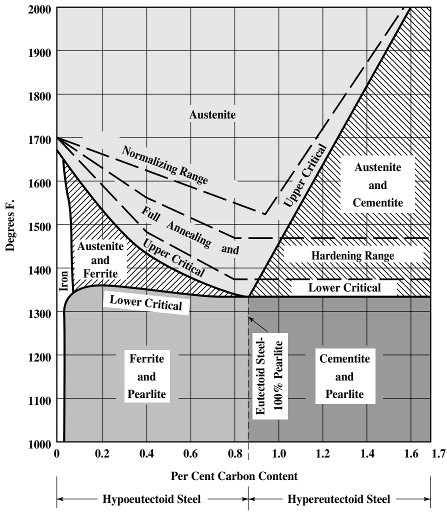

Fig. 1. Phase Diagram of Carbon Steel

Effect of Slow Cooling on Carbon Steel.—If carbon steel that has been heated to the point where it consists entirely of austenite is slowly cooled, the process of transformation that took place during the heating will be reversed, but the upper and lower critical points will occur at somewhat lower temperatures than they do on heating. Assuming that the steel was originally fully annealed, its structure on returning to atmospheric temperature after slow cooling will be the same as before in terms of the proportions of ferrite or cementite and pearlite present. The austenite will have entirely disappeared.

Effect of Rapid Cooling or Quenching on Carbon Steel.—Observations have shown that as the rate at which carbon steel is cooled from an austenitic state is increased, the temperature at which the austenite begins to change into pearlite drops more and more below the slow cooling transformation temperature of about 1300 degrees F. (For example, a 0.80 per cent carbon steel that is cooled at such a rate that the temperature drops 500 degrees in one second will show transformation of austenite beginning at 930 degrees F.) As the cooling rate is increased, the laminations of the pearlite formed by the transformation of the austenite become finer and finer up to the point where they cannot be detected under a high-power microscope, while the steel itself increases in hardness and tensile strength. As the rate of cooling is still further increased, this transformation temperature suddenly drops to around 500 degrees F or lower, depending on the carbon content of the steel. The cooling rate at which this sudden drop in transformation temperature takes place is called the *critical cooling rate*. When a piece of carbon steel is quenched at this rate or faster, a new structure is formed. The austenite is transformed into *martensite*, which is characterized by an angular needlelike structure and a very high hardness.

If carbon steel is subjected to a severe quench or to extremely rapid cooling, a small percentage of the austenite, instead of being transformed into martensite during the quenching operation, may be retained. Over a period of time, however, this remaining austenite tends to be gradually transformed into martensite even though the steel is not subjected to further heating or cooling. Martensite has a lower density than austenite, and such a change, or "aging" as it is called, often results in an appreciable increase in volume or "growth" and the setting up of new internal stresses in the steel.

Steel Heat-Treating Furnaces.—Various types of furnaces heated by gas, oil, or electricity are used for the heat treatment of steel. These furnaces include the oven or box type in various modifications for "in-and-out" or for continuous loading and unloading; the retort type; the pit type; the pot type; and the salt-bath electrode type.

Oven or Box Furnaces: This type of furnace has a box or oven-shaped heating chamber. The "in-and-out" oven furnaces are loaded by hand or by a track-mounted car that, when rolled into the furnace, forms the bottom of the heating chamber. The car type is used where heavy or bulky pieces must be handled. Some oven-type furnaces are provided with a full muffle or a semimuffle, which is an enclosed refractory chamber into which the parts to be heated are placed. The full-muffle, being fully enclosed, prevents any flames or burning gases from coming in contact with the work and permits a special atmosphere to be used to protect or condition the work. The semimuffle, which is open at the top, protects the work from direct impingement of the flame although it does not shut off the work from the hot gases. In the direct-heat-type oven furnace, the work is open to the flame. In the electric oven furnace, a retort is provided when gas atmospheres are to be employed to confine the gas and prevent it from attacking the heating elements. Where muffles are used, they must be replaced periodically, and a greater amount of fuel is required than in a direct-heat type of oven furnace.

For continuous loading and unloading, there are several types of furnaces such as rotary hearth car; roller-, furnace belt-, walking-beam, or pusher-conveyor; and a continuous-kiln-type through which track-mounted cars are run. In the continuous type of furnace, the work may pass through several zones that are maintained at different temperatures for preheating, heating, soaking, and cooling.

Retort Furnace: This is a vertical type of furnace provided with a cylindrical metal retort into which the parts to be heat-treated are suspended either individually, if large enough, or in a container of some sort. The use of a retort permits special gas atmospheres to be employed for carburizing, nitriding, etc.

Pit-Type Furnace: This is a vertical furnace arranged for the loading of parts in a metal basket. The parts within the basket are heated by convection, and when the basket is lowered into place, it fits into the furnace chamber in such a way as to provide a dead-air space to prevent direct heating.

Pot-Type Furnace: This furnace is used for the immersion method of heat treating small parts. A cast-alloy pot is employed to hold a bath of molten lead or salt in which the parts are placed for heating.

Salt Bath Electrode Furnace: In this type of electric furnace, heating is accomplished by means of electrodes suspended directly in the salt bath. The patented grouping and design of electrodes provide an electromagnetic action that results in an automatic stirring action. This stirring tends to produce an even temperature throughout the bath.

Vacuum Furnace: Vacuum heat treatment is a relatively new development in metallurgical processing, with a vacuum substituting for the more commonly used protective gas atmospheres. The most often used furnace is the "cold wall" type, consisting of a water-cooled vessel that is maintained near ambient temperature during operation. During quenching, the chamber is backfilled up to or above atmospheric pressure with an inert gas, which is circulated by an internal fan. When even faster cooling rates are needed, furnaces are available with capability for liquid quenching, performed in an isolated chamber.

Fluidized-Bed Furnace: Fluidized-bed techniques are not new; however, new furnace designs have extended the technology into the temperature ranges required for most common heat treatments. In fluidization, a bed of dry, finely divided particles, typically aluminum oxide, is made to behave like a liquid by feeding gas upward through the bed. An important characteristic of the bed is high-efficiency heat transfer. Applications include continuous or batch-type units for all general heat treatments.

Hardening

Basic Steps in Hardening.—The operation of hardening steel consists fundamentally of two steps. The first step is to heat the steel to some temperature above (usually at least 100 degrees F above) its transformation point so that it becomes entirely austenitic in structure. The second step is to quench the steel at some rate faster than the critical rate (which depends on the carbon content, the amounts of alloying elements present other than carbon, and the grain size of the austenite) to produce a martensitic structure. The hardness of a martensitic steel depends on its carbon content and ranges from about 460 Brinell at 0.20 per cent carbon to about 710 Brinell above 0.50 carbon. In comparison, ferrite has a hardness of about 90 Brinell, pearlite about 240 Brinell, and cementite around 550 Brinell.

Critical Points of Decalescence and Recalescence.—The critical or transformation point at which pearlite is transformed into austenite as it is being heated is also called the *decalescence point*. If the temperature of the steel was observed as it passed through the decalescence point, it would be noted that it would continue to absorb heat without appreciably rising in temperature, although the immediate surroundings were hotter than the steel. Similarly, the critical or transformation point at which austenite is transformed back into pearlite on cooling is called the *recalescence point*. When this point is reached, the steel will give out heat so that its temperature instead of continuing to fall, will momentarily increase.

The recalescence point is lower than the decalescence point by anywhere from 85 to 215 degrees F, and the lower of these points does not manifest itself unless the higher one has first been fully passed. These critical points have a direct relation to the hardening of steel. Unless a temperature sufficient to reach the decalescence point is obtained, so that the pearlite is changed into austenite, no hardening action can take place; and unless the steel is cooled suddenly before it reaches the recalescence point, thus preventing the changing back again from austenite to pearlite, no hardening can take place. The critical points vary for different kinds of steel and must be determined by tests. This variation in the critical points makes it necessary to heat different steels to different temperatures when hardening.

Hardening Temperatures.—The maximum temperature to which a steel is heated before quenching to harden it is called the hardening temperature. Hardening temperatures vary for different steels and different classes of service, although, in general, it may be said that the hardening temperature for any given steel is above the lower critical point of that steel.

Just how far above this point the hardening temperature lies for any particular steel depends on three factors: 1) the chemical composition of the steel; 2) the amount of excess ferrite (if the steel has less than 0.85 per cent carbon content) or the amount of excess cementite (if the steel has more than 0.85 per cent carbon content) that is to be dissolved in the austenite; and 3) the maximum grain size permitted, if desired.

The general range of full-hardening temperatures for carbon steels is shown by the diagram. This range is merely indicative of general practice and is not intended to represent absolute hardening temperature limits. It can be seen that for steels of less than 0.85 per cent carbon content, the hardening range is above the upper critical point — that is, above the temperature at which all the excess ferrite has been dissolved in the austenite. On the other hand, for steels of more than 0.85 per cent carbon content, the hardening range lies somewhat below the upper critical point. This indicates that in this hardening range, some of the excess cementite still remains undissolved in the austenite. If steel of more than 0.85 per cent carbon content were heated above the upper critical point and then quenched, the resulting grain size would be excessively large.

At one time, it was considered desirable to heat steel only to the minimum temperature at which it would fully harden, one of the reasons being to avoid grain growth that takes place at higher temperature. It is now realized that no such rule as this can be applied generally since there are factors other than hardness that must be taken into consideration. For example, in many cases, toughness can be impaired by too low a temperature just as much as by too high a temperature. It is true, however, that too high hardening temperatures result in warpage, distortion, increased scale, and decarburization.

Hardening Temperatures for Carbon Tool Steels.—The best hardening temperatures for any given tool steel are dependent on the type of tool and the intended class of service. Wherever possible, the specific recommendations of the tool steel manufacturer should be followed. General recommendations for hardening temperatures of carbon tool steels based on carbon content are as follows: For steel of 0.65 to 0.80 per cent carbon content, 1450 to 1550 degrees F; for steel of 0.80 to 0.95 per cent carbon content, 1410 to 1460 degrees F; for steel of 0.95 to 1.10 per cent carbon content, 1390 to 1430 degrees F; and for steels of 1.10 per cent and over carbon content, 1380 to 1420 degrees F. For a given hardening temperature range, the higher temperatures tend to produce deeper hardness penetration and increased compressional strength, whereas the lower temperatures tend to result in shallower hardness penetration but increased resistance to splitting or bursting stresses.

Determining Hardening Temperatures.—A hardening temperature can be specified directly or it may be specified indirectly as a certain temperature rise above the lower critical point of the steel. Where the temperature is specified directly, a pyrometer of the type that indicates the furnace temperature or a pyrometer of the type that indicates the work temperature may be employed. If the pyrometer shows furnace temperature, care must be taken to allow sufficient time for the work to reach the furnace temperature after the pyrometer indicates that the required hardening temperature has been attained. If the pyrometer indicates work temperature, then, where the workpiece is large, time must be allowed for the interior of the work to reach the temperature of the surface, which is the temperature indicated by the pyrometer.

Where the hardening temperature is specified as a given temperature rise above the critical point of the steel, a pyrometer that indicates the temperature of the work should be used. The critical point, as well as the given temperature rise, can be more accurately determined with this type of pyrometer. As the work is heated, its temperature, as indicated by the pyrometer, rises steadily until the lower critical or decalescence point of the steel is reached. At this point, the temperature of the work ceases to rise and the pyrometer indicating or recording pointer remains stationary or fluctuates slightly. After a certain elapsed period, depending on the heat input rate, the internal changes in structure of the steel that take place at the lower critical point are completed and the temperature of the work again begins to rise. A small fluctuations in temperature may occur in the interval during which structural changes are taking place, so for uniform practice, the critical point may be considered as the temperature at which the pointer first becomes stationary.

Heating Steel in Liquid Baths.—The liquid bath commonly used for heating steel tools preparatory to hardening are molten lead, sodium cyanide, barium chloride, a mixture of barium and potassium chloride, and other metallic salts. The molten substance is retained in a crucible or pot and the heat required may be obtained from gas, oil, or electricity. The principal advantages of heating baths are as follows: No part of the work can be heated to a temperature above that of the bath; the temperature can be easily maintained at whatever degree has proved, in practice, to give the best results; the submerged steel can be heated uniformly, and the finished surfaces are protected against oxidation.

Salt Baths.—Molten baths of various salt mixtures or compounds are used extensively for heat-treating operations such as hardening and tempering; they are also utilized for annealing ferrous and nonferrous metals. Commercial salt-bath mixtures are available that meet a wide range of temperature and other metallurgical requirements. For example, there are neutral baths for heating tool and die steels without carburizing the surfaces; baths for carburizing the surfaces of low-carbon steel parts; baths adapted for the usual tempering temperatures of, say, 300 to 1100 degrees F; and baths that may be heated to temperatures up to approximately 2400 degrees F for hardening high-speed steels. Salt baths are also adapted for local or selective hardening, the type of bath being selected to suit the requirements. For example, a neutral bath may be used for annealing the ends of tubing or other parts, or an activated cyanide bath for carburizing the ends of shafts or other parts. Surfaces that are not to be carburized are protected by copper plating. When the work is immersed, the unplated surfaces are subjected to the carburizing action.

Baths may consist of a mixture of sodium, potassium, barium, and calcium chlorides or nitrates of sodium, potassium, barium, and calcium in varying proportions, to which sodium carbonate and sodium cyanide are sometimes added to prevent decarburization. Various proportions of these salts provide baths of different properties. Potassium cyanide is seldom used as sodium cyanide costs less. The specific gravity of a salt bath is not as high as that of a lead bath; consequently, the work may be suspended in a salt bath and does not have to be held below the surface as in a lead bath.

The Lead Bath.—The lead bath is extensively used, but is not adapted to the high temperatures required for hardening high-speed steel, as it begins to vaporize at about 1190 degrees F. As the temperature increases, the lead volatilizes and gives off poisonous vapors; hence, lead furnaces should be equipped with hoods to carry away the fumes. Lead baths are generally used for temperatures below 1500 or 1600 degrees F. They are often employed for heating small pieces that must be hardened in quantities. It is important to use pure lead that is free from sulfur. The work should be preheated before plunging it into the molten lead.

Defects in Hardening.—Uneven heating is the cause of most of the defects in hardening. Cracks of a circular form, from the corners or edges of a tool, indicate uneven heating in hardening. Cracks of a vertical nature and dark-colored fissures indicate that the steel has been burned and should be put on the scrap heap. Tools that have hard and soft places have been either unevenly heated, unevenly cooled, or "soaked," a term used to indicate prolonged heating. A tool not thoroughly moved about in the hardening fluid will show hard and soft places, and have a tendency to crack. Tools that are hardened by dropping them to the bottom of the tank sometimes have soft places, owing to contact with the floor or sides.

Scale on Hardened Steel.—The formation of scale on the surface of hardened steel is due to the contact of oxygen with the heated steel; hence, to prevent scale, the heated steel must not be exposed to the action of the air. When using an oven heating furnace, the flame should be so regulated that it is not visible in the heating chamber. The heated steel should be exposed to the air as little as possible, when transferring it from the furnace to the quenching bath. An old method of preventing scale and retaining a fine finish on dies used in jewelry manufacture, small taps, etc., is as follows: Fill the die impression with powdered boracic acid and place near the fire until the acid melts; then add a little more acid to ensure covering all the surfaces. The die is then hardened in the usual way. If the boracic acid does not come off entirely in the quenching bath, immerse the work in boiling water. Dies hardened by this method are said to be as durable as those heated without the acid.

Hardening or Quenching Baths.—The purpose of a quenching bath is to remove heat from the steel being hardened at a rate that is faster than the critical cooling rate. Generally speaking, the more rapid the rate of heat extraction above the cooling rate, the higher will be the resulting hardness. To obtain the different rates of cooling required by different classes of work, baths of various kinds are used. These include plain or fresh water, brine, caustic soda solutions, oils of various classes, oil–water emulsions, baths of molten salt or lead for high-speed steels, and air cooling for some high-speed steel tools when a slow rate of cooling is required. To minimize distortion and cracking where such tendencies are present, without sacrificing depth-of-hardness penetration, a quenching medium should be selected that will cool rapidly at the higher temperatures and more slowly at the lower temperatures, that is below 750 degrees F. Oil quenches in general meet this requirement.

Oil Quenching Baths: Oil is used very extensively as a quenching medium as it results in a good proportion of hardness, toughness, and freedom from warpage when used with standard steels. Oil baths are used extensively for alloy steels. Various kinds of oils are employed, such as prepared mineral oils and vegetable, animal, and fish oils, either singly or in combination. Prepared mineral quenching oils are widely used because they have good quenching characteristics, are chemically stable, do not have an objectionable odor, and are relatively inexpensive. Special compounded oils of the soluble type are used in many plants instead of such oils as fish oil, linseed oil, cottonseed oil, etc. The soluble properties enable the oil to form an emulsion with water.

Oil cools steel at a slower rate than water, but the rate is fast enough for alloy steel. Oils have different cooling rates, however, and this rate may vary through the initial and final stages of the quenching operation. Faster cooling in the initial stage and slower cooling at lower temperatures are preferable because there is less danger of cracking the steel. The temperature of quenching oil baths should range ordinarily between 90 and 130 degrees F. A fairly constant temperature may be maintained either by circulating the oil through cooling coils or by using a tank provided with a cold-water jacket.

A good quenching oil should possess a flash and fire point sufficiently high to be safe under the conditions used and 350 degrees F should be about the minimum point. The specific heat of the oil regulates the hardness and toughness of the quenched steel; and the greater the specific heat, the higher will be the hardness produced. Specific heats of quenching oils vary from 0.20 to 0.75, the specific heats of fish, animal, and vegetable oils usually being from 0.2 to 0.4, and of soluble and mineral oils from 0.5 to 0.7. The efficient temperature range for quenching oil is from 90 to 140 degrees F.

Quenching in Water.—Many carbon tool steels are hardened by immersing them in a bath of fresh water, but water is not an ideal quenching medium. Contact between the water and work and the cooling of the hot steel are impaired by the formation of gas bubbles or an insulating vapor film especially in holes, cavities, or pockets. The result is uneven cooling and sometimes excessive strains which may cause the tool to crack; in fact, there is greater danger of cracking in a fresh-water bath than in one containing salt water or brine.

In order to secure more even cooling and reduce danger of cracking, either rock salt (8 or 9 per cent) or caustic soda (3 to 5 per cent) may be added to the bath to eliminate or prevent the formation of a vapor film or gas pockets, thus promoting rapid early cooling. Brine is commonly used and ¾ pound of rock salt per gallon of water is equivalent to about 8 per cent of salt. Brine is not inherently a more severe or drastic quenching medium than plain water, although it may seem to be because the brine makes better contact with the heated steel and, consequently, cooling is more effective. In still-bath quenching, a slow up-and-down movement of the tool is preferable to a violent swishing around.

The temperature of water-base quenching baths should preferably be kept around 70 degrees F, but 70 to 90 or 100 degrees F is a safe range. The temperature of the hardening bath has a great deal to do with the hardness obtained. The higher the temperature of the quenching water, the more nearly does its effect approach that of oil; and if boiling water is used for quenching, it will have an effect even more gentle than that of oil — in fact, it would leave the steel nearly soft. Parts of irregular shape are sometimes quenched in a water bath that has been warmed somewhat to prevent sudden cooling and cracking.

When water is used, it should be "soft" because unsatisfactory results will be obtained with "hard" water. Any contamination of water-base quenching liquids by soap tends to decrease their rate of cooling. A water bath having 1 or 2 inches of oil on the top is sometimes employed to advantage for quenching tools made of high-carbon steel as the oil through which the work first passes reduces the sudden quenching action of the water.

The bath should be amply large to dissipate the heat rapidly and the temperature should be kept about constant so that successive pieces will be cooled at the same rate. Irregularly shaped parts should be immersed so that the heaviest or thickest section enters the bath first. After immersion, the part to be hardened should be agitated in the bath; the agitation reduces the tendency of the formation of a vapor coating on certain surfaces, and a more uniform rate of cooling is obtained. The work should never be dropped to the bottom of the bath until quite cool.

Flush or Local Quenching by Pressure-Spraying: When dies for cold heading, drawing, extruding, etc., or other tools, require a hard working surface and a relatively soft but tough body, the quenching may be done by spraying water under pressure against the interior or other surfaces to be hardened. Special spraying fixtures are used to hold the tool and apply the spray where the hardening is required. The pressure spray prevents the formation of gas pockets previously referred to in connection with the fresh-water quenching bath; hence, fresh water is effective for flush quenching and there is no advantage in using brine.

Quenching in Molten Salt Bath.— A molten salt bath may be used in preference to oil for quenching high-speed steel. The object in using a liquid salt bath for quenching (instead of an oil bath) is to obtain maximum hardness with minimum cooling stresses and distortion that might result in cracking expensive tools, especially if there are irregular sections. The temperature of the quenching bath may be around 1100 or 1200 degrees F. Quenching is followed by cooling to room temperature and then the tool is tempered or drawn in a bath having a temperature range of 950 to 1100 degrees F. In many cases, the tempering temperature is about 1050 degrees F.

Tanks for Quenching Baths.— The main point to be considered in a quenching bath is to keep it at a uniform temperature, so that successive pieces quenched will be subjected to the same heat treatment. The next consideration is to keep the bath agitated, so that it will not be of different temperatures in different places; if thoroughly agitated and kept in motion, as the case with the bath shown in Fig. 1, it is not even necessary to keep the pieces in motion in the bath, as steam will not be likely to form around the pieces quenched. Experience has proved that if a piece is held still in a thoroughly agitated bath, it will come out much straighter than if it has been moved around in an unagitated bath, an important consideration, especially when hardening long pieces. It is, besides, no easy matter to keep heavy and long pieces in motion unless it be done by mechanical means.

In Fig. 1 is shown a water or brine tank for quenching baths. Water is forced by a pump or other means through the supply pipe into the intermediate space between the outer and inner tank. From the intermediate space, it is forced into the inner tank through holes as indicated. The water returns to the storage tank by overflowing from the inner tank into the outer one and then through the overflow pipe as indicated. In Fig. 3 is shown another water or brine tank of a more common type. In this case, the water or brine is pumped from the storage tank and continuously returned to it. If the storage tank contains a large volume of water, there is no need for a special means for cooling. Otherwise, arrangements must be made for cooling the water after it has passed through the tank. The bath is agitated by the force with which the water is pumped into it. The holes at A are drilled at an angle, so as to throw the water toward the center of the tank. In Fig. 2 is shown an oil-quenching tank in which water is circulated in an outer surrounding tank to keep the oil bath cool. Air is forced into the oil bath to keep it agitated. Fig. 4 shows the ordinary type of quenching tank cooled by water forced through a coil of pipe. This arrangement can be used for oil, water, or brine. Fig. 5 shows a similar type of quenching tank, but with two coils of pipe. Water flows through one of these and steam through the other. By these means, it is possible to keep the bath at a constant temperature.

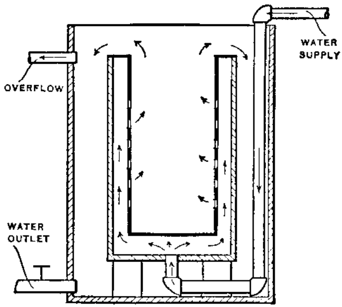

Fig. 1.

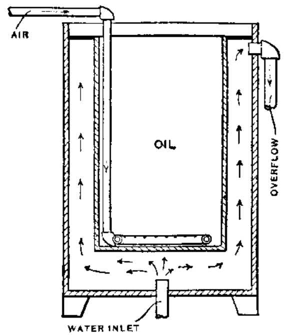

Fig. 2.

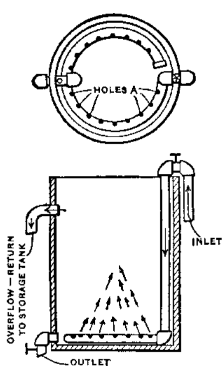

Fig. 3.

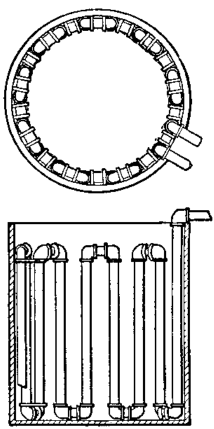

Fig. 4.

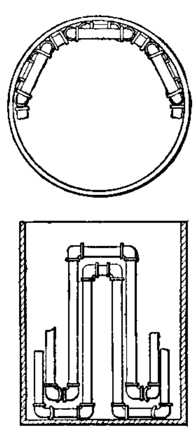

Fig. 5.

Interrupted Quenching.—*Austempering, martempering, and isothermal quenching* are three methods of interrupted quenching that have been developed to obtain greater toughness and ductility for given hardnesses and to avoid the difficulties of quench cracks, internal stresses, and warpage, frequently experienced when the conventional method of quenching steel directly and rapidly from above the transformation point to atmospheric temperature is employed. In each of these three methods, quenching is begun when the work has reached some temperature above the transformation point and is conducted at a rate faster than the critical rate. The rapid cooling of the steel is interrupted, however, at some temperature above that at which martensite begins to form. The three methods differ in the temperature range at which interruption of the rapid quench takes place, the length of time that the steel is held at this temperature, and whether the subsequent cooling to atmospheric temperature is rapid or slow, and is or is not preceded by a tempering operation.

One of the reasons for maintaining the steel at a constant temperature for a definite period of time is to permit the inside sections of the piece to reach the same temperature as the outer sections so that when transformation of the structure does take place, it will occur at about the same rate and period of time throughout the piece. In order to maintain the constant temperature required in interrupted quenching, a quenching arrangement for absorbing and dissipating a large quantity of heat without increase in temperature is needed. Molten salt baths equipped for water spray or air cooling around the exterior of the bath container have been used for this purpose.

Austempering: This is a heat-treating process in which steels are quenched in a bath maintained at some constant temperature in the range of 350 to 800 degrees F, depending on the analysis of the steel and the characteristics to be obtained. On immersion in the quenching bath, the steel is cooled more rapidly than the critical quenching rate. When the temperature of the steel reaches that of the bath, however, the quenching action is interrupted. If the steel is now held at this temperature for a predetermined length of time, say, from 10 to 60 minutes, the austenitic structure of the steel is gradually changed into a new structure, called *bainite*. The structure of bainite is acicular (needlelike) and resembles that of tempered martensite such as is usually obtained by quenching in the usual manner to atmospheric temperature and tempering at 400 degrees F or higher.

Hardnesses ranging up to 60 Rockwell C, depending on the carbon and alloy content of the steel, are obtainable and compare favorably with those obtained for the respective steels by a conventional quench and tempering to above 400 degrees F. Much greater toughness and ductility are obtained in an austempered piece, however, as compared with a similar piece quenched and tempered in the usual manner.

Two factors are important in austempering. First, the steel must be quenched rapidly enough to the specified subtransformation temperature to avoid any formation of pearlite, and, second, it must be held at this temperature until the transformation from austenite to bainite is completed. Time and temperature transformation curves (called S-curves because of their shape) have been developed for different steels and these curves provide important data governing the conduct of austempering, as well as the other interrupted quenching methods.

Austempering has been applied chiefly to steels having 0.60 per cent or more carbon content with or without additional low-alloy content, and to pieces of small diameter or section, usually under 1 inch, but varying with the composition of the steel. Case-hardened parts may also be austempered.

Martempering: In this process the steel is first rapidly quenched from some temperature above the transformation point down to some temperature (usually about 400 degrees F) just above that at which martensite begins to form. It is then held at this temperature for a length of time sufficient to equalize the temperature throughout the part, after which it is removed and cooled in air. As the temperature of the steel drops below the transformation point, martensite begins to form in a matrix of austenite at a fairly uniform rate throughout the piece. The soft austenite acts as a cushion to absorb some of the stresses which develop as the martensite is formed. The difficulties presented by quench cracks, internal stresses, and dimensional changes are largely avoided, thus a structure of high hardness can be obtained. If greater toughness and ductility are required, conventional tempering may follow. In general, heavier sections can be hardened more easily by the martempering process than by the austempering process. The martempering process is especially suited to the higher-alloyed steels.

Isothermal Quenching: This process resembles austempering in that the steel is first rapidly quenched from above the transformation point down to a temperature that is above that at which martensite begins to form and is held at this temperature until the austenite is completely transformed into bainite. The constant temperature to which the piece is quenched and then maintained is usually 450 degrees F or above. The process differs from austempering in that after transformation to a bainite structure has been completed, the steel is immersed in another bath and is brought up to some higher temperature, depending on the characteristics desired, and is maintained at this temperature for a definite period of time, followed by cooling in air. Thus, tempering to obtain the desired toughness or ductility takes place immediately after the structure of the steel has changed to bainite and before it is cooled to atmospheric temperature.

Tempering

The object of *tempering* or *drawing* is to reduce the brittleness in hardened steel and to remove the internal strains caused by the sudden cooling in the quenching bath. The tempering process consists in heating the steel by various means to a certain temperature and then cooling it. When steel is in a fully hardened condition, its structure consists largely of *martensite*. On reheating to a temperature of from about 300 to 750 degrees F, a softer and tougher structure known as *troostite* is formed. If the steel is reheated to a temperature of from 750 to 1290 degrees F, a structure known as *sorbite* is formed that has somewhat less strength than troostite but much greater ductility.

Tempering Temperatures.—If steel is heated in an oxidizing atmosphere, a film of oxide forms on the surface that changes color as the temperature increases. These oxide colors (see table) have been used extensively in the past as a means of gaging the correct amount of temper; but since these colors are affected to some extent by the composition of the metal, the method is not dependable.

The availability of reliable pyrometers in combination with tempering baths of oil, salt, or lead make it possible to heat the work uniformly and to a given temperature within close limits.

Suggested temperatures for tempering various tools are given in the accompanying table.

Tempering in Oil.—Oil baths are extensively used for tempering tools (especially in quantity), the work being immersed in oil heated to the required temperature, which is indicated by a thermometer. It is important that the oil have a uniform temperature throughout and that the work be immersed long enough to acquire this temperature. Cold steel should not be plunged into a bath heated for tempering, owing to the danger of cracking. The steel should either be preheated to about 300 degrees F, before placing it in the bath, or the latter should be at a comparatively low temperature before immersing the steel, and then be heated to the required degree. A temperature of from 650 to 700 degrees F can be obtained with heavy tempering oils; for higher temperatures, either a bath of nitrate salts or a lead bath may be used.

In tempering, the best method is to immerse the pieces to be tempered before starting to heat the oil, so that they are heated with the oil. After the pieces tempered are taken out of the oil bath, they should be immediately dipped in a tank of caustic soda, and after that in a tank of hot water. This will remove all oil that might adhere to the tools. The following tempering oil has given satisfactory results: mineral oil, 94 per cent; saponifiable oil, 6 per cent; specific gravity, 0.920; flash point, 550 degrees F; fire test, 625 degrees F.

Tempering in Salt Baths.—Molten salt baths may be used for tempering or drawing operations. Nitrate baths are particularly adapted for the usual drawing temperature range of, say, 300 to 1100 degrees F. Tempering in an oil bath usually is limited to temperatures of 500 to 600 degrees F, and some heat-treating specialists recommend the use of a salt bath for temperatures above 350 or 400 degrees F, as it is considered more efficient and economical. Tempering in a bath (salt or oil) has several advantages, such as ease in controlling the temperature range and maintenance of a uniform temperature. The work is also heated much more rapidly in a molten bath. A gas- or oil-fired muffle or semimuffle furnace may be used for tempering, but a salt bath or oil bath is preferable. A salt bath is recommended for tempering high-speed steel, although furnaces may also be used. The bath or furnace temperature should be increased gradually, say, from 300 to 400 degrees F up to the tempering temperature, which may range from 1050 to 1150 degrees F for high-speed steel.

Tempering in a Lead Bath.—The lead bath is commonly used for heating steel in connection with tempering, as well as for hardening. The bath is first heated to the temperature at which the steel should be tempered; the preheated work is then placed in the bath long enough to acquire this temperature, after which it is removed and cooled. As the melting temperature of pure lead is about 620 degrees F, tin is commonly added to it to lower the temperature sufficiently for tempering. Reductions in temperature can be obtained by varying the proportions of lead and tin, as shown by the table, "Temperatures of Lead Bath Alloys."

Temperatures of Lead Bath Alloys

Parts Lead	Parts Tin	Melting Temp., Deg. F	Parts Lead	Parts Tin	Melting Temp., Deg. F	Parts Lead	Parts Tin	Melting Temp., Deg. F
200	8	560	39	8	510	19	8	460
100	8	550	33	8	500	17	8	450
75	8	540	28	8	490	16	8	440
60	8	530	24	8	480	15	8	430
48	8	520	21	8	470	14	8	420

To Prevent Lead from Sticking to Steel.—To prevent hot lead from sticking to parts heated in it, mix common whiting with wood alcohol, and paint the part that is to be heated. Water can be used instead of alcohol, but in that case, the paint must be thoroughly dry, as otherwise the moisture will cause the lead to "fly." Another method is to make a thick paste according to the following formula: Pulverized charred leather, 1 pound; fine wheat flour, 1½ pounds; fine table salt, 2 pounds. Coat the tool with this paste and heat slowly until dry, then proceed to harden. Still another method is to heat the work to a blue color, or about 600 degrees F, and then dip it in a strong solution of salt water, prior to heating in the lead bath. The lead is sometimes removed from parts having fine projections or teeth, by using a stiff brush just before immersing in the cooling bath. Removal of lead is necessary to prevent the formation of soft spots.

Tempering in Sand.—The sand bath is used for tempering certain classes of work. One method is to deposit the sand on an iron plate or in a shallow box that has burners beneath it. With this method of tempering, tools such as boiler punches, etc., can be given a varying temper by placing them endwise in the sand. As the temperature of the sand bath is higher toward the bottom, a tool can be so placed that the color of the lower end will become a deep dark blue when the middle portion is a very dark straw, and the working end or top a light straw color, the hardness gradually increasing from the bottom up.

Double Tempering.—In tempering high-speed steel tools, it is common practice to repeat the tempering operation or "double temper" the steel. Double tempering is done by heating the steel to the tempering temperature (say, 1050 degrees F) and holding it at that temperature for two hours. It is then cooled to room temperature, reheated to 1050 degrees F for another two-hour period, and again cooled to room temperature. After the first tempering operation, some untempered martensite remains in the steel. This martensite is not only tempered by a second tempering operation but is relieved of internal stresses, thus improving the steel for service conditions. The hardening temperature for the higher-alloy steels may affect the hardness after tempering. For example, molybdenum high-speed steel when heated to 2100 degrees F had a hardness of 61 Rockwell C after tempering, whereas a temperature of 2250 degrees F resulted in a hardness of 64.5 Rockwell C after tempering.

Temperatures as Indicated by the Color of Plain Carbon Steel

Degrees Centigrade	Degrees Fahrenheit	Color of Steel	Degrees Centigrade	Degrees Fahrenheit	Color of Steel
221.1	430	Very pale yellow	265.6	510	Spotted red-brown
226.7	440	Light yellow	271.1	520	Brown-purple
232.2	450	Pale straw-yellow	276.7	530	Light purple
237.8	460	Straw-yellow	282.2	540	Full purple
243.3	470	Deep straw-yellow	287.8	550	Dark purple
248.9	480	Dark yellow	293.3	560	Full blue
254.4	490	Yellow-brown	298.9	570	Dark blue
260.0	500	Brown-yellow	337.8	640	Light blue

Tempering Temperatures for Various Plain Carbon Steel Tools

Degrees F	Class of Tool
495 to 500	Taps ½ inch or over, for use on automatic screw machines
495 to 500	Nut taps ½ inch and under
515 to 520	Taps ¼ inch and under, for use on automatic screw machines
525 to 530	Thread dies to cut thread close to shoulder
500 to 510	Thread dies for general work
495	Thread dies for tool steel or steel tube
525 to 540	Dies for bolt threader threading to shoulder
460 to 470	Thread rolling dies
430 to 435	Hollow mills (solid type) for roughing on automatic screw machines
485	Knurls
450	Twist drills for hard service
450	Centering tools for automatic screw machines
430	Forming tools for automatic screw machines
430 to 435	Cut-off tools for automatic screw machines
440 to 450	Profile cutters for milling machines
430	Formed milling cutters
435 to 440	Milling cutters
430 to 440	Reamers
460	Counterbores and countersinks
480	Cutters for tube- or pipe-cutting machines
460 to 520	Snaps for pneumatic hammers — harden full length, temper to 460 degrees, then bring point to 520 degrees

Annealing, Spheroidizing, and Normalizing

Annealing of steel is a heat-treating process in which the steel is heated to some elevated temperature, usually in or near the critical range, is held at this temperature for some period of time, and is then cooled, usually at a slow rate. Spheroidizing and normalizing may be considered as special cases of annealing.

The *full annealing* of carbon steel consists in heating it slightly above the *upper* critical point for hypoeutectoid steels (steels of less than 0.85 per cent carbon content) and slightly above the *lower* critical point for hypereutectoid steels (steels of more than 0.85 per cent carbon content), holding it at this temperature until it is uniformly heated and then slowly cooling it to 1000 degrees F or below. The resulting structure is layerlike, or lamellar, in character due to the pearlite that is formed during the slow cooling.

Anealing is employed 1) to soften steel for machining, cutting, stamping, etc., or for some particular service; 2) to alter ductility, toughness, electrical or magnetic characteristics or other physical properties; 3) to refine the crystal structure; 4) to produce grain reorientation; and 5) to relieve stresses and hardness resulting from cold working.

The *spheroidizing* of steel, according to the American Society of Metals, is "any process of heating and cooling that produces a rounded or globular form of carbide." High-carbon steels are spheroidized to improve their machinability especially in continuous cutting operations such as are performed by lathes and screw machines. In low-carbon steels, spheroidizing may be employed to meet certain strength requirements before subsequent heat treatment. Spheroidizing also tends to increase resistance to abrasion.

The *normalizing* of steel consists in heating it to some temperature above that used for annealing, usually about 100 degrees F above the upper critical range, and then cooling it in still air at room temperature. Normalizing is intended to put the steel into a uniform, unstressed condition of proper grain size and refinement so that it will properly respond to further heat treatments. It is particularly important in the case of forgings that are to be later heat treated. Normalizing may or may not (depending on the composition) leave steel in a sufficiently soft state for machining with available tools. Annealing for machinability is often preceded by normalizing and the combined treatment — frequently called a *double anneal* — produces a better result than a simple anneal.

Annealing Practice.—For carbon steels, the following annealing temperatures are recommended by the American Society for Testing and Materials: Steels of less than 0.12 per cent carbon content, 1600 to 1700 degrees F; steels of 0.12 to 0.29 per cent carbon content, 1550 to 1600 degrees F, steels of 0.30 to 0.49 per cent carbon content, 1500 to 1550 degrees F; and for 0.50 to 1.00 per cent carbon steels, from 1450 to 1500 degrees F. Slightly lower temperatures are satisfactory for steels having more than 0.75 per cent manganese content. Heating should be uniform to avoid the formation of additional stresses. In the case of large workpieces, the heating should be slow enough so that the temperature of the interior does not lag too far behind that of the surface.

It has been found that in annealing steel, the higher the temperature to which it is heated to produce an austenitic structure, the greater the tendency of the structure to become lamellar (pearlitic) in cooling. On the other hand, the closer the austenitizing temperature to the critical temperature, the greater is the tendency of the annealed steel to become spheroidal.

Rate of Cooling: After heating the steel to some temperature within the annealing range, it should be cooled slowly enough to permit the development of the desired softness and ductility. In general, the slower the cooling rate, the greater the resulting softness and ductility. Steel of a high-carbon content should be cooled more slowly than steel of a low-carbon content; and the higher the alloy content, the slower is the cooling rate usually required. Where extreme softness and ductility are not required. the steel may be cooled in the annealing furnace to some temperature well below the critical point, say, to about 1000 degrees F and then removed and cooled in air.

Annealing by Constant-Temperature Transformation.—It has been found that steel that has been heated above the critical point so that it has an austenitic structure can be transformed into a lamellar (pearlitic) or a spheroidal structure by holding it for a definite period of time at some constant subcritical temperature. In other words, it is feasible to anneal steel by means of a constant-temperature transformation as well as by the conventional continuous cooling method. When the constant-temperature transformation method is employed, the steel, after being heated to some temperature above the critical and held at this temperature until it is austenitized, is cooled as rapidly as feasible to some relatively high subcritical transformation temperature. The selection of this temperature is governed by the desired microstructure and hardness required and is taken from a transformation time and temperature curve (often called a TTT curve). As drawn for a particular steel, such a curve shows the length of time required to transform that steel from an austenitic state at various subcritical temperatures. After being held at the selected sub-critical temperature for the required length of time, the steel is cooled to room temperature — again, as rapidly as feasible. This rapid cooling down to the selected transformation temperature and then down to room temperature has a negligible effect on the structure of the steel and often produces a considerable saving in time over the conventional slow cooling method of annealing.

The softest condition in steel can be developed by heating it to a temperature usually less than 100 degrees F above the lower critical point and then cooling it to some temperature, usually less than 100 degrees, below the critical point, where it is held until the transformation is completed. Certain steels require a very lengthy period of time for transformation of the austenite when held at a constant temperature within this range. For such steels, a practical procedure is to allow most of the transformation to take place in this temperature range where a soft product is formed and then to finish the transformation at a lower temperature where the time for the completion of the transformation is short.

Spheroidizing Practice.—A common method of spheroidizing steel consists in heating it to or slightly below the lower critical point, holding it at this temperature for a period of time, and then cooling it slowly to about 1000 degrees F or below. The length of time for which the steel is held at the spheroidizing temperature largely governs the degree of spheroidization. High-carbon steel may be spheroidized by subjecting it to a temperature that alternately rises and falls between a point within and a point without the critical range. Tool steel may be spheroidized by heating to a temperature slightly above the critical range and then, after being held at this temperature for a period of time, cooling without removal from the furnace.

Normalizing Practice.—When using the lower-carbon steels, simple normalizing is often sufficient to place the steel in its best condition for machining and will lessen distortion in carburizing or hardening. In the medium- and higher-carbon steels, combined normalizing and annealing constitutes the best practice. For unimportant parts, the normalizing may be omitted entirely or annealing may be practiced only when the steel is otherwise difficult to machine. Both processes are recommended in the following heat treatments (for SAE steels) as representing the best metallurgical practice. The temperatures recommended for normalizing and annealing have been made indefinite in many instances because of the many different types of furnaces used in various plants and the difference in results desired.

Case Hardening

In order to harden low-carbon steel, it is necessary to increase the carbon content of the surface of the steel so that a thin outer "case" can be hardened by heating the steel to the hardening temperature and then quenching it. The process, therefore, involves two separate operations. The first is the *carburizing* operation for impregnating the outer surface with sufficient carbon, and the second operation is that of heat treating the carburized parts so as to obtain a hard outer case and, at the same time, give the "core" the required physical properties. The term "case hardening" is ordinarily used to indicate the complete process of carburizing and hardening.

Carburization.—Carburization is the result of heating iron or steel to a temperature below its melting point in the presence of a solid, liquid, or gaseous material that decomposes so as to liberate carbon when heated to the temperature used. In this way, it is possible to obtain by the gradual penetration, diffusion, or absorption of the carbon by the steel, a "zone" or "case" of higher-carbon content at the outer surfaces than that of the original object. When a carburized object is rapidly cooled or quenched in water, oil, brine, etc., from the proper temperature, this case becomes hard, leaving the inside of the piece soft, but of great toughness.

Use of Carbonaceous Mixtures.—When carburizing materials of the solid class are used, the case-hardening process consists in packing steel articles in metal boxes or pots, with a carbonaceous compound surrounding the steel objects. The boxes or pots are sealed and placed in a carburizing oven or furnace maintained usually at a temperature of from about 1650 to 1700 degrees F for a length of time depending on the extent of the carburizing action desired. The carbon from the carburizing compound will then be absorbed by the steel on the surfaces desired, and the low-carbon steel is converted into high-carbon steel at these portions. The internal sections and the insulated parts of the object retain practically their original low-carbon content. The result is a steel of a dual structure, a high-carbon and a low-carbon steel in the same piece. The carburized steel may now be heat treated by heating and quenching, in much the same way as high-carbon steel is hardened, in order to develop the properties of hardness and toughness; but as the steel is, in reality, two steels in one, one high-carbon and one low-carbon, the correct heat treatment after carburizing includes two distinct processes, one suitable for the high-carbon portion or the "case," as it is generally called, and one suitable for the low-carbon portion or core. The method of heat treatment varies according to the kind of steel used. Usually, an initial heating and slow cooling is followed by reheating to 1400–1450 degrees F, quenching in oil or water, and a final tempering. More definite information is given in the following section on S.A.E. steels.

Carburizers: There are many commercial carburizers on the market in which the materials used as the generator may be hard and soft wood charcoal, animal charcoal, coke, coal, beans and nuts, bone and leather, or various combinations of these. The energizers may be barium, cyanogen, and ammonium compounds, various salts, soda ash, or lime and oil hydrocarbons.

Pack-Hardening.—When cutting tools, gages, and other parts made from high-carbon steels are heated for hardening while packed in some carbonaceous material in order to protect delicate edges, corners, or finished surfaces, the process usually is known as pack-hardening. Thus, the purpose is to protect the work, prevent scale formation, ensure uniform heating, and minimize the danger of cracking and warpage. The work is packed, as in carburizing, and in the same type of receptacle. Common hardwood charcoal often is used, especially if it has had an initial heating to eliminate shrinkage and discharge its more impure gases. The lowest temperature required for hardening should be employed for pack-hardening — usually 1400 to 1450 degrees F for carbon steels. Pack-hardening has also been applied to high-speed steels, but modern developments in heat-treating salts have made it possible to harden high-speed steel without decarburization, injury to sharp edges, or marring the finished surfaces. See paragraph on Salt Baths.

Cyanide Hardening.—When low-carbon steel requires a very hard outer surface but does not need high shock-resisting qualities, the cyanide-hardening process may be employed to produce what is known as superficial hardness. This superficial hardening is the result of carburizing a very thin outer skin (which may be only a few thousandths inch thick) by immersing the steel in a bath containing sodium cyanide. The temperatures usually vary from 1450 to 1650 degrees F and the percentage of sodium cyanide in the bath extends over a wide range, depending on the steel used and properties required.

Nitriding Process.—Nitriding is a process for surface hardening certain alloy steels by heating the steel in an atmosphere of nitrogen (ammonia gas) at approximately 950 degrees F. The steel is then cooled slowly. Finish machined surfaces hardened by nitriding are subject to minimum distortion. The physical properties, such as toughness, high impact strength, etc., can be imparted to the core by previous heat treatments and are unaffected by drawing temperatures up to 950 degrees F. The "Nitralloy" steels suitable for this process may be readily machined in the heat-treated as well as in the annealed state, and they forge as easily as alloy steels of the same carbon content. Certain heat treatments must be applied prior to nitriding, the first being annealing to relieve rolling, forging, or machining strains. Parts or sections not requiring heat treating should be machined or ground to the exact dimensions required. Close tolerances must be maintained in finish machining, but allowances for growth due to adsorption of nitrogen should be made, and this usually amounts to about 0.0005 inch for a case depth of 0.02 inch. Parts requiring heat treatment for definite physical properties are forged or cut from annealed stock, heat treated for the desired physical properties, rough machined, normalized, and finish machined. If quenched and drawn parts are normalized afterwards, the drawing and normalizing temperatures should be alike. The normalizing temperature may be below but should never be above the drawing temperature.

Ion Nitriding.—Ion nitriding, also referred to as glow discharge nitriding, is a process for case hardening of steel parts such as tool spindles, cutting tools, extrusion equipment, forging dies, gears, and crankshafts. An electrical potential ionizes low-pressure nitrogen gas, and the ions produced are accelerated to and impinge on the workpiece, heating it to the appropriate temperature for diffusion to take place. Therefore, there is no requirement for a supplemental heat source. The inward diffusion of the nitrogen ions forms the iron and alloy nitrides in the case. White layer formation, familiar in conventional gas nitriding, is readily controlled by this process.

Liquid Carburizing.—Activated liquid salt baths are now used extensively for carburizing. Sodium cyanide and other salt baths are used. The salt bath is heated by electrodes immersed in it, the bath itself acting as the conductor and resistor. One or more groups of electrodes, with two or more electrodes per group, may be used. The heating is accompanied by a stirring action to ensure uniform temperature and carburizing activity throughout the bath. The temperature may be controlled by a thermocouple immersed in the bath and connecting with a pyrometer designed to provide automatic regulation. The advantages of liquid baths include rapid action; uniform carburization; minimum distortion; and elimination of the packing and unpacking required when carbonaceous mixtures are used. In selective carburizing, the portions of the work that are not to be carburized are copper-plated and the entire piece is then immersed in an activated cyanide bath. The copper inhibits any carburizing action on the plated parts, and this method offers a practical solution for selectively carburizing any portion of a steel part.

Gas Carburizing.—When carburizing gases are used, the mixture varies with the type of case and quality of product desired. The gaseous hydrocarbons most widely used are methane (natural gas), propane, and butane. These carbon-bearing gases are mixed with air, with manufactured gases of several types, with flue gas, or with other specially prepared "diluent" gases. It is necessary to maintain a continuous fresh stream of carburizing gases to the carburizing retort or muffle, as well as to remove the spent gases from the muffle continuously, in order to obtain the correct mixture of gases inside the muffle. A slight pressure is maintained on the muffle to exclude unwanted gases.

The horizontal rotary type of gas carburizing furnace has a retort or muffle that revolves slowly. This type of furnace is adapted to small parts such as ball and roller bearings, chain links, small axles, bolts, etc. With this type of furnace, very large pieces such as gears, for example, may be injured by successive shocks due to tumbling within the rotor.

The vertical pit type of gas carburizer has a stationary workholder that is placed vertically in a pit. The work, instead of circulating in the gases as with the rotary type, is stationary and the gases circulate around it. This type is applicable to long large shafts or other parts or shapes that cannot be rolled in a rotary type of furnace.

There are three types of continuous gas furnaces that may be designated as 1) direct quench and manually operated; 2) direct quench and mechanically operated; and 3) cooling-zone type.

Where production does not warrant using a large continuous-type furnace, a horizontal muffle furnace of the batch type may be used, especially if the quantities of work are varied and the production not continuous.

Vacuum Carburizing.—Vacuum carburizing is a high-temperature gas carburizing process that is performed at pressures below atmospheric. The furnace atmosphere usually consists solely of an enriching gas, such as natural gas, pure methane, or propane; nitrogen is sometimes used as a carrier gas. Vacuum carburizing offers several advantages such as combining of processing operations and reduced total processing time.

Carburizing Steels.—A low-carbon steel containing, say, from 0.10 to 0.20 per cent of carbon is suitable for carburized case hardening. In addition to straight-carbon steels, the low-carbon alloy steels are employed. The alloys add to case-hardened parts the same advantageous properties that they give to other classes of steel. Various steels suitable for case hardening will be found in the section on SAE steels.

To Clean Work after Case Hardening.—To clean work, especially if knurled, where dirt is likely to stick into crevices after case hardening, wash it in caustic soda (1 part soda to 10 parts water). In making this solution, the soda should be put into hot water gradually, and the mixture stirred until the soda is thoroughly dissolved. A still more effective method of cleaning is to dip the work into a mixture of 1 part sulfuric acid and 2 parts water. Leave the pieces in this mixture about three minutes; then wash them off immediately in a soda solution.

Flame Hardening.—This method of hardening is especially applicable to the selective hardening of large steel forgings or castings that must be finish-machined prior to heat-treatment, or that because of size or shape cannot be heat treated by using a furnace or bath. An oxyacetylene torch is used to heat quickly the surface to be hardened; this surface is then quenched to secure a hardened layer that may vary in depth from a mere skin to ¼ inch and with hardness ranging from 400 to 700 Brinell. A multiflame torchhead may be equipped with quenching holes or a spray nozzle back of the flame. This is not a carburizing or a case-hardening process as the torch is only a heating medium. Most authorities recommend tempering or drawing of the hardened surface at temperatures between 200 and 350 degrees F. This treatment may be done in a standard furnace, an oil bath, or with a gas flame. It should follow the hardening process as closely as possible. Medium-carbon and many low-alloy steels are suitable for flame hardening. Plain carbon steels ranging from 0.35 to 0.60 per cent carbon will give hardnesses of from 400 to 700 Brinell. Steels in the 0.40 to 0.45 per cent carbon range are preferred, as they have excellent core properties and produce hardnesses of from 400 to 500 Brinell without checking or cracking. Higher-carbon steels will give greater hardnesses, but extreme care must be taken to prevent cracking. Careful control of the quenching operation is required.

Spinning Method of Flame Hardening: This method is employed on circular objects that can be rotated or spun past a stationary flame. It may be subdivided according to the speed of rotation, as where the part is rotated slowly in front of a stationary flame and the quench is applied immediately after the flame. This method is used on large circular pieces such as track wheels and bearing surfaces. There will be a narrow band of material with lower hardness between adjacent torches if more than one path of the flame is required to harden the surface. There will also be an area of lower hardness where the flame is extinguished. A second method is applicable to small rollers or pinions. The work is spun at a speed of 50 to 150 rpm in front of the flame until the entire piece has reached the proper temperature; then it is quenched as a unit by a cooling spray or by ejecting it into a cooling bath.

The Progressive Method: With this method the torch travels along the face of the work while the work remains stationary. It is used to harden lathe ways, gear teeth, and track rails.

The Stationary or Spot-hardening Method: When this method is employed, the work and torch are both stationary. When the spot to be hardened reaches the quenching temperature, the flame is removed and the quench applied.

The Combination Method: This approach is a combination of the spinning and progressive methods, and is used for long bearing surfaces. The work rotates slowly past the torch as the torch travels longitudinally across the face of the work at the rate of the torch width per revolution of the work.

Equipment for the stationary method of flame hardening consists merely of an acetylene torch, an oxyacetylene supply, and a suitable means of quenching; but when the other methods are employed, work-handling tools are essential and specialty designed torches are desirable. A lathe is ideally suited for the spinning or combination hardening method, whereas a planer is easily adapted for progressive hardening. Production jobs, such as the hardening of gears, require specially designed machines. These machines reduce handling and hardening time, as well as assuring consistent results.

Induction Hardening.—The hardening of steel by means of induction heating and subsequent quenching in either liquid or air is particularly applicable to parts that require localized hardening or controlled depth of hardening and to irregularly shaped parts, such as cams that require uniform surface hardening around their contour.

Advantages offered by induction hardening are: 1) a short heating cycle that may range from a fraction of a second to several seconds (heat energy can be induced in a piece of steel at the rate of 100 to 250 Btu per square inch per minute by induction heating, as compared with a rate of 3 Btu per square inch per minute for the same material at room temperature when placed in a furnace with a wall temperature of 2000 degrees F); 2) absence of tendency to produce oxidation or decarburization; 3) exact control of depth and area of hardening; 4) close regulation of degree of hardness obtained by automatic timing of heating and quenching cycles; 5) minimum amount of warpage or distortion; and 6) possibility of substituting carbon steels for higher-cost alloy steels.

The principal advantage of induction hardening to the designer lies in its application to localized zones. Thus, specific areas in a given part can be heat treated separately to the respective hardnesses required. Parts can be designed so that the stresses at any given point in the finished piece can be relieved by local heating. Parts can be designed in which welded or brazed assemblies are built up prior to heat treating with only internal surfaces or projections requiring hardening.

Types of Induction Heating Equipment.—Induction heating is secured by placing the metal part inside or close to an "applicator" coil of one or more turns, through which alternating current is passed. The coil, formed to suit the general class of workto be heated, is usually made of copper tubing through which water is passed to prevent overheating of the coil itself. The workpiece is held either in a fixed position or is rotated slowly within or close to the applicator coil. Where the length of work is too great to permit heating in a fixed position, progressive heating may be employed. Thus, a rod or tube of steel may be fed through an applicator coil of one or more turns so that the heating zone travels progressively along the entire length of the workpiece.

The frequency of the alternating current used and the type of generator employed to supply this current to the applicator coil depend on the character of the work to be done.

There are three types of equipment used commercially to produce high-frequency current for induction heating: 1) motor generator sets that deliver current at frequencies of approximately 1000, 2000, 3000, and 10,000 cycles; 2) spark gap oscillator units that produce frequencies ranging from 80,000 to 300,000 cycles; and 3) vacuum tube oscillator sets, which produce currents at frequencies ranging from 350,000 to 15,000,000 cycles or more.

Depth of Heat Penetration.—Generally speaking, the higher the frequency used, the shallower the depth of heat penetration. For heating clear through, for deep hardening and for large workpieces, low power concentrations and low frequencies are usually employed. For very shallow and closely controlled depths of heating, as in surface hardening, and in localized heat treating of small workpieces, currents at high frequencies are employed.

For example, a ½-inch round bar of hardenable steel will be heated through its entire structure quite rapidly by an induced current of 2000 cycles. After quenching, the bar would show through hardness with a decrease in hardness from surface to center. The same piece of steel could be readily heated and surface hardened to a depth of 0.100 inch with current at 9600 cycles, and to an even shallower depth with current at 100,000 cycles. A ¼-inch bar, however, would not reach a sufficiently high temperature at 2000 cycles to permit hardening, but at 9600 cycles through hardening would be accomplished. Current at over 100,000 cycles would be needed for surface hardening such a bar.

Types of Steel for Induction Hardening.—Most of the standard types of steels can be hardened by induction heating, providing the carbon content is sufficient to produce the desired degree of hardness by quenching. Thus, low-carbon steels with a carburized case, medium- and high-carbon steels (both plain and alloy), and cast iron with a portion of the carbon in combined form, may be used for this purpose. Induction heating of alloy steels should be limited primarily to the shallow hardening type, that is those of low alloy content, otherwise the severe quench usually required may result in a highly stressed surface with consequent reduced load-carrying capacity and danger of cracking.

Through Hardening, Annealing, and Normalizing by Induction.—For through hardening, annealing, and normalizing by induction, low power concentrations are desirable to prevent too great a temperature differential between the surface and the interior of the work. A satisfactory rate of heating is obtained when the total power input to the work is slightly greater than the radiation losses at the desired temperature. If possible, as low a frequency should be used as is consistent with good electrical coupling. A number of applicator coils may be connected in a series so that several workpieces can be heated simultaneously, thus reducing the power input to each. Widening the spacing between work and applicator coil also will reduce the amount of power delivered to the work.

Induction Surface Hardening.—As indicated earlier in "Depth of Heat Penetration," currents at much higher frequencies are required in induction surface hardening than in through hardening by induction. In general, the smaller the workpiece, the thinner the section, or the shallower the depth to be hardened, the higher will be the frequency required. High power concentrations are also needed to make possible a short heating period so that an undue amount of heat will not be conducted to adjacent or interior areas, where a change in hardness is not desired. Generators of large capacity and applicator coils of but a few turns, or even a single turn, provide the necessary concentration of power in the localized area to be hardened.

Induction heating of internal surfaces, such as the interior of a hollow cylindrical part or the inside of a hole, can be accomplished readily with applicator coils shaped to match the cross-section of the opening, which may be round, square, elliptical or other form. If the internal surface is of short length, a multiturn applicator coil extending along its entire length may be employed. Where the power available is insufficient to heat the entire internal surface at once, progressive heating is used. For this purpose, an applicator coil of few turns — often but a single turn — is employed, and either coil or work is moved so that the heated zone passes progressively from one end of the hole or opening to the other. For bores of small diameter, a hairpin-shaped applicator, extending the entire length of the hole, may be employed and the work rotated about the axis of the hole to ensure even heating.

Quenching After Induction Heating.—After induction heating, quenching may be by immersion in a liquid bath (usually oil), by liquid spray (usually water), or by self-quenching. (The term "self-quenching" is used when there is no quenching medium and hardening of the heated section is due chiefly to rapid absorption of heat by the mass of cool metal adjacent to it.) Quenching by immersion offers the advantage of even cooling and is particularly satisfactory for through heated parts. Spray quenching may be arranged so that the quenching ring and applicator coil are in the same or adjacent units, permitting the quenching cycle to follow the heating cycle immediately without removal of the work from the holding fixture. Automatic timing to a fraction of a second may also be employed for both heating and quenching with this arrangement to secure the exact degree of hardness desired. Self-quenching is applicable only in thin-surface hardening where the mass of adjacent cool metal in the part is great enough to conduct the heat rapidly out of the surface layer that is being hardened. It has been recommended that for adequate self-quenching, the mass of the unheated section should be at least ten times that of the heated shell. It has been found difficult to use the self-quenching technique to produce hardened shells of much more than about 0.060 inch thickness. Close to this limit, self-quenching can only be accomplished with the easily hardenable steels. By using a combination of self-quench and liquid quench, however, it is possible to produced hardened shells on work too thin to self-quench completely. In general, self-quenching is confined chiefly to relatively small parts and simple shapes.

Induction Hardening of Gear Teeth.—Several advantages are claimed for the induction hardening of gear teeth. One advantage is that the gear teeth can be completely machined, including shaving, when in the soft-annealed or normalized condition, and then hardened, because when induction heating is used, distortion is held to a minimum. Another advantage claimed is that bushings and inserts can be assembled in the gears before hardening. A wide latitude in choice of built-up webs and easily machined hubs is afforded because the hardness of neither web nor hub is affected by the induction-hardening operation although slight dimensional changes may occur in certain designs. Regular carbon steels can be used in place of alloy steels for a wide variety of gears, and a steel with a higher carbon content can frequently be substituted for a carburizing steel so that the carburizing operation can be eliminated. Another saving in time is the elimination of cleaning after hardening.

In heating spur gear teeth by induction, the gear is usually placed inside a circular unit that combines the applicator coil and quenching ring. An automatic timing device controls both the heating and quenching cycles. During the heating cycle, the gear is rotated at 25 to 35 rpm to ensure uniform heating.

In hardening bevel gears, the applicator coil is wound to conform to the face angle of the gear. In some spiral-bevel gears, there is a tendency to obtain more heat on one side of the tooth than on the other. In some sizes of spiral-bevel gears, this tendency can be overcome by applying slightly more heat to ensure hardening of the concave side. In some forms of spiral-bevel gears, it has been the practice to carburize that part of the gear surface which is to be hardened, after the teeth have been rough-cut. Carburizing is followed by the finish-cutting operation, after which the teeth can be induction heated, using a long enough period to heat the entire tooth. When the gear is quenched, only the carburized surface will become hardened.

Table 1a. Typical Heat Treatments for SAE Carbon Steels (Carburizing Grades)

SAE No.	Normalize, Deg. F	Carburize, Deg. F	Cool[a]	Reheat, Deg. F	Cool[a]	2nd Reheat, Deg. F	Cool[a]	Temper,[b] Deg. F
1010 to 1022	…	1650–1700	A	…	…	…	…	250–400
	…	1650–1700	B	1400–1450	A	…	…	250–400
	…	1650–1700	C	1400–1450	A	…	…	250–400
	…	1650–1700	C	1650–1700	B	1400–1450	A	250–400
	…	1500–1650[cd]	B	…	…	…	…	Optional
	…	1350–1575[ed]	D	…	…	…	…	Optional
1024	1650–1750[f]	1650–1700	E	……	…	…	…	250–400
	…	1350–1575[ed]	D	…	…	…	…	Optional
1025 1026 1027	…	1650–1700	A	…	…	…	…	250–400
	…	1500–1650[cd]	B	…	…	…	…	Optional
	…	1350–1575[ed]	D	…	…	…	…	Optional
1030	…	1500–1650[cd]	B	…	…	…	…	Optional
	…	1350–1575[ed]	D	…	…	…	…	Optional
1111 1112 1113	…	1500–1650[cd]	B	…	…	…	…	Optional
	…	1350–1575[ed]	D	…	…	…	…	Optional
1109 to 1120	…	1650–1700	A	…	…	…	…	250–400
	…	1650–1700	B	1400–1450	A	…	…	250–400
	…	1650–1700	C	1400–1450	A	…	…	250–400
	…	1650–1700	C	1650–1700	B	1400–1450	A	250–400
	…	1500–1650[cd]	B	…	…	…	…	Optional
	…	1350–1575[ed]	D	…	…	…	…	Optional
1126	…	1500–1650[cd]	B	…	…	…	…	Optional
	…	1350–1575[ed]	D	…	…	…	…	Optional

[a] Symbols: A = water or brine; B = water or oil; C = cool slowly; D = air or oil; E = oil; F = water, brine, or oil.

[b] Even where tempering temperatures are shown, tempering is not mandatory in many applications. Tempering is usually employed for partial stress relief and improves resistance to grinding cracks.

[c] Activated or cyanide baths.

[d] May be given refining heat as in other processes.

[e] Carbonitriding atmospheres

[f] Normalizing temperatures at least 50 deg. F above the carburizing temperature are sometimes recommended where minimum heat-treatment distortion is of vital importance.

Table 1b. Typical Heat Treatments for SAE Carbon Steels (Heat-Treating Grades)

SAE Number	Normalize, Deg. F		Anneal, Deg. F	Harden, Deg. F	Quench[a]	Temper, Deg. F
1025 & 1030	…		…	1575–1650	A	To Desired Hardness
1033 to 1035	…		…	1525–1575	B	
1036	1600–1700		…	1525–1575	B	
	…		…	1525–1575	B	
1038 to 1040	1600–1700		…	1525–1575	B	
	…		…	1525–1575	B	
1041	1600–1700	and/or	1400–1500	1475–1550	E	
1042 to 1050	1600–1700		…	1475–1550	B	
1052 & 1055	1550–1650	and/or	1400–1500	1475–1550	E	
1060 to 1074	1550–1650	and/or	1400–1500	1475–1550	E	
1078	…		1400–1500[a]	1450–1500	A	
1080 to 1090	1550–1650	and/or	1400–1500[a]	1450–1500	E[b]	
1095	…		1400–1500[a]	1450–1500	F	
	…		1400–1500[a]	1500–1600	E	
1132 & 1137	1600–1700	and/or	1400–1500	1525–1575	B	
1138 & 1140	…		…	1500–1550	B	
	1600–1700		…	1500–1550	B	
1141 & 1144	…		1400–1500	1475–1550	E	
	1600–1700		1400–1500	1475–1550	E	
1145 to 1151	…		…	1475–1550	B	
	1600–1700		…	1475–1550	B	

[a] Slow cooling produces a spheroidal structure in these high-carbon steels that is sometimes required for machining purposes.

[b] May be water- or brine-quenched by special techniques such as partial immersion or time quenched; otherwise they are subject to quench cracking.

Table 2a. Typical Heat Treatments for SAE Alloy Steels (Carburizing Grades)

SAE No.	Normalize[a]	Cycle Anneal[b]	Carburized, Deg. F	Cool[c]	Reheat, Deg. F	Cool[c]	Temper,[d] Deg. F
1320	yes	…	1650–1700	E	1400–1450[e]	E	250–350
	yes	…	1650–1700	E	1475–1525[f]	E	250–350
	yes	…	1650–1700	C	1400–1450[e]	E	250–350
	yes	…	1650–1700	C	1500–1550[f]	E	250–350
	yes	…	1650–1700	E[g]	…	…	250–350
	yes	…	1500–1650[h]	E	…	…	250–350
2317	yes	yes	1650–1700	E	1375–1425[e]	E	250–350
	yes	yes	1650–1700	E	1450–1500[f]	E	250–350
	yes	yes	1650–1700	C	1375–1425[e]	E	250–350
	yes	yes	1650–1700	C	1475–1525[f]	E	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	yes	1450–1650[h]	E	…	…	250–350
2512 to 2517	yes[i]	…	1650–1700	C	1325–1375[e]	E	250–350
	yes[i]	…	1650–1700	C	1425–1475[f]	E	250–350
3115 & 3120	yes	…	1650–1700	E	1400–1450[e]	E	250–350
	yes	…	1650–1700	E	1475–1525[f]	E	250–350
	yes	…	1650–1700	C	1400–1450[e]	E	250–350
	yes	…	1650–1700	C	1500–1550[f]	E	250–350
	yes	…	1650–1700	E[g]	…	…	250–350
	yes	……	1500–1650[h]	E	…	…	250–350
3310 & 3316	yes[i]	…	1650–1700	E	1400–1450[e]	E	250–350
	yes[i]	…	1650–1700	C	1475–1500[f]	E	250–350
4017 to 4032	yes	yes	1650–1700	E[g]	…	…	250–350
4119 & 4125	yes	…	1650–1700	E[g]	…	…	250–350
4317 & 4320, 4608 to 4621	yes	yes	1650–1700	E	1425–1475[e]	E	250–350
	yes	yes	1650–1700	E	1475–1527[f]	E	250–350
	yes	yes	1650–1700	C	1425–1475[e]	E	250–350
	yes	yes	1650–1700	C	1475–1525[f]	E	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	…	1500–1650[h]	E	…	…	250–350
4812 to 4820	yes[i]	yes	1650–1700	E	1375–1425[e]	E	250–350
	yes[i]	yes	1650–1700	E	1450–1500[f]	E	250–350
	yes[i]	yes	1650–1700	C	1375–1425[e]	E	250–350
	yes[i]	yes	1650–1700	C	1450–1500[f]	E	250–350
	…	…	1650–1700	E[g]	…	…	250–350
5115 & 5120	yes	…	1650–1700	E	1425–1475[e]	E	250–350
	yes	…	1650–1700	E	1500–1550[f]	E	250–350
	yes	…	1650–1700	C	1425–1475[e]	E	250–350
	yes	…	1650–1700	C	1500–1550[f]	E	250–350
	yes	…	1500–1650[h]	E	…	…	250–350
8615 to 8625, 8720	yes	yes	1650–1700	E	1475–1525[e]	E	250–350
	yes	yes	1650–1700	E	1525–1575[f]	E	250–350
	yes	yes	1650–1700	C	1475–1525[e]	E	250–350
	yes	yes	1650–1700	C	1525–1575[f]	E	250–350
	yes	yes	1650–1700	E[g]	…	…	250–350
	yes	yes	1500–1650[h]	E	…	…	250–350
9310 to 9317	yes[i]	…	1650–1700	E	1400–1450[e]	E	250–350
	yes[i]	…	1650–1700	C	1500–1525	E	250–350

[a] Normalizing temperatures should be not less than 50 deg. F higher than the carburizing temperature. Follow by air cooling.

[b] For cycle annealing, heat to normalizing temperature—hold for uniformity—cool rapidly to 1000–1250 deg. F; hold 1 to 3 hours, then air or furnace cool to obtain a structure suitable for machining and finishing.

[c] Symbols: C = cool slowly; E = oil.

[d] Tempering treatment is optional and is generally employed for partial stress relief and improved resistance to cracking from grinding operations.

[e] For use when case hardness only is paramount.

[f] For use when higher core hardness is desired.

[g] Treatment is for fine-grained steels only, when a second reheat is often unnecessary.

[h] Treatment is for activated or cyanide baths. Parts may be given refining heats as indicated for other heat-treating processes.

[i] After normalizing, reheat to temperatures of 1000–1200 deg. F and hold approximately 4 hours.

Table 3a. Typical Heat Treatments for SAE Alloy Steels (Directly Hardenable Grades)

SAE No.	Normalize, Deg. F		Anneal, Deg. F	Harden, Deg. F	Quench[a]	Temper, Deg. F
1330	…		…	1525–1575	B	To desired hardness
	1600–1700	and/or	1500–1600	1525–1575	B	To desired hardness
1335 & 1340	…		…	1500–1550	E	To desired hardness
	1600–1700	and/or	1500–1600	1525–1575	E	To desired hardness
2330	…		…	1450–1500	E	To desired hardness
	1600–1700	and/or	1400–1500	1450–1500	E	To desired hardness
2340 & 2345	…		…	1425–1475	E	To desired hardness
	1600–1700	and/or	1400–1500	1425–1475	E	To desired hardness
3130	1600–1700		…	1500–1550	B	To desired hardness
3135 to 3141	…		…	1500–1550	E	To desired hardness
	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness
3145 & 3150	…		…	1500–1550	E	To desired hardness
	1600–1700	and/or	1400–1500	1500–1550	E	To desired hardness
4037 & 4042	…		1525–1575	1500–1575	E	Gears, 350–450 To desired hardness
4047 & 4053	…		1450–1550	1500–1575	E	To desired hardness
4063 & 4068	…		1450–1550	1475–1550	E	To desired hardness
4130	1600–1700	and/or	1450–1550	1600–1650	B	To desired hardness
4137 & 4140	1600–1700	and/or	1450–1550	1550–1600	E	To desired hardness
4145 & 4150	1600–1700	and/or	1450–1550	1500–1600	E	To desired hardness
4340	1600–1700	and draw	1100–1225	1475–1525	E	To desired hardness
4640	1600–1700	and/or	1450–1550	1450–1500	E	To desired hardness
	1600–1700	and/or	1450–1500	1450–1500	E	Gears, 350–450
5045 & 5046	1600–1700	and/or	1450–1550	1475–1500	E	250–300
5130 & 5132	1650–1750	and/or	1450–1550	1500–1550	G	To desired hardness
5135 to 5145	1650–1750	and/or	1450–1550	1500–1550	E	To desired hardness Gears, 350–400
5147 to 5152	1650–1750	and/or	1450–1550	1475–1550	E	To desired hardness Gears, 350–400
50100	…		1350–1450	1425–1475	H	To desired hardness
51100 52100	…		1350–1450	1500–1600	E	To desired hardness
6150	1650–1750	and/or	1550–1650	1600–1650	E	To desired hardness
9254 to 9262	…		…	1500–1650	E	To desired hardness
8627 to 8632	1600–1700	and/or	1450–1550	1550–1650	B	To desired hardness
8635 to 8641	1600–1700	and/or	1450–1550	1525–1575	E	To desired hardness
8642 to 8653	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness
8655 & 8660	1650–1750	and/or	1450–1550	1475–1550	E	To desired hardness
8735 & 8740	1600–1700	and/or	1450–1550	1525–1575	E	To desired hardness
8745 & 8750	1600–1700	and/or	1450–1500	1500–1550	E	To desired hardness
9437 & 9440	1600–1700	and/or	1450–1550	1550–1600	E	To desired hardness
9442 to 9747	1600–1700	and/or	1450–1550	1500–1600	E	To desired hardness
9840	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness
9845 & 9850	1600–1700	and/or	1450–1550	1500–1550	E	To desired hardness

[a] Symbols: B = water or oil; E = oil; G = water, caustic solution, or oil; H = water.

Table 4a. Typical Heat Treatments for SAE Alloy Steels
(Heat-Treating Grades—Chromium–Nickel Austenitic Steels)

SAE No.	Normalize	Anneal,[a] Deg. F	Harden, Deg. F	Quenching Medium	Temper
30301 to 30347	…	1800–2100	…	Water or Air	…

[a] Quench to produce full austenitic structure using water or air in accordance with thickness of section. Annealing temperatures given cover process and full annealing as used by industry, the lower end of the range being used for process annealing.

Table 5a. Typical Heat Treatments for SAE Alloy Steels
(Heat-Treating Grades — Stainless Chromium Irons and Steels)

SAE No.[a]	Normalize	Aub-critical Anneal, Deg. F	Full Anneal Deg. F	Harden Deg. F	Quenching Medium	Temper Deg. F
51410	…	1300–1350[b]	1550–1650[c]	…	Oil or air	To desired hardness
	…	…	…	1750–1850		
51414	…	1200–1250[b]	…	…	Oil or air	To desired hardness
	…	…	…	1750–1850		
51416	…	1300–1350[b]	1550–1650[c]	…	Oil or air	To desired hardness
	…	…	…	1750–1850		
51420 51420F	…	1350–1450[b]	1550–1650[c]	…	Oil or air	To desired hardness
	…	…	…	1800–1850		
51430	…	1400–1500[d]	…	…	…	…
51430F	…	1250–1500[d]	…	…	…	…
51431	…	1150–1225[b]	…	1800–1900	Oil or air	To desired hardness
51440A 51440B 51440C 51440F	…	1350–1440[b]	1550–1650[c]	1850–1950	Oil or air	To desired hardness
51442	…	1400–1500[d]	…	…	…	…
51446	…	1500–1650[d]	…	…	…	…
51501	…	1325–1375[b]	1525–1600[c]	1600–1700	Oil or air	To desired hardness

[a] Suffixes A, B, and C denote three types of steel differing in carbon content only. Suffix F denotes a free-machining steel.
[b] Usually air cooled, but may be furnace cooled.
[c] Cool slowly in furnace.
[d] Cool rapidly in air.

Laser and Electron-Beam Surface Hardening.—Industrial lasers and electron-beam equipment are now available for surface hardening of steels. The laser and electron beams can generate very intense energy fluxes and steep temperature profiles in the workpiece, so that external quench media are not needed. This self-quenching is due to a cold interior with sufficient mass acting as a large heat sink to rapidly cool the hot surface by conducting heat to the interior of a part. The laser beam is a beam of light and does not require a vacuum for operation. The electron beam is a stream of electrons and processing usually takes place in a vacuum chamber or envelope. Both processes may normally be applied to finished machined or ground surfaces, because little distortion results.