**Heat Treatment**

The Internal Structure of Metals

The results obtained by heat treatment depend to a great extent on the structure of the metal and on the manner in which the structure changes when the metal is heated and cooled. A pure metal cannot be hardened by heat treatment because there is little change in its structure when heated. On the other hand, most alloys respond to heat treatment since their structures change with heating and cooling.

An alloy may be in the form of a solid solution, a mechanical mixture, or a combination of a solid solution and a mechanical mixture. When an alloy is in the form of a solid solution, the elements and compounds which form the alloy are absorbed, one into the other, in much the same way that salt is dissolved in a glass of water, and the constituents cannot be identified even under a microscope.

When two or more elements or compounds are mixed but can be identified by microscopic examination, a mechanical mixture is formed. A mechanical mixture can be compared to the mixture of sand and gravel in concrete. The sand and gravel are both visible. Just as the sand and gravel are held together and kept in place by the matrix of cement, the other constituents of an alloy are embedded in the matrix formed by the base metal.

An alloy in the form of a mechanical mixture at ordinary temperatures may change to a solid solution when heated. When cooled back to normal temperature, the alloy may return to its original structure. On the other hand, it may remain a solid solution or form a combination of a solid solution and mechanical mixture. An alloy which consists of a combination of solid solution and mechanical mixture at normal temperatures may change to a solid solution when heated. When cooled, the alloy may remain a solid solution, return to its original structure, or form a complex solution.

**Heat-Treating Equipment**

Successful heat treating requires close control over all factors affecting the heating and cooling of metals. Such control is possible only when the proper equipment is available and the equipment is selected to fit the particular job. Thus, the furnace must be of the proper size and type and must be so controlled that temperatures are kept within the limits prescribed for each operation. Even the atmosphere within the furnace affects the condition of the part being heat treated. Further, the quenching equipment and the quenching medium must be selected to fit the metal and the heat treating operation.

**Temperature Measurement and Control**

Temperature in the heat-treating furnace is measured by a thermoelectric instrument known as a pyrometer. This instrument measures the electrical effect of a thermocouple and, hence, the temperature of the metal being treated.   
Furnaces intended primarily for tempering may be heated by gas or electricity and are frequently equipped with a fan for circulating the hot air.

Salt baths are available for operating at either tempering or hardening temperatures. When metal is to be heated in a bath of molten salt or lead, the furnace must contain a pot or crucible for the molten bath.

Accurate temperature measurement is essential to good heat treating. The usual method is by means of thermocouples

Pyrometers may have meters either of the indicating type or recording type. Indicating pyrometers give direct reading of the furnace temperature. The recording type produces a permanent record of the temperature range throughout the heating operation by means of an inked stylus attached to an arm which traces a line on a sheet of calibrated paper or temperature chart.

**Heat Treatment of Ferrous Metals**

The first important consideration in the heat treatment of a steel part is to know its chemical composition. This, in turn, determines its upper critical point. When the upper critical point is known, the next consideration is the rate of heating and cooling to be used. Carrying out these operations involves the use of uniform heating furnaces, proper temperature controls, and suitable quenching mediums.

*Behaviour of Steel During Heating and Cooling*

Changing the internal structure of a ferrous metal is accomplished by heating to a temperature above its upper critical point, holding it at that temperature for a time sufficient to permit certain internal changes to occur, and then cooling to atmospheric temperature under predetermined, controlled conditions.

At ordinary temperatures, the carbon in steel exists in the form of particles of iron carbide scattered throughout an iron matrix known as “ferrite.” The number, size, and distribution of these particles determine the hardness of the steel. At elevated temperatures, the carbon is dissolved in the iron matrix in the form of a solid solution called “austenite,” and the carbide particles appear only after the steel has been cooled. If the cooling is slow, the carbide particles are relatively coarse and few. In this condition, the steel is soft. If the cooling is rapid, as by quenching in oil or water, the carbon precipitates as a cloud of very fine carbide particles, and the steel is hard. The fact that the carbide particles can be dissolved in austenite is the basis of the heat treatment of steel. The temperatures at which this transformation takes place are called the critical points and vary with the composition of the steel. The percentage of carbon in the steel has the greatest influence on the critical points of heat treatment.

*Hardening*

Pure iron, wrought iron, and extremely low carbon steels cannot be appreciably hardened by heat treatment, since they contain no hardening element. Cast iron can be hardened, but its heat treatment is limited. When cast iron is cooled rapidly, it forms white iron, which is hard and brittle. When cooled slowly, it forms grey iron, which is soft but brittle under impact.

In plain carbon steel, the maximum hardness depends almost entirely on the carbon content of the steel. As the carbon content increases, the ability of the steel to be hardened increases. However, this increase in the ability to harden with an increase in carbon content continues only to a certain point. In practice, that point is 0.85 percent carbon content. When the carbon content is increased beyond 0.85 percent, there is no increase in wear resistance.

For most steels, the hardening treatment consists of heating the steel to a temperature just above the upper critical point, soaking or holding for the required length of time, and then cooling it rapidly by plunging the hot steel into oil, water, or brine. Although most steels must be cooled rapidly for hardening, a few may be cooled in still air. Hardening increases the hardness and strength of the steel but makes it less ductile.

When hardening carbon steel, it must be cooled to below 540 °C in less than 1 second. Should the time required for the temperature to drop to 540 °C exceed 1 second, the austenite begins to transform into fine pearlite. This pearlite varies in hardness, but is much harder than the pearlite formed by annealing and much softer than the martensite desired. After the 540 °C temperature is reached, the rapid cooling must continue if the final structure is to be all martensite.

When alloys are added to steel, the time limit for the temperature drop to 540 °C increases above the 1 second limit for carbon steels. Therefore, a slower quenching medium will produce hardness in alloy steels.

Because of the high internal stresses in the “as quenched” condition, steel must be tempered just before it becomes cold. The part should be removed from the quenching bath at a temperature of approximately 95°C, since the temperature range from 95°C down to room temperature is the cracking range.

*Tempering*

Tempering reduces the brittleness imparted by hardening and produces definite physical properties within the steel. Tempering always follows, never precedes, the hardening operation. In addition to reducing brittleness, tempering softens the steel.

Tempering is always conducted at temperatures below the low critical point of the steel. In this respect, tempering differs from annealing, normalizing, or hardening, all of which require temperatures above the upper critical point. When hardened steel is reheated, tempering begins at 100°C and continues as the temperature increases toward the low critical point.

Generally, the rate of cooling from the tempering temperature has no effect on the resulting structure; therefore, the steel is usually cooled in still air after being removed from the furnace.

*Annealing*

Annealing of steel produces a fine grained, soft, ductile metal without internal stresses or strains. In the annealed state, steel has its lowest strength. In general, annealing is the opposite of hardening.

Annealing of steel is accomplished by heating the metal to just above the upper critical point, soaking at that temperature, and cooling very slowly in the furnace. Soaking time is approximately 1 hour per 25mm of thickness of the material. To produce maximum softness in steel, the metal must be cooled very slowly. Slow cooling is obtained by shutting off the heat and allowing the furnace and metal to cool together to 480°C or lower, then removing the metal from the furnace and cooling in still air. Another method is to bury the heated steel in ashes, sand, or other substance that does not conduct heat readily.

*Normalizing*

The normalizing of steel removes the internal stresses set up by heat treating, welding, casting, forming, or machining. Stress, if not controlled, will lead to failure. Because of the better physical properties, aircraft steels are often used in the normalized state, but seldom, if ever, in the annealed state.

One of the most important uses of normalizing in aircraft work is in welded parts. Welding causes strains to be set up in the adjacent material. In addition, the weld itself is a cast structure as opposed to the wrought structure of the rest of the material. These two types of structures have different grain sizes, and to refine the grain as well as to relieve the internal stresses, all welded parts should be normalized after fabrication.

Normalizing is accomplished by heating the steel above the upper critical point and cooling in still air. The more rapid quenching obtained by air cooling, as compared to furnace cooling, results in a harder and stronger material than that obtained by annealing.

*Casehardening*

Casehardening produces a hard wear-resistant surface or case over a strong, tough core. Casehardening is ideal for parts which require a wear-resistant surface and, at the same time, must be tough enough internally to withstand the applied loads. The steels best suited to casehardening are the low carbon and low alloy steels. If high carbon steel is casehardened, the hardness penetrates the core and causes brittleness. In casehardening, the surface of the metal is changed chemically by introducing a high carbide or nitride content. The core is unaffected chemically. When heat treated, the surface responds to hardening while the core toughens. The common forms of casehardening are carburizing and nitriding.

**Carburizing**

Carburizing is a casehardening process in which carbon is added to the surface of low carbon steel. Thus, a carburized steel has a high carbon surface and a low carbon interior. When the carburized steel is heat treated, the case is hardened while the core remains soft and tough.

A common method of carburizing is called “pack carburizing.” When carburizing is to be done by this method, the steel parts are packed in a container with charcoal or some other material rich in carbon. The container is then sealed with fire clay, placed in a furnace, heated to approximately 926°C, and soaked at that temperature for several hours. As the temperature increases, carbon monoxide gas forms inside the container and, being unable to escape, combines with the gamma iron in the surface of the steel. The depth to which the carbon penetrates depends on the length of the soaking period. For example, when carbon steel is soaked for 8 hours, the carbon penetrates to a depth of about 1.5mm.

In another method of carburizing, called “gas carburizing,” a material rich in carbon is introduced into the furnace atmosphere. The carburizing atmosphere is produced by the use of various gases or by the burning of oil, wood, or other materials. When the steel parts are heated in this atmosphere, carbon monoxide combines with the gamma iron to produce practically the same results as those described under the pack carburizing process.

A third method of carburizing is that of “liquid carburizing.” In this method, the steel is placed in a molten salt bath that contains the chemicals required to produce a case comparable with one resulting from pack or gas carburizing.

Alloy steels with low carbon content as well as low carbon steels may be carburized by any of the three processes. However, some alloys, such as nickel, tend to retard the absorption of carbon. As a result, the time required to produce a given thickness of case varies with the composition of the metal.

*Nitriding*

Nitriding is unlike other casehardening processes in that, before nitriding, the part is heat treated to produce definite physical properties. Thus, parts are hardened and tempered before being nitrided. Most steels can be nitrided, but special alloys are required for best results. These special alloys contain aluminum as one of the alloying elements and are called “nitralloys.”

In nitriding, the part is placed in a special nitriding furnace and heated to a temperature of approximately 760°C. With the part at this temperature, ammonia gas is circulated within the specially constructed furnace chamber. The high temperature cracks the ammonia gas into nitrogen and hydrogen. The ammonia which does not break down is caught in a water trap below the regions of the other two gases. The nitrogen reacts with the iron to form nitride. The iron nitride is dispersed in minute particles at the surface and works inward. The depth of penetration depends on the length of the treatment. In nitriding, soaking periods as long as 72 hours are frequently required to produce the desired thickness of case.

Nitriding can be accomplished with a minimum of distortion, because of the low temperature at which parts are casehardened and because no quenching is required after exposure to the ammonia gas.

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