



Heat Treating

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Overview

Heat treating, as the name implies, is a series of treatments in which heat is used to alter the properties of a metal or alloy. Because time at temperature is also important, heat treatment can be further defined as a series of time-temperature treatments. Heat treatments are used for a variety of purposes, the most important being to control the mechanical properties, especially hardness, ductility, strength, toughness, and internal stresses.

Hardness is the resistance of a material to plastic indentation. Hardness values are roughly proportional to the strength of a metal and can give an indication of the wear properties of a material. Hardness values can be useful during the materials selection process and for quality-control evaluations, but the values cannot be applied directly during the design of a part.

Ductility is the capability of a material to deform plastically without fracturing, and it is usually measured by the amount that a bar under tensile load will elongate before fracturing. The elongation is expressed as a percentage of the original length of the bar.

Strength is the ability of a material to withstand an applied force, and three types are commonly discussed. Elastic strength, referred to as the elastic limit, is strength before the material deforms permanently. The yield strength is the strength of a material before appreciable plastic deformation occurs. The ultimate tensile strength is the maximum strength that a metal exhibits during tensile deformation.

Toughness is the ability of a metal to absorb energy in the plastic range. Although there are a number of approaches for defining toughness, one of the oldest is to consider it as the total area under the stress-strain curve. This area is an indication of the amount of work per unit area that can be done without causing it to fail. Because toughness is the area under the stress-strain curve, it is a function of both strength and ductility.

Residual or locked-in stresses arise in components from many sources and, if left untreated, can lead to component distortion, stress concentration, and failure. One of the most common causes of residual stresses is nonuniform cooling from elevated temperatures. On cooling, the surface cools quickly and contracts, while the inner core remains hotter longer and cools more slowly, thus setting up residual stresses. Components are heated to a suitable temperature and held at temperature for a time long enough to reduce residual stresses and are then cooled slowly enough so that new residual stresses are not introduced.

There are many types of heat treatment processes, some of which are applied only to steels and others that are applied only to other alloys. Heat treatment processes can be classified into four general categories:

- Annealing (softening)
- Hardening
- Surface hardening
- Miscellaneous

Annealing

When a metal is cold worked (deformed at room temperature), the microstructure becomes severely distorted because of an increased dislocation density resulting from the deformation. Cold working is also referred to as work hardening or strain hardening. As a metal is cold worked, the strength and hardness increase while ductility decreases. Eventually, it is necessary to anneal the piece to allow further forming operations without the risk of breaking it. In addition, some metals are strengthened primarily by cold working. In this case, it is important that the metal not soften appreciably when placed in service.

Cold-worked materials with highly distorted microstructures are in a high-energy state and are thermodynamically unstable. Annealing is the heat treatment process that softens a metal that has been hardened by cold working. Annealing consists of three stages: recovery, recrystallization, and grain growth. Although a reduction in stored energy provides the driving force, annealing usually does not spontaneously occur at room temperature. Because the reduction in stored energy must occur by diffusion, the activation energy needed to start the diffusion process is normally insufficient at room temperature. Therefore, heating is necessary to provide the thermal activation energy needed to transform the material to a lower-energy state. As the internal lattice strains are relieved during annealing, the strength decreases while the ductility increases. It should be noted that some low-melting-point metals have recrystallization temperatures lower than room temperature and cannot be hardened by cold working. For example, lead, tin, and zinc have recrystallization temperatures below room temperature.

The three distinct processes that occur during annealing—recovery, recrystallization, and grain growth—are described as follows.

Recovery. During recovery, there is a rearrangement of internal defects, known as dislocations, into lower-energy configurations; however, the grain shape and orientation remain the same. There is also a significant reduction in residual stresses, but the strength and ductility are largely unaffected. Because there is a large decrease in residual stress during recovery, recovery-type processes are usually conducted to reduce residual stresses, often to prevent stress-corrosion cracking or minimize distortion. During stress-relief operations, the temperature and time are controlled so there is not a major reduction in strength or hardness.



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Recrystallization is characterized by the nucleation and growth of strain-free grains out of the matrix of the cold-worked metal. During recrystallization, the badly deformed cold-worked grains are replaced by new, strain-free grains. New orientations, new grain sizes, and new grain morphologies form during recrystallization. The driving force for recrystallization is the remaining stored energy that was not expended during recovery. The strength reduces and the ductility increases to levels similar to those of the metal before cold working.

Recrystallization is considered complete when the mechanical properties of the recrystallized metal approach those of the metal before it was cold worked. Recrystallization and the resulting mechanical softening completely cancel the effects of cold working on the mechanical properties of the piece. An annealing curve for an alloy, such as a typical brass, will show minimal changes in mechanical properties during recovery and large changes in properties that occur during recrystallization (Fig. 1). Mechanical properties, such as hardness, yield strength, tensile strength, percent elongation, and reduction in area, change drastically over a very small temperature range. Although physical properties, such as electrical conductivity, undergo large increases during recovery, they also continue to increase during recrystallization.

Grain growth is the growth of some recrystallized grains, and it can only happen at the expense of other recrystallized grains. Because fine grain size leads to the best combination of strength and ductility, in almost all cases, grain growth is an undesirable process. Although excessive grain growth can occur by holding the material for too long at the annealing temperature, it is usually a result of heating at too high a temperature.

Some steel-specific annealing heat treatments include normalizing, spheroidizing, and solution annealing, which is described as follows.

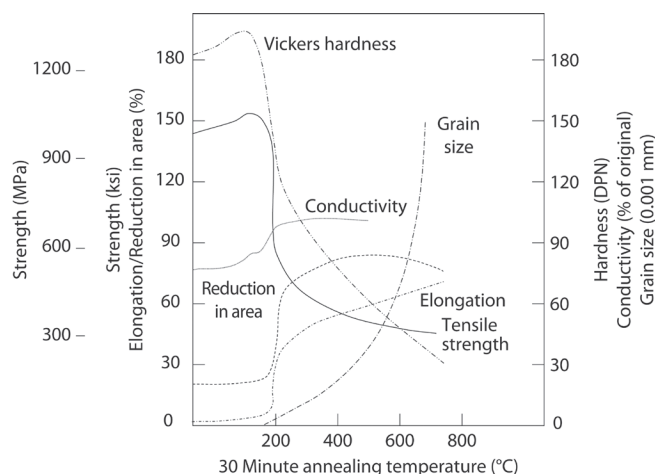


Fig. 1 Effects of annealing on brass (Cu-35%Zn). Source: Ref 1

Solution annealing, sometimes referred to as quench annealing, is an important category of annealing. The heat treatment is called solution annealing because the heat treatment takes advantage of the solid-solution regions of the iron-carbon phase diagram (for steels) or, in the case of nonferrous alloys, the phase diagrams for the major components of the alloy system (see the topic summary “Phase Diagrams”).

For steels, solution annealing involves heating to a sufficiently high temperature for a sufficiently long time to drive free carbides into solid solution and then rapidly quenching to freeze them. The resulting steel has improved formability, and corrosion resistance to certain acids can be improved.

For nonferrous alloys, solution annealing is a preliminary step to hardening of the alloys. The solution heat treatment involves heating the alloy to a high enough temperature to drive the alloying elements into solid solution, yielding a metastable, supersaturated solid solution. These alloys are then precipitation hardened (also known as age hardening).

Hardening

Hardening is the process by which heat treatments are employed to harden an alloy. Hardenability is the capability of an alloy to be hardened by heat treatment. There are several hardening treatments.

Quench Hardening. For ferrous alloys, quench hardening is an austenite-forming (austenitizing) heat treatment, followed by cooling at a rate such that a substantial amount of austenite transforms to martensite. Quench hardening can be applied to suitable alpha-beta alloys (usually copper or titanium alloys) by solution treating them, followed by quenching to develop a martensite-like structure.

Tempering of steel is a process in which previously hardened or normalized steel is heated to a temperature below the lower critical temperature and cooled at a suitable rate, primarily to increase ductility and toughness but also to increase the grain size of the matrix. Tempering is used to reach specific values of mechanical properties, to relieve quenching stresses, and to ensure dimensional stability. It usually follows quenching from above the upper critical temperature; however, tempering is also used to relieve the stresses and reduce the hardness developed during welding and to relieve stresses induced by forming and machining. In the context of aluminum alloys, temper designations are used to codify combinations of heat treatments. These are described in Table 1 in the section “Heat Treatment of Aluminum-Base Alloys.”

Precipitation hardening (age hardening) involves heating an alloy to a sufficiently high temperature so that enough of an alloying element is dissolved to form a supersaturated solid solution. It is then rapidly cooled (quenched) to room temperature, freezing the alloying elements in solution (Fig. 2). On reheating to

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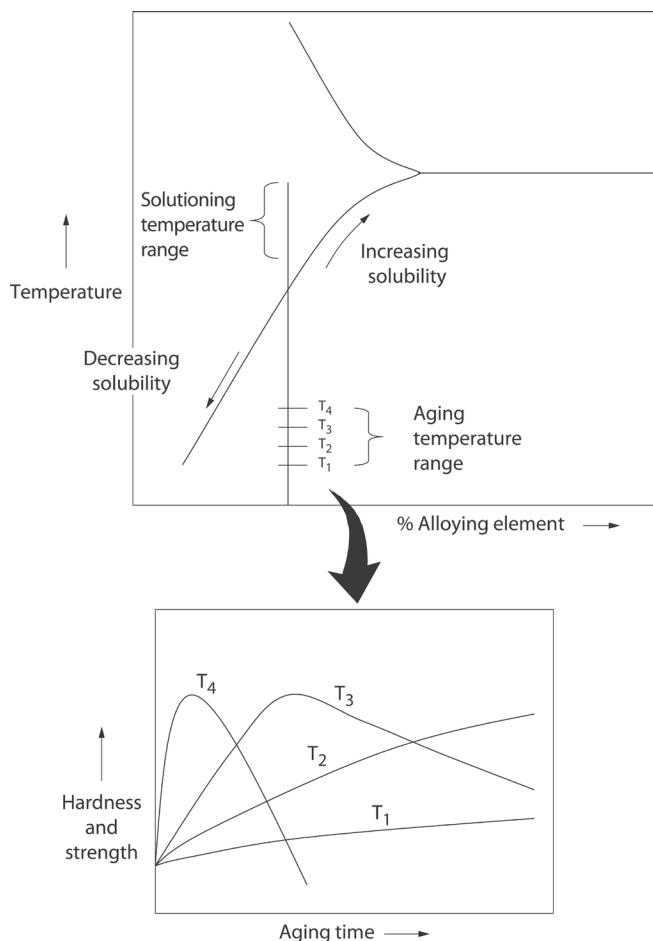


Fig. 2 Precipitation-hardenable phase diagram and heat treatment.
Source: Ref 1

an intermediate temperature, the host metal rejects the alloying element in the form of a fine, uniformly distributed precipitate in the alloy matrix. These fine precipitate particles act as barriers to the motion of dislocations and provide resistance to slip, thereby increasing the strength and hardness. There are some alloys, such as copper-beryllium alloys, that will age harden at room temperature.

Alloy systems that lend themselves to precipitation hardening include aluminum alloys, some copper alloys, iron- and nickel-base superalloys, maraging steels, and precipitation-hardening stainless steels.

Oxide Dispersion Strengthening. With this powder metallurgy method, oxides such as yttria or alumina or metals that are strong oxide formers, such as tantalum, are added during the mechanical alloying step. They become uniformly distributed through the alloy and impart strength to the component.

Variants of quenching and tempering as they relate to specific steel heat treatments include marquenching, austempering, and ausforming.

Surface Hardening

Surface hardening is used to impart desirable properties in the surface of the component that are not needed (or achievable) through the part.

Flame hardening consists of austenitizing the surface of a steel by heating with an oxyacetylene or oxyhydrogen torch and quenching immediately. A hard surface layer of martensite forms over a softer interior core.

Induction Hardening. Electromagnetic induction is used to heat the surface layer of a ferrous workpiece to above the critical temperature and is followed immediately by quenching.

Case hardening is any of several processes applicable to steel that change the chemical composition of the surface layer by absorption of carbon, nitrogen, or a mixture of the two and, by diffusion, create a concentration gradient on the surface. The processes commonly used are carburizing and quench hardening, cyaniding, nitriding, and carbonitriding.

There are other surface diffusion treatments, such as boronizing and siliconizing, that diffuse elements other than carbon and nitrogen into the workpiece surface for the purpose of altering the surface properties.

Miscellaneous Heat Treatments

There are numerous heat treatments designed for specific materials, forms (e.g., wire), or property outcomes. Examples include patenting, stiffening tempering, and malleablizing, among others.

Heat Treatment of Steel

Because over 80% by weight of all metals in use are iron and steel alloys, the heat treatment of ferrous alloys is of great industrial importance. One of the primary advantages of steels is their capability to attain high strengths through heat treatment while still retaining some degree of ductility. This capability of steels to be strengthened is a direct consequence of the amount of carbon present. As the carbon content is increased, higher strength levels are obtainable. Although the ductility decreases with increasing strength, it is still high enough to satisfy most engineering applications. Heat treatments can be used not only to harden steels but also to provide other useful combinations of properties, such as ductility, formability, and machinability.

The important heat treatment processes for ferrous alloys include annealing, stress relieving, normalizing, spheroidizing, hardening by quenching and tempering, and case hardening. In all of these processes, the steel is heated fairly slowly to some predetermined temperature and then cooled. It is the temperature and the rate of

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cooling that determines the resultant structure of the steel. The final structure is independent of the rate of heating, provided it has been slow enough for the steel to reach structural equilibrium at its maximum temperature. However, the subsequent rate of cooling, which determines the nature of the final structure, is critical and may vary between slow furnace cooling to sudden cooling by quenching in water.

Annealing. In steels, annealing usually means a heat treatment with furnace cooling from the austenitizing range (Fig. 3). Annealing is used to reduce hardness, obtain a relatively near-stable microstructure, refine grain size, improve machinability, and facilitate cold working. For hypoeutectoid steels (steels with a carbon content of less than 0.80%), full annealing consists of heating to 90 to 180 °C (50 to 100 °F) above the A_3 temperature, and for hypereutectoid steels (steels with a carbon content of more than 0.80%), heating above the A_1 temperature, followed by very slow cooling.

Process annealing consists of heating steel to a temperature just below the A_1 eutectoid temperature for a short time. This provides stress relief, makes the steel easier to form, and is applied to low-carbon cold-rolled sheet steels to restore ductility. The temperatures used range from 550 to 650 °C (1020 to 1200 °F). Slow cooling is not essential for process annealing, because any cooling rate from temperatures below A_1 will not affect the microstructure or hardness. Although recrystallization can occur due to the stored energy from cold working, there are no phase changes, and the ferrite and cementite constituents remain the same throughout the process.

Normalizing. Steel is normalized by heating 160 to 200 °C (90 to 110 °F) into the austenite-phase field at temperatures somewhat higher than those used by annealing, followed by cooling at a medium rate. For carbon steels and low-alloy steels, normalizing means air cooling. Many steels are normalized to establish a uniform microstructure and grain size. The faster cooling rate during normalizing results in a much finer microstructure, which is harder and stronger than the coarser microstructure produced by full annealing. Steel is normalized to refine grain size, make its structure more uniform, make it more responsive to hardening, and to improve machinability. When steel is heated to a high temperature, the carbon can readily diffuse, resulting in a reasonably uniform composition from one area to the next. The steel is then more homogeneous and will respond to the heat treatment more uniformly. The properties of normalized steels depend on their chemical composition and the cooling rate, with the cooling rate being a function of the size of the part. Although there can be a considerable variation in the hardness and strengths of normalized steels, the structure usually contains a fine microstructure.

Spheroidizing. To produce a steel in its softest possible condition with minimum hardness and maximum ductility, it can be spheroidized by heating just above or just below the A_1 eutectoid temperature and then holding at that temperature for an

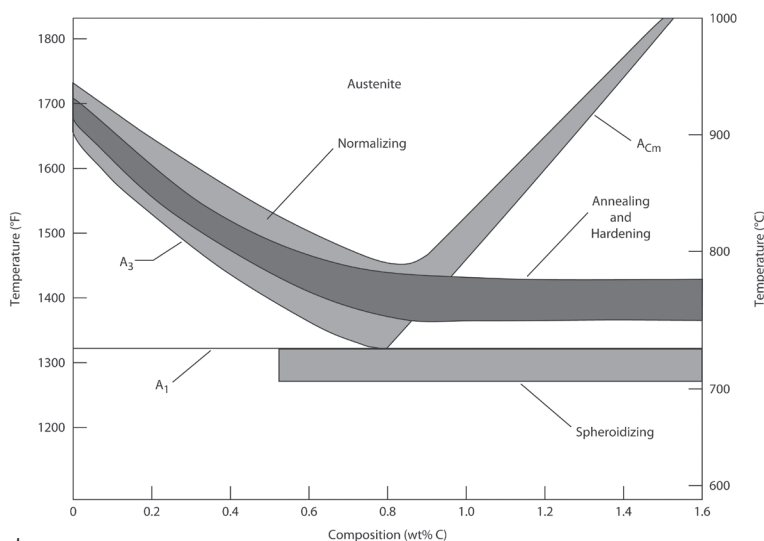


Fig. 3 Steel heat treating ranges. Source: Ref 1

extended period of time. Spheroidizing can also be conducted by cyclic processing, in which the temperature of the steel is cycled above and below the A_1 line. This process breaks down lamellar structure into small pieces that form small spheroids through diffusion in a continuous matrix. Surface tension causes the carbide particles to develop a spherical shape. Because a fine initial carbide size accelerates spheroidization, the steel is often normalized prior to spheroidizing.

Hardening. To harden a steel by quenching, it must be heated to a sufficiently high temperature to produce an austenitic crystalline phase and then quenched (quickly cooled). On quenching, the austenite phase transforms to martensite, which is a hard and strong but brittle crystalline phase. The quenched hardness depends on the chemical composition and the cooling rate during quenching.

Steels with higher carbon contents produce higher hardness, and the addition of alloying elements allows martensitic structures to develop through thicker sections. The carbon content is critical to the ability to harden steel. Because ductility decreases with increasing carbon content, the carbon content is held to approximately 0.45% in many engineering steels. However, when wear resistance is required, for example, in tool and die steels, it may be increased to over 1.0%. The addition of alloying elements allows thicker sections to be hardened or allows less drastic quenches. The effect of alloying elements and section size on hardenability can be illustrated by comparing the plain carbon steel 1040 with the alloy steel 4140 (Fig. 4). In this example, both the 1040 and 4140 steels contain nominal carbon contents of 0.40%, and yet, due to the alloying elements in 4140, the 4140 hardens to a much greater depth. However, as the diameter of a bar of 4140 is increased from 5 to 10 cm (2 to 4 in.), the depth of hardening



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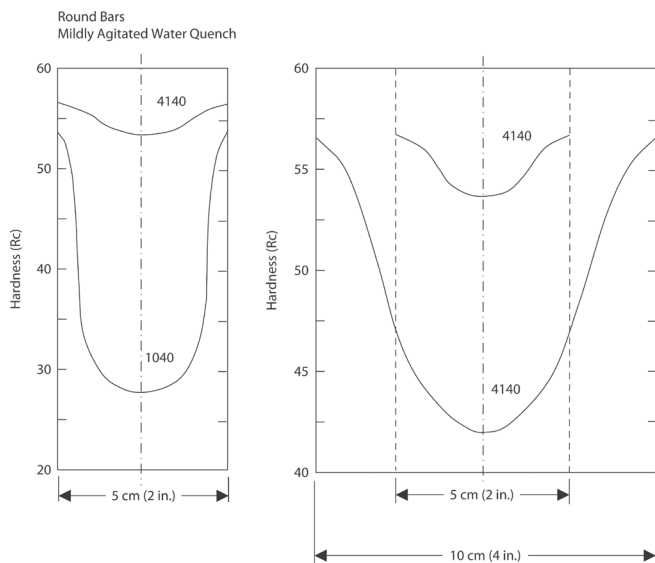


Fig. 4 Effect of alloying and section size on hardenability. Source: Ref 1

decreases. Some more highly alloyed steels are so deep hardening that they will form fully martensitic structures in fairly thick sections by air cooling to room temperature.

Cooling rates are controlled by the quenchant used, with brine, water, oil, and forced air producing progressively slower quenching speeds. While plain carbon steels such as 1040 must be quenched in brine or water to develop 100% martensite in even thin sections, alloy steels such as 4140 can be oil quenched to produce fully martensitic structures in thicker sections. When a steel is quenched to room temperature, the outside cools much faster than the interior, setting up contraction stresses in the steel. Then, when the austenite transforms to martensite, there is a volume expansion that causes large residual tensile stresses on the surface. The combined effect of these contraction and expansion stresses can cause distortion and even cracking. The milder oil quench minimizes residual quenching stresses that cause distortion and cracking problems. Some tool steels are so highly alloyed that they can be air quenched and still produce fully martensitic structures in thick sections.

The martensite produced by quenching is extremely strong and hard but is too brittle to be used in most applications. It must be tempered by reheating to an intermediate temperature. The temperature selected depends on the application. For example, a tempering temperature of 150 °C (300 °F) will impart some toughness with a minimal loss in strength, while a higher tempering temperature (e.g., 700 °C, or 1300 °F) will produce much greater ductility and toughness but at a significant loss in strength.

Another strategy to reduce quenching stresses is to use an interrupted quench. The most frequent type of interrupted quench-

ing process is called martempering. In martempering, the part is quenched into a molten salt bath at a temperature just above the temperature at which martensite starts to form. When the part reaches thermal equilibrium, it is removed from the salt bath and allowed to air cool and form martensite. The objective is to delay the cooling just above the martensitic transformation for long enough to equalize the temperature throughout the piece and minimize distortion, cracking, and residual stresses. It should be noted that even though this process is called martempering, it is not a tempering process; instead, it is a hardening process. Thus, martempered steels must be tempered before being placed in service.

Austempering is another interrupted quenching process in which the objective is to form a bainitic structure. Bainite can be considered to be a structure that is intermediate between ferrite and martensite. Like martempering, the part is quenched into a salt bath above the temperature at which martensite starts to form. However, it is allowed to remain at that temperature until the transformation to bainite is complete. Austempering offers several potential advantages, including increased ductility, toughness, and strength at a given hardness, reduced distortion, and the ability to heat treat steels to a hardness of 35 to 55 HRC without having to temper. One of the outstanding attributes of austempered steels is their high impact resistance.

Case Hardening. There are some applications where it is necessary to have a hard, wear-resistant surface but a tough, shock-resistant inner core. Examples include camshafts, gears, and rods that require hard surfaces to resist wear but tough inner cores to resist shock. While a low-carbon steel containing 0.1% C will have a tough core, its surface hardness will be low after hardening. On the other hand, a high-carbon steel containing 0.8% C will have a high surface hardness after hardening, but the core will not be tough and shock resistant. There are two main approaches to this problem. One is to use a medium-carbon steel and only harden the surface through heat treatment such as flame or induction hardening. The other approach is to diffuse carbon or nitrogen into the surface layers of a low-carbon steel in processes such as carburizing, nitriding, cyaniding, carbonitriding, and ferritic nitrocarburizing. When a carburized steel is heat treated, the high-carbon surface layers will attain a much higher hardness than the low-carbon core.

Heat Treatment of Aluminum-Base Alloys

For an aluminum alloy to be precipitation hardened (i.e., aged), the alloy must contain a sufficient amount of at least one element or compound that has an appreciable solubility at high temperatures and minimal solubility at lower temperatures. Elements that have this characteristic are copper, zinc, silicon, and magnesium. Additionally, the element or compound must be capable of forming an intermetallic precipitate in the aluminum matrix. Alloys that are not aged sufficiently to obtain maximum hardness are said to be underaged, while those that are aged past peak hardness are said to be overaged. Underaging can be a result of artificially aging at an insufficiently high temperature or for an



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aging time that is too short, while overaging is usually a result of aging at too high a temperature.

Aluminum alloys classified as heat treatable are the 2xxx, 6xxx, 7xxx, and some of the 8xxx wrought alloys. Precipitation hardening is conducted in three steps:

1. Heating to the solution heat treating temperature and soaking long enough to put the elements or compounds into solution
2. Quenching to room or some intermediate temperature (e.g., water) to keep the alloying elements or compounds in solution; essentially creating a supersaturated solid solution
3. Aging at either room temperature (natural aging) or a moderately elevated temperature (artificial aging) to cause the

supersaturated solution to form a very fine precipitate in the aluminum matrix

The solution heat treating temperature is as high above the solid-solubility curve as possible without melting the lowest-melting-point eutectic constituents. Therefore, close temperature control, normally $\pm 5^\circ\text{C}$ ($\pm 10^\circ\text{F}$), is required for the furnaces used to heat treat aluminum alloys. If the temperature is too high, incipient grain-boundary melting occurs; the part is ruined and must be scrapped. On the other hand, if the temperature is too low, dissolution will be incomplete, and the aged alloy will not develop as much strength as expected. The solution heat treating time should be long enough to allow diffusion to establish an equilibrium solid solution. Table 1 summarizes the temper designations for combinations of heat treatments for aluminum alloys.

Table 1 Temper designations for aluminum alloys

Suffix letter “F,” “O,” “H,” “T,” or “W,” indicates basic treatment condition	First suffix digit indicates secondary treatment used to influence properties	Second suffix digit for condition H only indicates residual hardening
F—As-fabricated		
O—Annealed-wrought products only		
H—Cold worked, strain hardened		
	1—Cold worked only	2—1/4 hard
	2—Cold worked and partially annealed	4—1/2 hard
	3—Cold worked and stabilized	6—3/4 hard
		8—Hard
		9—Extra hard
W—Solution heat treated		
T—Heat treated, stable		
	T1—Cooled from an elevated-temperature shaping operation + natural aged	
	T2—Cooled from an elevated-temperature shaping operation + cold worked + natural aged	
	T3—Solution treated + cold worked + natural aged	
	T4—Solution treated + natural aged	
	T5—Cooled from an elevated-temperature shaping operation + artificial aged	
	T6—Solution treated + artificial aged	
	T7—Solution treated + overaged	
	T8—Solution treated + cold worked + artificial aged	
	T9—Solution treated + artificial aged + cold worked	
	T10—Cooled from an elevated-temperature shaping operation + cold worked + artificial aged	

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The product form can determine the time required for solution heat treatment. For example, castings require more time than wrought products to dissolve their relatively large constituents into solution. The time required can vary anywhere from less than a minute for thin sheet up to 20 h for large sand castings.

After the elements are dissolved into solution, the alloy is quenched to a relatively low temperature to keep the elements in solution. Quenching is perhaps the most critical step in the heat treating operation. The challenge is to quench the part fast enough to keep the hardening elements in solution while, at the same time, minimizing residual quenching stresses that cause warpage and distortion. In general, the highest strength levels and the best combinations of strength and toughness are obtained by using the fastest quench rate possible. Resistance to corrosion and stress-corrosion cracking (SCC) is usually improved by faster quenching rates; however, the resistance to SCC of certain copper-free 7xxx alloys is actually improved by slow quenching. While fast quenching rates can be achieved by cold water, slower quenching rates (e.g., hot or boiling water) are often used to sacrifice some strength and corrosion resistance for reduced warpage and distortion.

If premature precipitation during quenching is to be avoided, two requirements must be met. First, the time required to transfer the part from the furnace to the quench tank must be short enough to prevent slow cooling through the critical temperature range where very rapid precipitation takes place. The second requirement is that the volume of the quenching tank must be large enough so that the quench tank temperature does not rise appreciably during quenching and allow premature precipitation.

Aging is conducted at either room temperature (natural aging) or at elevated temperature (artificial aging). Naturally aged

alloys are often solution treated and quenched (W temper), refrigerated until they are ready to be formed, and then allowed to age at room temperature to peak strength (T3 temper). To prevent premature aging, cold storage temperatures must be in the range of -45 to -75 °C (-50 to -100 °F). Artificial aging treatments are generally low-temperature, long time processes; temperatures range from 115 to 190 °C (240 to 375 °F) for times of 5 to 48 h.

Verification of heat treatment is usually conducted by a combination of hardness and electrical conductivity tests.

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