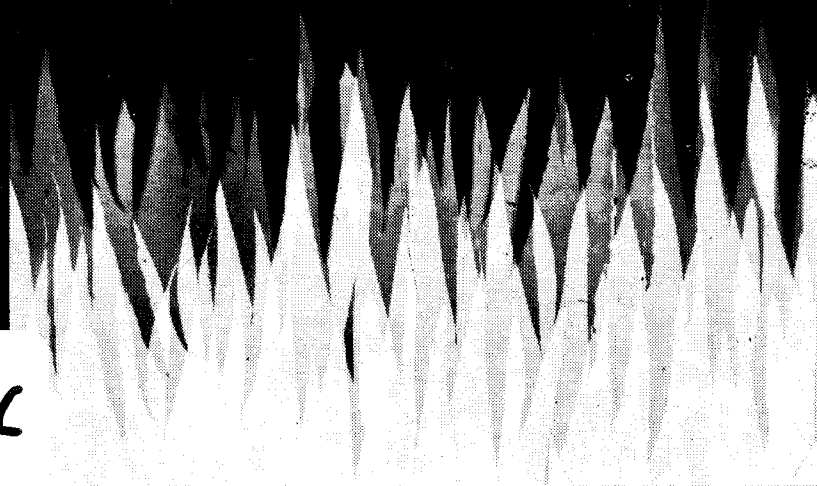


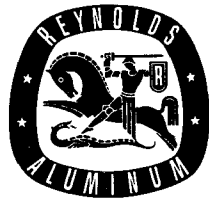
Ross Glidewell

# ALUMINUM HEAT TREATING



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REYNOLDS  
METALS CO.

# HEAT TREATING ALUMINUM ALLOYS

**Foreword:** This book explains the principles and procedures for heat treating the aluminum alloys. You do not need to be a metallurgist to understand the simple concepts used here to provide the reader with a clear picture of what happens when aluminum is heat treated.

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**REYNOLDS METALS COMPANY**

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# **METALLURGY, HEAT TREATMENT OF ALUMINUM ALLOYS**

**METALLURGY** is an exceedingly complex subject, because the metal structures involved are themselves quite complex. Where electricity lends itself to simple analogies (electricity flowing in a wire being similar to water flowing in a pipe, etc.), there are very few such analogies that can be used in explaining metallurgical reactions. So the reader can be forewarned that the subject is not easy to master.

However, if we disregard for the moment some of the fine technical details, it is possible to present a few comparatively simple concepts that may enable the reader to obtain a little better understanding of what goes on in producing and heat treating aluminum alloys. Production is included with heat treatment because the two are so closely allied.

The metallurgist will recognize we have taken certain liberties with the subject to enable the non-technical reader to more easily understand some of the "reasons why" in the metallurgy and heat treatment of the aluminum alloys.

Combinations of metals like those found in the aluminum alloys may have an exceedingly complex structure. A molten aluminum alloy will be composed of six to nine different metals, some dissolved in others (like ink in water) and some not dissolved but just mixed in (like oil in water). As the molten alloy is allowed to cool, it will reach a point where solidification begins.

At this point "crystals" begin to form. With continued cooling, additional crystals form, building up on the first ones, in turn producing "grains". Thus, for our purpose, we will say that the solidified metal is composed of grains, in turn composed of crystals.

In addition, certain compounds are formed by the various combinations of metals. These compounds may solidify out separately, either between the grains along the grain boundaries, or in the grains between the crystals. Too, certain other elements may separate out during cooling to room temperature. Obviously, the resulting structure is quite complex, as previously mentioned.

## **Work Hardening**

For the moment, let's disregard some of these additional particles and say that in general, aluminum alloys are composed of "grains", in turn composed of "crystals". Adjoining crystals can "slip" against each other in many different directions; that is, they are said to have many different "slip planes". A metal is called "soft" when its crystals have a "fresh" set of slip planes that have "not been used".

We say "not been used" because application of mechanical force will cause crystals to slip along any given slip plane only a certain amount. When a soft metal is hammered or stretched out or has its dimensions changed mechanically by any other method of applying force at room temperature, the adjoining crystals move along a slip plane. But because

only a certain amount of slippage can occur along any one slip plane, the limit of movement on that plane is quickly reached and further working then requires slippage along other planes.

However, the planes along which subsequent slippage then occurs may not be so favorably positioned with respect to the applied force. The result is that the application of the same amount of force as before produces much less change in shape. Or saying it in another way — to produce the same amount of change in shape, much more force must be applied. As further work is done on the piece, this resistance increases greatly and the metal is said to "work harden".

Thus as the shape of the metal piece is changed by working it mechanically, more and more slip planes are used up and the metal becomes progressively harder and less capable of further working. It is evident that metals possessing few slip planes quickly reach a point where excessive force is required for further working, or where the metal structure may even break down if all available slip planes have been "used up".

### **Annealing**

However, the original workability of the metal can be restored by producing a "fresh" set of crystals having an entirely new set of slip planes. This is done by heating the previously worked metal to a point where a new crystal structure is produced. This temperature is called the "recrystallization" point or "temperature of recrystallization". Aluminum alloys require comparatively low temperatures, in the neighborhood of 650-750° F. This operation is easy to control and reliable results can be had with little difficulty on most of the aluminum alloys. (Note specific recommended treating cycles in Tables 1 and 5, Pages 29 and 32.)

Suppose we are forming a deep drawn aluminum cup from a flat circle. Instead of attempting to produce the cup from the flat in a single forming operation, the final shape may be attained in steps or stages, annealing the part between successive operations wherever necessary to correct work hardening. In this manner it is possible to keep each step within the practical working limits of the material and not draw the sheet past the point where excessive work hardening would cause cracks or breaks. This is why many articles formed from aluminum alloy sheet involve a sequence of press operations with a series of intermediate anneals.

### **The Time Element**

It is important to understand the influence of time in heat treating metals. For instance, if in the above described annealing process, the work is not held above the recrystallization temperature long enough, the new crystals will not have a chance to form completely. It takes a certain amount of time to form the new grain structure. In fact, most changes in the structure of the metal require a certain amount of time for completion.

Also time is required for the heat to soak thoroughly throughout all portions of the metal piece being treated. This is necessary in order that sufficient temperature rise be produced in all sections to provide the change in metallurgical structure that we desire. While a fast treatment in a furnace operated at a higher temperature might bring the interior of the work up to temperature quicker, it would be sure to heat the edges and corners of the work to excessive temperatures and probably damage those portions.

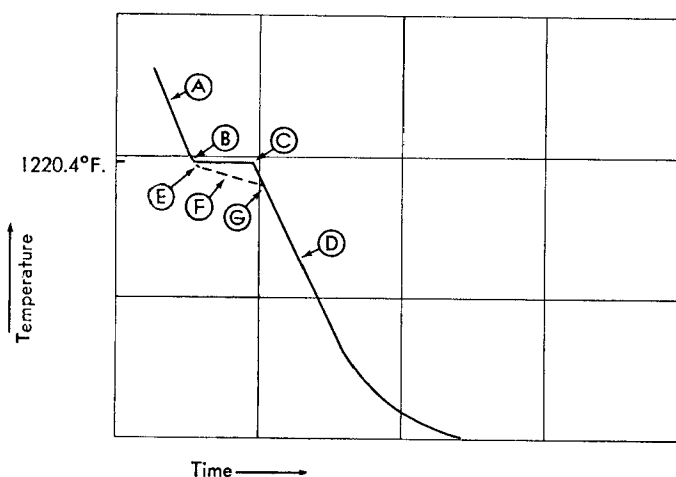


Chart 1 — Time versus Temperature for a pure metal. See text.

For these reasons, allowance for proper time "at temperature" is essential in any heat treatment.

The time element enters into heat treatment in another important manner. Because a certain period of time is required for structural or metallurgical changes (such as solid diffusion, Page 11) to reach a completed or stable stage, it is possible to quickly change the temperature of the metal and thereby obtain at room temperature certain desired types of structures that could not otherwise be had at room temperature.

But before getting into heat-treating cycles and structures of aluminum alloys, let's start out with a pure metal for the sake of simplicity and see how this time element influences the structure. Chart 1, Page 5, indicates the relation between time and temperature as a pure metal is allowed to cool from the molten state, represented by point "A". As its temperature falls, it reaches a point "B" where the metal begins to solidify or freeze. For pure aluminum, this freezing point is 1220.4°F.

Note that the curve indicates the temperature remains at this value for a period of time. This is because the change from a liquid to a solid is accompanied by the release of heat, the mechanism of the operation being such that just enough heat is released to balance that being lost, thus retaining the temperature of the metal constant during the period this solidification is taking place. So the curve is level from "B" to "C".

As soon as the metal has completely solidified, its temperature again falls gradually as it is allowed to cool, represented by the sloping line "D".

It should be noted that only a pure metal follows this type of curve . . . and each different metal has a different solidification or freezing point; that is, the level portion of the curve or "plateau" will come at a different temperature.

Now let's see what happens when we melt two pure metals together — let's say aluminum and copper — and allow them to cool. We find that we have a curve of an entirely different shape because the combination of the two metals has a freezing "range" instead of a freezing "point"; that is, the material begins to freeze at one temperature and continues to freeze while the temperature falls to a lower value before all of it has solidified. This is shown by the dotted portion of the curve at "F" in Chart 1 where the curve slopes from "E" to "G".

The combination of aluminum and copper does not freeze or solidify completely at a single temperature because the mixture formed by the two metals behaves in an entirely different manner than a pure metal like copper or aluminum (alone). Suppose we examine this freezing action for a moment, tracing the new curve on Chart 1.

### Differential Freezing

At "E", Chart 1, the crystals forming out as the molten metal is just beginning to solidify will consist of an alloy of almost pure aluminum. As the temperature falls, crystals with appreciable amounts of copper will begin forming. With continued dropping temperature, the crystals forming will contain more and more copper. Thus at "E", the alloy particles freezing out may contain 99.9 percent aluminum, 0.1 percent copper. Just below "E", the particles freezing out of solution may contain 98 percent aluminum, 2 percent copper. Similarly, particles containing 97 percent aluminum, 3 percent copper will freeze out at a lower temperature, and so on.

*Thus as the temperature falls, the material freezing out of solution at any particular moment corresponds to the alloy of aluminum and copper that freezes at that particular temperature.*

This accounts for the fact that as the temperature curve traverses the "F" portion, Chart 1, the alloy particles or crystals forming out of the molten metal contain more and more copper. At "G", the entire mass becomes solidified and the temperature drops along the same type curve as before.

When the molten metal contains more than two elements, this curve changes considerably and the freezing action becomes increasingly complicated. It is evident, that in an aluminum alloy where we may have six to nine different elements, the action may be extremely complicated. Especially because the many different elements in turn form various mixtures or compounds which may behave in still different ways to further complicate the situation.

### Precipitation

One of the complications that results from having these many different elements in the aluminum alloy is that certain combinations of elements may form mixtures or compounds which may freeze out of solution or separate out in small independent particles before or even after most of the other material has solidified.

These particles may be extremely small and may exist between the surfaces of adjoining crystals in such a manner as to "lock" the crystals by hindering them from sliding and thus increasing the resistance to mechanically working the material. This in turn may make the metal hard,

tough, brittle, etc. Depending upon circumstances, the result may be desirable or undesirable.

This precipitation or separating out from the molten metal can be demonstrated in this manner: Place several spoonfuls of salt in a glass of boiling water, adding salt until no more will dissolve and some remains in the bottom of the glass even after repeated stirring. Pour this solution into another glass, leaving behind the extra salt. We now have a "saturated" solution of salt in water.

Then place this glass in a basin of cold water and stir the solution. As it cools, the temperature will drop to a point where the water can not hold all of the salt in solution. We now have a "supersaturated" solution in which the extra salt will immediately form salt crystals as it "precipitates" out of the solution.

**Cooling:** The same thing happens when a molten aluminum alloy is allowed to cool. Various elements and combinations of elements will precipitate out of the molten alloy as the temperature falls to a point where they can no longer be held in solution. Certain compounds may precipitate out after solidification.

When a constituent precipitates out, it may accumulate between grains along grain boundaries, or in the form of minute particles between crystals inside the grains. These particles may thus be present in the slip planes between adjacent crystals. If the same particle is partially imbedded in both surfaces of adjoining crystals, it is evident that it will tend to lock those surfaces together and prevent them from sliding freely one on the other. Thus such particles will tend to increase the resistance to slippage between crystals because of this "keying" effect.

With slippage made more difficult, the metal acts like it had fewer slip planes, is harder to work and may be considerably stronger. So the end result may be that the mechanical properties of the metal are greatly improved. As we will see, this is the aim of certain heat-treating cycles.

Remember, we have not only solids precipitating out of a liquid (the molten metal), but also solids precipitating out of solids, because just as a solid metal can diffuse into another solid metal (described under "homogenizing" Page 8), so can a solid precipitate out from another solid. To illustrate this latter action, however, there is no simple analogy like that of the salt and water previously mentioned.

At this point, the picture becomes increasingly difficult to follow. So before getting any deeper in this direction, let's look at some other factors.

### Segregation

When molten aluminum alloys are poured into molds and allowed to cool to form ingots (casting), the surfaces of the ingot that contact the mold naturally cool faster. So the first crystals to be formed are in the ingot surfaces contacting the mold walls. Then as the temperature of the metal continues to fall and more crystals are formed, the new ones form on top of the older ones, causing the metal grains to "grow" toward the center of the ingot in a direction at right angles to the mold walls.

At the same time the rapid extraction of heat through the mold walls is causing the grains to grow inwardly from the ingot surface, the tempera-

ture difference existing between the solidifying outer layers of the ingot and the still molten inner portion produces another important action.

We have seen how certain constituents of the metal may precipitate or separate out from the remainder as the temperature drops. Now with uneven temperatures throughout the ingot, it becomes evident that precipitation will occur unevenly. This in turn results in an uneven distribution of the precipitate (the material that precipitates out).

Since these precipitates may have an exceptionally important influence on the characteristics of the metal, it is essential that they be uniformly distributed throughout the entire body of the metal. This is done by mechanically working or "kneading" the ingot, supplemented by the heat treatment called "homogenizing".

### Homogenizing

Let's go back for a moment to where all the metal had just solidified. Note that the crystals forming first were almost pure aluminum and that succeeding crystals contained more and more copper in the form of a richer copper-aluminum alloy. Thus the grains in the solidified metal have what is termed a "cored" structure; that is, the inside crystals near the core are much different than the outer crystals of a grain. As the metal freezes and cools to room temperature, the resultant "cast" metal possesses this undesirable cored structure. So it becomes necessary to change this structure to a more desirable one.

To do this, we resort to "solid diffusion" — a term used to denote the diffusion or spreading out or dissolving of one metal into another when both are in the solid state. It is well known that some liquids will readily dissolve into others, such as ink into water. Likewise certain liquids will readily dissolve certain solids, as water dissolves salt. But it is not so well known that certain solids can dissolve other solids.

It is a fact, however, that if a gold block and a silver block are cleaned carefully and pressed tightly together, the dividing line will gradually disappear, one metal blending or dissolving into the other. While this action will occur at room temperature, it is greatly speeded by heating both metals.

In a similar manner, the copper is caused to diffuse throughout the metal structure by heating the metal to a temperature just under its melting point, followed by slow cooling. This treatment is known as "homogenizing". For many aluminum alloys it is done in the temperature range of 900-1000° F. By this means it is possible to overcome the tendency of certain constituents to segregate or separate to form thin and dense areas. Homogenizing thus is an aid in bringing about proper uniform distribution of the alloying elements and other constituents, and so helps in producing the desired homogeneous structure.

### Strengthening Aluminum Alloys by Heat Treatment

As was explained briefly under "precipitation," Page 6, it is possible to strengthen the aluminum alloys by causing certain constituents to precipitate out inside the grains along the crystal boundaries or in the slip planes between crystals in such a manner as to lock or key the crystals,

thus hindering slippage and so producing a "harder" and stronger material.

Also resistance to slippage can be increased by controlling the material that is precipitated between the crystals so that it acts like a "sharp grit" instead of like a "ball bearing". It is evident that a material that tends to aid free movement of one crystal on another will produce a softer, weaker alloy, whereas a precipitate that tends to prevent such movement will in turn produce a harder and stronger structure.

Table 2, Page 30, details typical times and temperatures for controlling both of the above factors. Of course the different aluminum alloys require slightly different treatments because of the cumulative effect of the different combinations of elements in them.

Let's examine Chart 2, Page 10, to see why these particular temperature ranges are required and to find out about the "aging" treatment — either natural or artificial — that is necessary to develop maximum strength in the aluminum alloys.

The vertical scale in Chart 2 represents temperature, starting with a low temperature at the bottom and going up above the melting point of the aluminum alloys. Since the alloys we are going to look at have aluminum and copper as the principle constituents, we can make the horizontal or base scale a double scale. Going from left to right, the upper scale measures per cent of copper from zero to 40 percent. Disregarding other constituents, we can say that remainder at any point is aluminum. So we can put in another scale immediately below the copper one reading 100-90-80-70-60 percent aluminum for the same points designated as 0-10-20-30-40 percent copper respectively.

For our purpose, we have selected an alloy containing 3 percent copper at room temperature (97 percent aluminum), represented by Point 8 on the chart. Now let's see what happens when we heat and cool this alloy. First the temperature of the material will be raised along the vertical dotted line to Point 1 — say 1300° F. At this temperature all the material is molten and the copper has dissolved in the aluminum.

Now the material is allowed to cool to 1190° F — Point 2 lying on Curve A. This curve represents the temperature at which the molten metal starts to solidify. The first crystals that start to form here will be almost pure aluminum. These crystals will serve as the nuclei or center points around which the grains will form by solidification of other crystals on them as cooling continues.

### Solid Solution

Now we will allow the material to cool to 1160° F — Point 3 — and hold it at this temperature while we see what is happening here. Since solidification began at Point 2, the material is now partly solidified and partly molten. Because the aluminum has been crystallizing out of solution with very little copper, the copper content of the still molten material is increasing.

Since the information in the chart we are studying was obtained from tests upon a whole series of alloys with different compositions as indicated by the two horizontal scales, it is possible to tell exactly how much copper

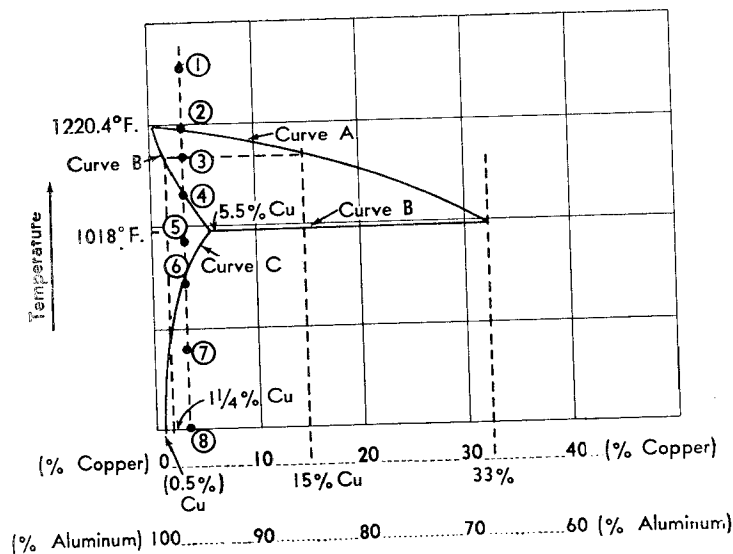


Chart 2 — "Constitution" diagram for copper-aluminum alloys.  
See text for detailed explanation.

is contained in the aluminum-copper alloy that is solidifying out of solution and also to tell how much copper is in the still molten portion of the material. In fact, such diagrams are called "constitution" diagrams. First we extend a horizontal dotted line left from Point 3 to Curve B (which represents the temperature at which freezing is completed — for the different compositions). Then from the point where we strike Curve B, we run a vertical line to the base. Here the copper scale tells us that the alloy that completes freezing at 1160° F. contains about 1 1/4 percent copper. So now we know that at Point 3, the crystals forming contain 1 1/4 percent copper.

To find the copper content of the still molten portion, we run a horizontal line to the right from Point 3 to Curve A — the curve that indicates the beginning of freezing. Where this line strikes Curve A then tells the amount of copper in the alloy just beginning to freeze. By extending a vertical line from this point on Curve A to the base scale, we find that the molten material contains about 15 percent copper.

At lower temperatures (between Points 3 and 4), the crystals just forming will contain more and more copper. Likewise, the remaining molten material will also contain a greater percentage of copper. Thus as the temperature falls, the material freezing out of solution at any particular moment corresponds to the alloy of aluminum and copper that freezes at that particular temperature. This "differential freezing" was first pointed out under that heading on Page 6.

Thus at any point between Curve A and Curve B, we have a mixture of solid particles and still molten liquid. The solid particles consist of aluminum with a certain amount of copper dissolved in them. When one

metal remains dissolved in another like this, the combination is called a "solid solution".

### Diffusion

At Point 4, all the material has solidified. By extending a horizontal line to the right to Curve A, we note that the very last crystals to solidify contained about 26 percent copper, while the very first crystals to solidify (at Point 2) contained practically pure aluminum. So at Point 4 we have grains whose center consists of almost pure aluminum crystals and whose extreme outer surface is formed of crystals having 26 percent copper. The entire copper content or average throughout the entire grain, however, is 3 percent, since we can have no more or no less than the 3 percent with which we started.

Now let's go somewhat below Curve B, to say 1018° F. — Point 5 — and hold the material at this temperature while we examine what is happening. At any position below Point 4, the material is a solid. But that does not mean that more changes do not occur.

To understand this last statement, we must go back to a fundamental. Any metal can exist in at least three different forms — vapor, liquid or solid. *In addition, many common metals appear in more than one solid form.* These are known as "phases".

The aluminum-copper alloys we are studying have four phases — a completely liquid phase in the chart above Curve A, a second phase consisting of solid particles in molten material in the area between Curve A and Curve B, a third phase in the area below Curve B and to the left of Curve C where the material is a solid, and a fourth phase in the area below Curve B and to the right of Curve C where the material is also solid but in a different form as will be explained.

But let's get back to see what happens when we hold the temperature at Point 5 — 1018° F. At this comparatively high temperature, the phenomena we called solid diffusion (explained under "homogenizing", Page 8) proceeds at a comparatively rapid rate. This means that the fairly large amounts of copper near the grain boundaries diffuse rapidly inward throughout all portions of the grain so that it is not long before every crystal in the grain contains the same amount of copper — 3 percent in our example. Point 5 can be said to be typical of any point between Point 4 and Point 6 in that anywhere in this range, the copper will diffuse throughout the entire structure if the temperature is held for a sufficient period of time. Of course, the diffusion progresses more rapidly at the higher temperatures, which means that a shorter period of time would be required for complete diffusion at those temperatures . . . again emphasizing the importance of time in the heat-treating cycle.

### Precipitation

Curve C is the line indicating the beginning of the formation of a compound containing copper and aluminum called copper aluminide ( $\text{CuAl}_2$ ). This compound starts to separate or precipitate out of the material at any temperature below Point 6 — 920° F. for the 3 percent alloy under consideration. This precipitation of a solid from out of another solid was mentioned previously in our discussion of precipitation on Page 6.

At Point 7, more copper has separated out as copper aluminide. In fact at this temperature (around 850° F.) about 99 percent of the material is in the form of a copper-aluminum alloy containing 2½ percent copper, the remainder of the copper being in the copper-aluminide particles which have precipitated out of the copper-aluminum alloy and now exist between crystals and between grains. The other 1 percent of material is in the form of copper aluminide. This now contains about ½ percent of the total amount of copper, which of course is still 3 percent since we have not added or taken away any of the original copper content.

At Point 8 on Chart 2, still more copper has precipitated out in the form of copper aluminide.

To develop maximum strength in the aluminum alloys, it is necessary to control carefully the size and distribution of the material precipitated out as it is this material which affords the added strength (due to keying, etc.) as previously explained.

### Controls, Quenching

Now let's examine the recommended heat treatments (Pages 30 through 32) for strengthening the aluminum alloys and see what controls are employed to bring about the proper size and distribution of the precipitated particles.

First step is to bring the aluminum alloy up to the specified temperature, which will lie somewhere between Curve B and Curve C on the constitution diagram for the particular alloy under consideration. A whole series of constitution diagrams for various aluminum alloys will be found in the METALS HAND-BOOK. A diagram for aluminum-copper alloys, similar to our Chart 2, can be found there.

Purpose of this first step is to dissolve the precipitated constituents, so they can later be re-precipitated in the form wanted. The material must be held at the specified temperature for a sufficient period of time for this dissolving action to occur throughout all portions of the piece being treated. This maintaining "at temperature" for the specified length of time is called "soaking" and constitutes the second step in the heat-treating cycle.

The third step is to cool the work rapidly by plunging the part into cold water. This is called "quenching". Purpose of suddenly dropping the temperature of the part in this manner is to prevent certain constituents from precipitating out, which they would do if cooled slowly. Here slow cooling would tend to produce a precipitate consisting of large particles instead of the type we want.

Quenching from any particular temperature range tends to retain in the metal the structure present just before quenching. Thus quenching not only prevents the precipitation of certain constituents that *we do not want to precipitate at that time*, but it also helps control the constituents that *we do want out of solution*.

The purpose of the entire heat-treating cycle is to develop the *right kind* of precipitate in the *right place* in the metal structure. The precipitate we want should be of the "gritty" type rather than the "ball bearing" type, as previously explained, in order to provide the maximum resistance

to slippage of crystals. Also the precipitate must be uniformly distributed in extremely minute particles between crystals where it can exert maximum keying effect, rather than outside the grains or along grain boundaries.

### Aging

The fast cooling to near room temperature upon quenching produces a "supersaturated" condition where the material has already dissolved in it more of the constituents than it normally can carry in solution at that temperature. Such a condition obviously is unstable. The result is that certain constituents begin to separate out or precipitate from the main mass of the aluminum alloy.

This precipitation occurs at room temperature with many of the aluminum alloys and this action then is known as "natural aging". Certain other alloys must be heated slightly to bring this precipitation to completion within a reasonable length of time. This is called "artificial aging". In either case, this controlled re-precipitation is aimed at providing the correct size, character and distribution of the precipitated particles in the aluminum to produce maximum strength and other desired mechanical properties.

It should be pointed out that aluminum alloys hardened in this manner can be made soft and easily workable again by an annealing treatment. However, annealing alone will not produce maximum workability in aluminum alloys that have been heat treated, for additional cold working and subsequent re-annealing is required in these instances.

Recommended annealing cycles are designed to produce a precipitate in the form of large particles outside the grains along the grain boundaries and not inside between crystals. In this manner, minimum keying effect results and the material is "soft" because the crystals easily slip along their slip planes. This redistribution of the precipitate is in addition to the recrystallization effect mentioned in our first discussion of annealing, Page 4.

It will be evident from the explanation presented here that it is necessary to follow closely the recommended heat-treating cycles in order to produce maximum mechanical properties in the aluminum alloy. Even slight variations from the recommendations can cause considerable difficulty.

Recommended heat-treating cycles for the various aluminum alloys will be found in Tables 2, 3, and 4, Pages 30, 31, and 32.

## TEMPER DESIGNATION SYSTEM

(The Temper Designation Is Always Separated from the Alloy Designation by a Hyphen. . . . Do Not Omit the Hyphen. Note Certain Designations Apply Only To Wrought Products; Others to Cast Products; Still Others Apply to Both.)

- F As fabricated. (Wrought Products)
- O Annealed, recrystallized. (Wrought Products Only.  
See —T2 for Cast)
- H Strain hardened. (Wrought Products Only)
  - H1, plus one or more digits. Strain hardened only.
  - H2, plus one or more digits. Strain hardened and then partially annealed.
  - H3, plus one or more digits. Strain hardened and then stabilized.
- W Solution heat treated — an unstable temper — before any straightening, flattening, or other shape-correcting operations. (Wrought Products)
- T Treated to produce stable tempers other than—F, —O, or —H.
  - T2, Annealed. (Cast Products Only)
  - T3, Solution heat treated and then cold worked. (Wrought Products)
  - T4, Solution heat treated. (Wrought or Cast Products)
  - T5, Artificially aged only. (Wrought or Cast Products)
  - T6, Solution heat treated and then artificially aged. (Wrought or Cast Products)
  - T7, Solution heat treated and then stabilized. (Cast Products Only)
  - T8, Solution heat treated, cold worked, and then artificially aged. (Wrought Products Only)
  - T9, Solution heat treated, artificially aged, and then cold worked. (Wrought Products Only)
  - T10, Artificially aged and then cold worked. (Wrought Products Only)

NOTE: The “—T” designations above may have one or more digits added to denote certain variations of the basic heat treatments described.

## HEAT-TREATABLE ALLOYS

versus

## NON-HEAT-TREATABLE ALLOYS

Aluminum alloys are composed of a major percentage of aluminum with one to nine other elements present. Some of these are added intentionally to give the alloy certain desired characteristics, while others may be there as impurities.

The presence of certain elements in an aluminum alloy (copper, for example) produces a metallic structure whose strength and hardness can be improved by heat treating. There may also be other elements present as alloy constituents that are unaffected by heat treating.

Thus, based on their reaction to thermal treatment, the aluminum alloys (both wrought and cast) can be divided into two groups . . . heat-treatable alloys and non-heat-treatable alloys.

**Heat-Treatable Alloys:** Wrought alloys in the heat-treatable group include 2011, 2014, 2017, 2018, 2218, 2024, Alclad 2024, 2025, 4032, 6151, 6061, 6063, and 7075. Casting alloys in the heat-treatable group include 122, A132, D132, 142, 195, B195, 319, 333, 355, and 356. These alloys contain elements, groups of elements, or constituents that have considerable solid solubility at elevated temperatures and limited solubility at lower temperatures . . . the principal characteristic that makes an alloy heat-treatable. Note this group includes the high copper-bearing alloys 2014, 2017, 2024, and 2025; the magnesium silicide alloys 6151, 6061, and the high zinc-bearing alloy 7075.

Strength of these alloys is increased primarily by heat treatment. The complete process consists of two parts: First, a high temperature solution heat treatment followed by a drastic quench in a cooling medium; and second, a precipitation or aging treatment at room or slightly elevated temperatures.

These alloys are strengthened principally by thermal treatments, supplemented by plastic deformation in special cases. Annealed material is designated as "—O" temper. Immediately after solution heat treatment, the material is in the "—FQ" temper or freshly quenched condition.

The alloys 2017 and 2024 are known as natural aging alloys since they will precipitation harden at room temperature. The alloys that require an artificial aging treatment will also age a limited amount at room temperature, the degree of hardening being dependent upon the alloy. Those alloys that attain full strength and hardness after natural aging are given the "—T4" temper designation, (or "—T3" if sufficient cold work has been done on the "—T4" material to improve mechanical properties). Material artificially aged (by thermal treatment) is designated "—T6" temper. Additional stabilizing thermal treatment and/or cold work is indicated by tempers "—T7" through "—T9".

Material that has received no thermal treatment after the final plastic deformation operations is referred to as being in the "as fabricated" or "—F" temper.

**Clad Aluminum Alloys** are produced by bonding a layer of one alloy to one or both sides of a core of a different alloy. The resulting composite material has special desirable combinations of characteristics. Alclad sheet and plate are products of this type. High-purity aluminum may be used for cladding to provide high resistance to corrosion.

Special clad products are made for such purposes as maximum reflectivity (Reflector Sheet), ease of brazing (Brazing Sheet) and the like.

**Non-Heat-Treatable Alloys:** Strength of these alloys depends on the amount of cold work introduced after the last annealing operation. Properties so obtained are destroyed by subsequent heating and cannot be restored except by additional cold work. Six tempers are supplied, ranging from the soft or annealed temper designated by the symbol "—O", to the extra-hard temper designated as "—H19" in 1100 and 3003, and "—H39" in 5052 alloy.

In addition, there is the "as fabricated" or "—F" temper. The "—F" temper is produced by a variable amount of strain-hardening; usually heavy sections are almost in the annealed temper, while thin sections may have properties approximating those of the "—H14" (half-hard) temper. If definite mechanical properties are required, the "—F" temper should not be specified. Commodities in the "as fabricated" condition show reasonable uniformity of properties, but these properties are not guaranteed.

## ANNEALING

**Reasons for Annealing:** Many fabricating procedures for the wrought aluminum alloys incorporate an annealing treatment. The anneal may be required to remove the effects of plastic deformation or to soften solution-heat-treated-and-aged material. The practices used for each of these types of material are different but their purposes are identical — to obtain material of optimum workability. See Table 1, Page 29 for recommended cycles.

Thus, when repeated cycles of cold working cause so much hardening that further reductions are difficult, annealing is employed to soften the material and permit further working . . . also when a sheet product with maximum drawability is desired, it is annealed after the final rolling operation.

**Requirements:** To obtain annealed material with optimum workability, the following requirements should be met:

- complete recrystallization
- equiaxed grains of optimum size
- random orientation of slip planes
- low degrees of solid solution
- uniform distribution of insoluble and precipitated particles
- optimum size of soluble and precipitated particles

It should be realized that these are ideal requirements that are seldom completely fulfilled in actual practice. However, they are the basis upon which annealing practices are set up. Any change from the basic annealing practices should always take these points under consideration.

### Mechanics of Annealing

**Recovery:** Recovery takes place during the initial stages of the annealing process. During this period some of the internal stresses are relieved with a recovery of part of the ductility lost through cold work.

**Recrystallization:** As the annealing process continues, the temperature becomes sufficiently high to permit fragments of the original grains to recrystallize or form new unstrained grains. This, of course, will take place only if sufficient cold work is present in the material.

**Grain Growth:** After recrystallization, the new grains are subject to growth, due to the tendency of the grains to revert to their lowest energy form. In most cases, the final grain size of annealed material is not substantially affected by grain growth after recrystallization. A notable exception is high-purity aluminum. There is no definite breaking point between the periods of recovery, recrystallization, and grain growth. It is known that the recovery period comes first and that grain growth must, of necessity, follow recrystallization. Since the recrystallization process is a time-temperature-stress reaction, it is entirely probable that recovery, recrystallization and grain growth are occurring simultaneously in various parts of the material.

**Effect of Soluble Constituents:** Basically, the mechanics of annealing cold-work alloys are the same for all the aluminum alloys. The addition of the elements used to produce the heat-treatable class of alloys makes it necessary to modify the practices used with these alloys. The heat-treatable alloys contain elements that possess considerable solid solubility at high temperatures and restricted solubility at lower temperatures. See the chapter on Heat Treating, Page 20. The annealing practices, therefore, must be such that the effects of cold work are removed without obtaining a solution-heat-treating effect.

**Effect of Previous Heat Treatment:** The annealing of solution heat-treated-and-aged material requires additional modification of practices because the finely dispersed precipitate must be coalesced by using a higher than normal temperature. However, solution of the precipitate is also occurring at this temperature. Therefore, a slow cool is required after coalescence to allow the dissolved constituents to re-precipitate.

### Annealing Practices

**Methods of Annealing:** There are three types of anneals that are extensively used with the aluminum alloys; namely, horizontal bulk anneal, vertical anneal and flash anneal.

The horizontal bulk anneal is generally used when the heating rate is not critical. With this process, the material can be stacked to a depth of several inches.

The vertical anneal can be used when a fast heating rate is required. Here the material is spaced vertically in the furnace in such a manner that fast but uniform heating is obtained.

The horizontal flash anneal is ideal for small, comparatively thin gauge parts that require a fast heating rate. With this method, the material is carried through the furnace on a continuously moving conveyor. The time

of the anneal is controlled by the speed of the conveyor, the length of the furnace, and the temperature of the furnace atmosphere.

The practices given in the succeeding paragraphs are based on horizontal bulk annealing processes. If other types of annealing are to be employed, the practices should be changed accordingly.

#### **Non-Heat-Treatable Alloys**

The non-heat-treatable alloys, such as high-purity aluminum, 1100, 3003, 5052, and 5056, are annealed to remove the effects of strain hardening produced by cold work.

A 1-hour "soak" at a metal temperature of  $650^{\circ}\text{F} \pm 15^{\circ}\text{F}$ , is satisfactory for all of these alloys except 3003. A temperature of  $750^{\circ}\text{F}$  must be used for 3003 because of its higher recrystallization temperature and to insure a faster heating rate through the critical nucleation period.

**Heating Rate:** The heating rate is critical for alloy 3003, a relatively fast rate being required to produce a fine grain material. The heating rate for the other non-heat-treatable alloys is not too important for general applications.

**Temperature:** The upper temperature limit for this class of alloys, with the exception of high-purity aluminum and 5052, is not critical. The higher temperatures promote discoloration and increase the thickness of the oxide film on 5052 which contains an appreciable amount of magnesium. Because of this, the maximum temperature employed for 5052 is  $700^{\circ}\text{F}$ , when maximum drawability is desired. Optimum is  $650^{\circ}\text{F}$ .

**Time at Temperature:** The time at temperature will vary depending upon the temperature, the type of anneal, the thickness of the material, the method of loading and similar factors. Generally, the soaking period will vary from  $\frac{1}{2}$  to 2 hours. A 1-hour soak is widely employed.

The most satisfactory ways of determining the best soaking time are by furnace temperature surveys and by actual trial. One point that should not be overlooked when establishing minimum soaking times is that the mechanical properties may vary widely throughout a load if a critical time is employed. This may be disadvantageous for mass production operations.

**Rate of Cooling:** The rate of cooling is not an important factor although a rapid quench is definitely not recommended due to the quenching strains set up. Air cooling will generally be found entirely satisfactory.

#### **Heat-Treatable Alloys**

The heat-treatable alloys are annealed to remove the effects of strain hardening produced by plastic deformation or to remove the effects of solution heat treatment.

To remove strain hardening due to cold work, a 1-hour soak at  $640\text{--}660^{\circ}\text{F}$  followed by air cooling is generally satisfactory. This practice is also satisfactory to remove the effects of heat treatment if the maximum degree of softness is not required.

To remove the effects of partial or full heat treatment, a 2-hour soak at  $750\text{--}800^{\circ}\text{F}$ , followed by a maximum cooling rate of  $50^{\circ}\text{F}$  per hour to

500°F, is required to obtain maximum softness. However, it should be kept in mind that the use of high annealing temperatures adversely affects the drawability of the material. Diffusion of copper and other soluble constituents may also be excessive in clad material.

To remove the effects of solution heat treatment or hardening due to cold work, the high zinc-bearing alloy 7075 should be soaked 2 hours at 775°F, air cooled to 450°F, and soaked 6 hours at 450°F. The stabilizing treatment at 450°F is necessary to precipitate the soluble constituents from solid solution.

The annealing of solution-heat-treated material should be avoided whenever possible if subsequent forming and drawing operations are to be performed. If such operations are not severe, it is generally advantageous to repeat the solution heat treatment and form the material in the freshly quenched condition.

**Heating Rate:** A moderately fast heating rate, while not essential, is desirable. If slow heating rates are employed, diffusion of copper and other soluble constituents may be excessive in clad products. There may also be a slight tendency to produce a coarse grain size.

**Temperature:** The use of temperatures in excess of those recommended should be avoided.

**Time at Temperature:** The time at temperature will vary depending upon the temperature, the type of anneal, the material, and similar factors. Excessive time at temperature promotes grain growth, diffusion and discoloration.

**Cooling Rate:** The cooling rate is important only if the annealing practices cause part of the soluble constituents to go into solution. When this occurs, the rate of cooling must be controlled to permit their reprecipitation and coalescence.

The use of a cooling rate, sufficiently low to allow precipitation from a solid solution, (resulting from excessively high temperatures) results — with most heat-treatable alloys — in preferential precipitation and coalescence of plate-like particles at and between the grain boundaries. When this condition exists, the forming characteristics of the material are seriously impaired, although the mechanical properties may be only slightly affected.

**Poor Drawing Properties** — in conjunction with normal annealed mechanical properties. The condition is generally due to the shape and distribution of the coalesced precipitate and is caused by the use of too high an annealing temperature. The condition is always present when solution-heat-treated material is annealed. Poor drawing properties also result from improper blank size, incorrect hold-down pressure, insufficient lubrication, and incorrect degree of drawing.

**Discoloration:** Localized spots are generally oil or water stains. The use of a higher annealing temperature in the presence of air will generally remove oil stains. Severe darkening of the entire surface is an indication of an excessively high temperature or too long a soak at a high temperature. The alloy 5052 is particularly susceptible to discoloration at high temperatures.

## STABILIZING

Stabilizing is a process applied only to the non-heat-treatable aluminum-magnesium alloys (3004, 5050, 5052, and 5056) in the cold-worked tempers. This group has the greatest strengths and hardnesses of all the non-heat-treatable alloys due to the higher internal stresses developed by the cold-working processes.

In turn, this extremely high degree of internal stress results in an unstable condition. So the aluminum-magnesium alloys in the cold-work tempers have a tendency to soften and lose some of their strength after extended periods at room temperature, because of partial relieving of the internal stresses.

Such an uncontrolled change of properties often is undesirable, particularly where other fabricating operations are to be performed on the material.

However, a low-temperature short-cycle heat treatment will convert the stock to a stable condition. This stabilized temper will exhibit mechanical properties somewhat below maximum but there will be no further change even upon extended periods of storage.

This treatment is known as "stabilizing". The temperature used is about 350°F. The stabilizing treatment is always applied by the prime producer of the wrought product.

## SOLUTION HEAT TREATMENT

There are certain types of heat treatments which are applied to both wrought and cast products. These are "solution" heat treatment and "precipitation" heat treatment. The first is detailed below; the second on Page 23.

**Difference Between Annealing and Solution Heat Treatment:** The solution heat treatment of an alloy is different from annealing in several ways. The processes of recovery, recrystallization and grain growth are similar in both treatments. However, when annealing, the temperature is such that the precipitate of soluble constituents is coalesced or allowed to grow into coarse particles so that they will have less effect in restricting deformation. *During solution heat treating, the soluble constituents are actually dissolved in the aluminum.*

**Basis for Selecting Temperature:** The relatively large amounts of the soluble elements added to some of the alloys make the temperature necessary for solution heat treatment so high that it is near the melting point of the lower melting constituents present. With these alloys, overheating by only a few degrees will cause incipient melting. Once this occurs, the metal must be remelted and reprocessed.

Several of the alloys, particularly those strengthened principally by the constituent  $Mg_2Si$  (6061), can be solution heat treated at temperatures in excess of those recommended without encountering melting. The use of such temperatures, however, increases the degree of warping and promotes the formation of a heavy oxide film. With some of the high zinc-

bearing alloys, the susceptibility to stress corrosion cracking is increased by the use of high temperatures.

After solution of the soluble constituents is substantially complete, the material must be rapidly quenched to prevent their immediate re-precipitation. If excessive re-precipitation occurs during the solution heat-treatment operation, the size and distribution of the particles are such that little strengthening is accomplished. In addition, the precipitate is formed along the grain boundaries and certain slip planes, causing a serious decrease in the resistance to corrosion of many of the alloys.

### Mechanics

**Operations in Hardening by Heat Treatment:** The hardening of an aluminum alloy by heat treatment consists of four distinct steps:

- heating to a predetermined temperature
- soaking at temperature for a specified length of time
- rapidly quenching to a relatively low temperature
- aging or precipitation hardening either spontaneously at room temperature or as a result of a low temperature thermal treatment.

The first three steps above are known as "solution heat treatment", although it has become common practice to use the shorter term "heat treatment". Room temperature hardening is known as "natural aging" while a hardening done at moderate temperatures is called "artificial aging", or "precipitation" thermal treatment.

**Production of "W" Temper:** The alloys that require precipitation thermal treatment (artificial aging) to develop their full strength also age to a limited extent at room temperature, the rate and amount of strengthening depending upon the alloy. Some reach their maximum natural or room-temperature aging strength in a few days, and are designated as "—T4" or "—T3" temper. Others continue to age appreciably over a long period of time.

Because of this natural aging, the "—W" designation is specific only when the period of aging is indicated, e.g., 7075-W (½ hr.).

Thus, there is considerable difference in the mechanical and physical properties of freshly quenched ("—W") material and material that is in the "—T3" or "—T4" temper. The fact that material in the "—T3" or "—T4" temper is already in a partially aged condition should always be kept in mind.

### Practices

**Temperature:** The temperatures used for solution heat treating vary with different alloys, ranging from 825 to 980° F. They must be controlled within a very narrow range ( $\pm 10^\circ\text{F.}$ ) to obtain specified properties.

If the temperature is too low, maximum strength will not be obtained. When excessive temperatures are used, there is danger of melting the low-melting constituents of some alloys. Even if melting does not occur, the use of higher-than-recommended temperatures promotes discoloration and increases quenching strains.

**Time at Temperature:** The time at temperature, referred to as soaking time, is measured from the time the coldest metal reaches the minimum

limit of the desired temperature range. The soaking period varies, depending upon the alloy and thickness, from 10 minutes for thin sheet to approximately 12 hours for heavy forgings. For the heavy sections, the nominal soaking time is approximately one hour for each inch of cross-sectional thickness.

The soaking time is so chosen as to put substantially all of the soluble elements into solid solution. The effect of an abbreviated soaking period is obvious. An excessive soaking period aggravates high temperature oxidation if conditions conducive to its inception are prevalent. With clad material, prolonged heating results in excessive diffusion of copper and other soluble constituents into the protective cladding and may defeat the purpose of the cladding.

**Heating Rate:** If cold-work is present in the material, the heating rate should be reasonably fast to prevent the formation of coarse grains. Generally no grain size difficulty will be encountered unless a critical amount of cold-work is present.

**Quenching:** After the soluble constituents are in solid solution, the material is quenched to prevent or retard immediate re-precipitation. Three distinct quenching methods are employed. The one to be used in any particular instance depends upon the commodity, the alloy, and the properties desired.

**Cold Water Quenching:** Parts and articles produced from sheet, extrusions, tubing, small forgings and similar type material are generally quenched in a cold water bath. The temperature of the water, before quenching, should not be in excess of 85°F. A sufficient volume of water should be used to keep the temperature rise under 20°F. Such a drastic quench insures maximum resistance to corrosion, particularly important when working with such alloys as 2017 and 2024. This is the reason a drastic quench is preferred, even though a slower quench may produce the required mechanical properties.

**Hot Water Quenching:** Large forgings and heavy sections can be quenched in hot (150-180°F), or boiling water. This type of quench minimizes distortion and alleviates cracking which may be produced by the unequal temperatures obtained during the quench. The use of such a quench is permitted with these classes of material because the temperature of the quench water does not critically affect the resistance to corrosion of the forging alloys. In addition, the resistance to corrosion of heavy sections is not as critical a factor as for thin sections.

**Spray Quenching:** High velocity water sprays are useful for parts formed from clad sheet and for large sections of almost all alloys. This type of quench also minimizes distortion and alleviates quench cracking. However, many specifications forbid the use of spray quenching for bare 2017 and 2024 sheet due to its effect on their resistance to corrosion.

Nevertheless, the resistance to corrosion of spray quenched Alclad 2024 is superior to cold-water-bath-quenched unprotected 2024 because of the galvanic protection by the cladding.

**Lag Between Soaking and Quenching:** The time interval between the removal of the material from the furnace and quenching is critical for some alloys and should be held to a minimum. When solution heat treat-

ing 2017 and 2024 sheet material, the elapsed time must not exceed 10 seconds. The allowable time interval for heavy sections may be slightly greater.

Allowing the metal to cool slightly before quenching promotes re-precipitation from the solid solution. The precipitation occurs along grain boundaries and in certain slip planes causing poorer formability and, in the case of 2017 and 2024, adversely affecting their resistance to intergranular corrosion. The strengths and hardness of most alloys are not seriously affected unless the precipitation is severe.

**Re-Solution Heat Treatment:** The bare heat-treatable alloys can be solution heat treated repeatedly without harmful effects. However, it is advisable to use either sodium or potassium fluoborate during the heating cycle as a protection against possible high temperature oxidation.

The number of solution heat treatments allowed for clad sheet is limited due to increased diffusion of core and cladding with each re-heating. Existing specifications allow one to three re-heat-treatments of clad sheet, depending upon cladding thickness.

**Straightening After Solution Heat Treatment:** Some warping occurs during solution heat treatment, producing kinks, buckles, waves, and twists. These imperfections are generally removed by straightening and flattening operations, or, in the case of formed parts, by restriking.

Where the straightening operations produce an appreciable increase in the tensile and yield strengths and a slight decrease in the percent elongation, the material is designated "—T3" temper. When the above values are not materially affected, the material is designated "—T4" temper.

**"—T4" Temper:** For certain forming operations, sheet material of naturally aged alloys is sometimes furnished in the "—T4" temper. This material is superior in ductility to normal "—T3" material because final flattening operations have been held to a minimum.

## AGING OR PRECIPITATION HARDENING

**Basic Principles:** As previously stated, the aluminum alloys are in a comparatively soft state immediately after quenching from a solution-heat-treating temperature. To obtain their maximum strengths, they must be "aged" or "precipitation hardened".

During this hardening and strengthening operation, precipitation of the soluble constituents from the supersaturated solid solution takes place. As precipitation progresses, the strength of the material increases, often by a series of peaks, until a maximum is reached. Further aging (overaging) causes the strength to steadily decline until a somewhat stable condition is obtained. The submicroscopic particles that are precipitated provide the keys or locks within the grain structure and between the grains to resist internal slippage and distortion when a load of any type is applied. In this manner, the strength and hardness of the alloy are increased.

Precipitation hardening produces a large increase in the strength and hardness of the material with corresponding decreases in the ductile

properties. The process used to obtain the desired increase in strength is therefore known as aging or precipitation hardening.

The strengthening of the heat-treatable alloys by aging is not due merely to the presence of a precipitate. Instead, it is due to both the uniform distribution of a finely dispersed submicroscopic precipitate and the distortion and other effects of its formation upon the crystal structure.

The aging practices used depend upon many properties other than strength. As a rule, the artificially aged alloys are slightly "over-aged" to increase their resistance to corrosion. This is especially true with the artificially aged, high-copper-bearing alloys that are susceptible to intergranular corrosion when inadequately aged.

The heat-treatable aluminum alloys are subdivided into two classes—those that obtain their full strength at room temperature and those that require artificial aging. The alloys that obtain their full strength after 4 or 5 days at room temperature are known as "natural aging" alloys. Precipitation from the supersaturated solid solution starts soon after quenching, with 90 percent of the maximum strength generally being obtained in 24 hours.

The alloys that require precipitation thermal treatment to develop their full strength are "artificially aged" alloys. However, these alloys also age a limited amount at room temperature, the rate and extent of the strengthening depending upon the alloy.

Many of the artificially aged alloys reach their maximum natural or room temperature aging strengths after a few days. These can be stocked for fabrication in the "—T4" or "—T3" temper. Others (e.g. some of the high zinc-bearing alloys) continue to age appreciably over a long period of time, their mechanical property changes being sufficient to cause their formability to continue to be reduced. The advantage of "W" temper formability can be utilized, however, in the same manner as with natural aging alloys, and that is by fabricating shortly after solution heat treatment, or retaining formability by the use of refrigeration.

Refrigeration retards the rate of natural aging. At 32°F, the beginning of the aging process is delayed for several hours, while dry ice (—50 to —100°F) retards aging for an extended period of time.

The strengths of the natural aging alloys can be increased by subjecting the naturally aged material to a precipitation thermal treatment. Although a considerable decrease in the percent elongation is obtained, it is not considered detrimental for many applications.

The presence of small amounts of cold work, subsequent to natural aging but prior to artificial aging, has a pronounced effect on the strength of 2024. The increase in strength realized by this method is dependent upon the degree of cold work present.

Artificially aging the natural aging alloys increases the susceptibility of the material to intergranular corrosion. For this reason, the process is generally confined to clad sheet, extrusions and similar products.

### Mechanics

The natural aging alloys 2017 and 2024 require only exposure at room temperature for several days to develop their full strength. The other commercial heat-treatable alloys require a controlled precipitation thermal treatment to develop their full strength.

The degree of strengthening of a properly solution heat-treated alloy by precipitation or aging depends upon both time and temperature. An increase in temperature decreases the time necessary to obtain maximum hardening. Thus, there may be several aging practices applicable to an alloy. See Table 2, Page 30.

The use of higher temperatures and shorter times generally produces lower elongations and higher yield strengths, whereas the lower temperature procedures give higher elongations with slightly lower yield strengths.

The elapsed time between quenching from solution-heat-treating temperature and artificially aging has an effect on the mechanical properties obtained but is, at present, commercially important only with the high zinc-bearing alloys such as 7075. This alloy requires an incubation period of a least 24 hours at room temperature prior to the precipitation thermal treatment to obtain the desired mechanical properties.

### Precipitation Practices

The temperatures used for precipitation hardening depend upon the alloy and the properties desired, ranging from 240 to 460°F. They should be controlled within a very narrow range ( $\pm 5^\circ\text{F}$ ) to obtain best results. See Table 2, Page 30.

The time at temperature (soaking time) is dependent upon the temperature used, the alloy and the properties desired. It ranges from 6 to 24 hours. Increasing the aging temperature decreases the soaking period necessary for proper aging. However, a closer control of both time and temperature is necessary when using the higher temperatures.

The rate of heating is not critical, but the material should be placed in the furnace in such a manner that a large temperature differential between various parts of the load will not exist for an extended period of time. If this occurs, part of the material will receive an incorrect aging treatment.

After receiving the precipitation thermal treatment the material should preferably be air cooled to room temperature. Water quenching, while not necessary, produces no deleterious effects. Furnace cooling has a tendency to produce overaging.

## HEAT TREATING CAST PRODUCTS

As previously pointed out, the theory and principles involved in the heat treatment of the aluminum casting alloys are similar to those for the wrought alloys. That is, by controlled rearrangement of the main alloy constituents through thermal treatment, the mechanical properties or other characteristics of certain alloys can be enhanced.

However, in some instances, notably "Annealing", the terms as applied to castings do not imply the same treatment as used for wrought alloys. The designations applicable to the heat treatment of cast aluminum alloys are as follows:

- T2, Annealed. (Cast or Wrought Products)
- T4, Solution Heat Treated. (Cast or Wrought Products)
- T5, Artificially Aged. (Cast or Wrought Products)
- T6, Solution Heat Treated and then Artificially Aged  
(Cast or Wrought Products)
- T7, Solution Heat Treated and then Stabilized (Over-aged)  
(Cast Products Only)

### Solution Heat Treatment

Solution-heat-treating temperatures and time at temperature for the heat-treatable aluminum casting alloys are given in Tables 3 and 4, Pages 31 and 32.

Steel baskets or racks, which allow free circulation of the air during heat treatment and of water during quenching, should be used in the solution heat treatment of aluminum castings. Proper packing of the castings in these baskets is most important. There should be sufficient space between castings to insure free circulation and to minimize distortion.

Owing to their relatively low strength at elevated temperatures, aluminum castings distort rather easily if crowded or jammed together during solution heat treatment. In fact, it may often be necessary to support intricate castings on special fixtures to prevent distortion.

Under normal operating conditions, the usual practice is to charge the load into a furnace operating at the specified temperature. However, the load can be charged into a cold furnace and then be brought up to the soaking temperature. In either case, the soaking period at the solution heat treatment temperature should be as specified in Tables 3 and 4.

Different alloys may be heat treated together in the same load if their heat treatment temperatures are similar. Soaking for periods longer than those specified has no detrimental effects on the castings. Therefore, if different alloys are treated together, the soaking time should be governed by the alloy requiring the longest period.

At the completion of the soaking period, the castings are rapidly quenched from the solution temperature. Drastic quenching tends to set up stresses which will often result in distortion, especially if the castings are intricately designed. To avoid quench stresses and distortion, boiling water is generally used as the quenching medium. In certain instances, quenching in still air (—T77 type treatment) or moving air is employed.

Quenching should be performed as quickly as possible, with a minimum delay in transferring the load from the furnace to the quench tank. In actual practice, transfer intervals of one minute or less should be attained. Immediately after quenching, the alloys have increased ductility, so that warped or distorted castings may be straightened easily. Since as-quenched castings begin to age even at room temperatures, the straightening operation should be performed as soon as possible after quenching.

#### **Artificial Aging or Precipitation Heat Treatment**

With the casting alloys, "Artificial Aging" (sometimes termed "Precipitation Heat Treatment") may be used for several different purposes. Aging treatment may be applied to castings in the as-cast or solution-heat-treated conditions to improve the mechanical properties, or it may be employed to stabilize solution-heat-treated castings. In either case, changes in the properties result from controlled precipitation of constituents from solid solution.

**Mechanical Properties:** Artificial aging treatment, temperatures and times are listed in Tables 3 and 4, Pages 31 and 32. It should be understood that aging treatment varies with different alloys, depending on the properties required. For instance, strength and hardness are only increased at the expense of the ductility of the alloy.

The extent to which these properties are changed depends both upon the aging temperature and the duration of the aging period. The treatments outlined in Tables 3 and 4 for the different alloys produce mechanical properties typical of those usually specified. By the selection of other suitable aging periods and temperatures, various combinations of these mechanical properties may be attained. However, before any non-standard treatments are attempted, preliminary tests should be performed on the alloy in question to determine the proper time and temperature.

Castings in the solution-heat-treated condition can be artificially aged to produce tensile strengths and hardnesses in excess of those obtained by solution heat treatment alone (—T6 type treatment). If the desired properties are lower than those produced by solution heat treatment, the castings can be aged directly from the as-cast condition without the benefit of previous solution heat treatment. Moderately increased hardness and tensile strength are realized with this —T75 type treatment, along with a slight reduction in ductility.

#### **Stabilization by Artificial Aging**

Certain cast aluminum alloys in the solution-heat-treated condition have a definite tendency to "grow" when subjected to elevated temperatures. This growth causes permanent dimensional changes in the castings after they are cooled to normal temperatures. With proper aging treatment (designated as —T7 type treatment), growth can be minimized. This treatment accelerates the growth process and brings it to completion, thereby stabilizing the casting and eliminating the possibility of further dimensional changes at elevated temperatures.

Temperatures involved in the —T7 type treatment are higher than those employed for normal aging operations. Owing to these increased tem-

peratures, the castings are aged beyond the point required for maximum mechanical properties. For this reason, the process is often termed "over-aging". Over-aging for stabilization also reduces residual quench stresses in the castings. However, the resulting tensile strengths and hardnesses are usually lower than for normal aging treatments.

#### **General Precautions and Recommendations**

Castings can be artificially aged in baskets similar to those used in solution heat treatment. At the relatively low temperatures employed in aging treatments, distortion is practically negligible. Therefore, castings may be stacked higher than for solution heat treatment. But when packing, adequate space should be left between the castings to insure free circulation of air during the aging treatment.

As in the case of solution heat treatment, castings of different alloys which have the same aging temperatures may be treated together. But the various alloys must be removed from the furnace at the completion of their correct aging period. Castings which have not received sufficient treatment may be returned to the furnace for further aging. Except where required (—T7 type treatment), over-aging should be avoided. If over-aging does occur, material may be recovered by repeating the solution heat treatment and then aging again at the correct temperature and time.

#### **Annealing or Stress Relieving**

Castings in the as-cast condition are annealed to relieve internal stresses and reduce growth. Although annealing does not generally produce any extensive changes in mechanical properties, certain alloys may show slightly reduced tensile strength, while the ductility may increase.

The usual annealing treatment consists of heating the material at a temperature of 650° F for about 2 hours. However, another less common method of annealing involves heating the castings up to their solution temperature for a short period, followed by furnace cooling to room temperature.

#### **Heat Treatment of Die Castings**

In contrast to other casting processes, die castings solidify so rapidly that they are practically in the as-quenched condition when removed from the die. Therefore, the usual thermal treatments will not appreciably change their mechanical properties. However, die castings are occasionally heat treated for stress relief or to obtain increased ductility. If extremely close machining tolerances are required, the material is stress relieved by heating to temperatures between 350 and 500°F for periods of 4 to 6 hours, followed by cooling in still air. Although the ductility may be slightly decreased by this treatment, it eliminates residual stresses, which could cause distortion when the part is machined.

Treatments for increasing the ductility consist of heating the die casting to temperatures between 500 and 700°F for periods of 4 to 6 hours and then cooling in the furnace or still air.

**Table 1.**  
**TYPICAL ANNEALING CYCLES FOR WROUGHT ALUMINUM ALLOYS**

ALLOY	To Soften After Heat Treatment (1)			To Remove Cold Work		
	Soaking Temperature °F	Soaking Time Hours	Cooling Rate (2)	Soaking Temperature °F	Soaking Time Hours	Cooling Rate (2)
EC	...	(3)	...	650	1/2 - 2	A
1100	...	(3)	...	650	1/2 - 2	A
2011	775	2-3	C	650	2	B
2014	775	2-3	C	650	2	B
2017	775	2-3	C	650	2	B
2018	775	2-3	C	650	2	B
2024	775	2-3	C	650	2	B
2025	775	2-3	C	650	2	B
2117	775	2-3	C	650	2	B
2218	775	2-3	C	650	2	B
3003	...	(3)	...	775	2	A
3004	...	(3)	...	650	2	A
4032	775	2-3	C	650	2	B
4043	...	(3)	...	650	2	A
5005	...	(3)	...	650	2	A
5050	...	(3)	...	650	2	A
5052	...	(3)	...	650	2	A
5056	...	(3)	...	650	2	A
5083	...	(3)	...	775	2	A
5086	...	(3)	...	650	2	A
5154	...	(3)	...	650	2	A
5357	...	(3)	...	650	2	A
5454	...	(3)	...	750	2	A
5456	...	(3)	...	775	2	A
6053	775	2-3	C	650	2	B
6061	775	2-3	C	650	2	B
6062	775	2-3	C	650	2	B
6063	775	2	C	650	2	B
6066	775	2-3	C	650	2	B
6151	775	2-3	C	650	2	B
6951	775	2-3	C	650	2	B
7001	775	2-3	D	650	2	D
7072	...	(3)	...	650	2 - 3	A
7075	800	2-3	D	775	2	D
7079	775	2-3	C	650	2	B
7178	775	2-3	C	650	2	B

- (1) Maximum formability can be obtained only by mechanical working and subsequent re-annealing.
- (2) Annealing cooling rates:
- A. Rate of cooling is unimportant.
  - B. Air cool.
  - C. Furnace cool at a rate not to exceed 50°F per hour to 500°F then air cool.
  - D. Air cool to 450°F, soak 6 hours at 450° F, air cool to room temperature.
- (3) Alloy not susceptible to heat treatment.

**Table 2. — TYPICAL HEAT TREATMENTS  
FOR THE WROUGHT ALUMINUM ALLOYS**

ALLOY	SOLUTION HEAT TREATMENT (1) (2)		PRECIPITATION HEAT TREATMENT		
	Metal Temperature Deg. F (3)	Temper Designation (4)	Metal Temperature Deg. F (3)	Approx. Time of Heating Hours (5)	Temper Designation (4)
2011	950	—T4	320	12-16	—T6
2014(6)	940	—T4(11)	340	8-12	—T6(7)
2017	940	—T4	...	...	...
2018	950	—T4	340	8-12	—T61
2024(6)	920	—T4(11)	{ 375(8)	11-13(12)	{ —T81
			{ 375(8)	7-9	{ —T84 —T86
2025	960	—T4	340	8-12	—T6
2117	940	—T4	...	...	...
2218	950	—T4	460	5-8	—T72
4032	950	—T4	340	8-12	—T6
6053	970	—T4	350	6-8	—T6
			450	1-2	—T5
6061	970	—T4	{ 320	16-20	{ —T6
			{ 350	6-10	
6062	970	—T4	{ 320	16-20	{ —T6
			{ 350	6-10	
6063	...	....	{ 450	1-2	{ —T5
			{ 365	4-6	
			{ 350	6-8	
6066	970	—T4	{ 320	16-20	{ —T6
			{ 350	6-10	
6101	...	....	350	6-8	—T6
6151	960	—T4	340	8-12	—T6
6959	895	—W	250	24-28	—T6
7001	870(9)	—W	250(10)	24-28	—T6
7075(6)	870(9)	—W	250(10)	24-28	—T6
7079	830	—W	240	46-50	—T6
7178	895	—W	280	24-28	—T6
7277	890	—W	(13)	(13)	—T6

(1) The time of heating varies with the product, the type of furnace and the size of load. For sheet heat treated in a bath of molten salt, the time may range from 10 minutes for thin material to 60 minutes for thick material. Time of several hours may be required in air furnaces because the metal comes to temperature less rapidly. A minimum of 4 hours is suggested for average forgings. When heat treating in air furnaces, it may be desirable to use a protective compound to prevent oxidation along the grain boundaries in certain alloys.

(2) The material should be quenched from the solution-heat-treating temperature as rapidly as possible and with a minimum delay after removal from the furnace. Quenching in cold water is preferred although less drastic chilling (hot or boiling water, air blast) is sometimes employed for bulky sections, such as forgings, to minimize quenching stresses.

(3) The temperature specified should be attained by all portions of the load as rapidly as possible and should be maintained, with as little variation as possible, during the recommended time at temperature. Furnaces capable of maintaining the temperature well within plus or minus 10°F of that desired are readily available.

(4) These designations apply to material which has been heat treated by the user. (See Notes 7 and 11 for exceptions). A different designation may apply to material heat treated by the producer.

(5) The rate of cooling from the precipitation heat treatment is unimportant but should not be unduly slow. (Concluded next page)

**Table 3. — TYPICAL HEAT TREATMENTS  
FOR ALUMINUM PERMANENT-MOLD CASTINGS**

ALLOY AND HEAT TREATMENT	SOLUTION HEAT TREATMENT			ARTIFICIAL AGING TREATMENT	
	Time Hours (1)	Temp. ° F (2)	Quench (3)	Time Hours (4)	Temp. ° F (2)
122—T4	12	945	Water	...	...
122—T52	...	...	...	5-7	310
122—T551	...	...	...	18-22	340
122—T65	12	945	Water	7-9	340
A132—T4	12	955	Water	...	...
A132—T551	...	...	...	14-18	325
A132—T65	12	955	Water	14-18	325
D132—T5	...	...	...	7-9	400
142—T4	6	965	Water	...	...
142—T571	...	...	...	22-26	340
142—T61	6	965	Water	3-5	400
B195—T4	8	950	Water	...	...
B195—T6	8	950	Water	5-7	310
B195—T7	8	950	Water	4-6	500
319—T6	8	940	Water	2-5	310
333—T5	...	...	...	7-9	400
333—T6	8	940	...	2-5	310
333—T7	8	940	...	4-6	500
355—T4	12	975	Water	...	...
355—T51	...	...	...	7-9	440
355—T6	12	975	Water	3-5	310
355—T62	12	975	Water	14-18	340
355—T7	12	975	Water	7-9	440
355—T71	12	975	Water	4-6	475
356—T4	12	995	Water	...	...
356—T6	12	995	Water	3-5	310
356—T7	12	995	Water	7-9	440

- (1) Soaking time periods, after load has reached specified temperature, required for average casting. Time can be decreased or may have to be increased, depending on particular castings, as demonstrated by experience.
- (2) Temperature setting for control instrument. Variation of temperature in furnace should not exceed plus or minus 10°F.
- (3) Water temperature from 150 to 212°F can be employed. Boiling water recommended since it minimizes quenching stresses and distortion.
- (4) Exact time required influenced by foundry variables. Select on basis of obtaining typical hardness values.

*(Concluded from previous page)*

- (6) Alclad sheet is heat treated under the same conditions as the core alloy but the shortest heat-treatment time consistent with reheat treatment should be avoided. Prolonged heating or repeated reheat treatments cause diffusion of alloying elements into the coating and impair the resistance to corrosion.
- (7) For plate and extrusions, the correct temper designation is —T62.
- (8) Cold-working subsequent to the solution heat treatment and prior to the precipitation treatment is necessary to secure the required properties.
- (9) Sheet may also be heat treated at higher temperatures (up to 925°F. if desired).
- (10) Two-stage treatments comprising 4 to 6 hours at 210°F. followed by 8 to 10 hours at 315°F. or 2 to 4 hours at 250°F. followed by 2½ to 3½ hours at 325°F. are recommended for sheet and cold drawn wire.
- (11) For plate and extrusions, the correct temper designation is —T42 when material is heat treated by the user.
- (12) For extrusions, a time of 6 hours should be used.
- (13) Two-stage treatment comprising 4 hours at 210°F, then 8 hours at 315°F.

**Table 4.—TYPICAL HEAT TREATMENTS  
FOR ALUMINUM SAND CASTINGS**

ALLOY AND HEAT TREATMENT	SOLUTION HEAT TREATMENT			ARTIFICIAL AGING TREATMENT	
	Time Hours (1)	Temp. ° F (2)	Quench (3)	Time Hours (4)	Temp. ° F (2)
112—T2	...	...	...	2-4	600
122—T4	12	945	Water	...	...
122—T61	12	945	Water	10-12	310
142—T21	...	...	...	2-4	650
142—T4	6	965	Water	...	...
142—T571	...	...	...	22-26	340
142—T77	6	965	Water	1-3	650
195—T4	12	955	Water	...	...
195—T6	12	955	Water	3-6	310
195—T62	12	955	Water	12-20	310
220—T4	18	810	Water	...	...
319—T4	12	935	Water	...	...
319—T6	12	935	Water	1-6	315
355—T4	12	975	Water	...	...
355—T51	...	...	...	7-9	440
355—T6	12	975	Water	3-5	310
355—T61	12	975	Water	8-10	310
355—T7	12	975	Water	3-5	440
355—T71	12	975	Water	4-6	475
356—T4	12	995	Water	...	...
356—T51	...	...	...	7-9	440
356—T6	12	995	Water	2-5	310
356—T7	12	995	Water	3-5	400
356—T71	12	995	Water	2-4	475
40E—T51	...	...	...	9-11	355

- (1) Soaking time periods, after load has reached specified temperature, required for average casting. Time can be decreased or may have to be increased, depending on particular castings, as demonstrated by experience.
- (2) Temperature setting for control instrument. Variation of temperature in furnace should not exceed plus or minus 10°F.
- (3) Water temperature from 150 to 212°F can be employed. Boiling water recommended since it minimizes quenching stresses and distortion.
- (4) Exact time required influenced by foundry variables. Select on basis of obtaining typical hardness values.

**Table 5.—ANNEALING & STRESS RELIEVING  
FOR SAND, PERMANENT-MOLD AND DIE CASTINGS**

TREATMENT	APPLICATION	PURPOSE	TEMP.°F.	TIME-HRS.	TYPE OF QUENCH
Annealing	Sand and P.M. castings	To stress relieve & reduce growth	700	2	Air cooled
Stress Relieving	Die castings	To reduce internal stresses	350-500	4-6	Cooled in still air
Annealing	Die castings	To increase ductility	500-700	4-6	Furnace cooled or cooled in still air

**Table 4.—TYPICAL HEAT TREATMENTS  
FOR ALUMINUM SAND CASTINGS**

ALLOY AND HEAT TREATMENT	SOLUTION HEAT TREATMENT			ARTIFICIAL AGING TREATMENT	
	Time Hours (1)	Temp. ° F (2)	Quench (3)	Time Hours (4)	Temp. ° F (2)
112—T2	...	...	...	2-4	600
122—T4	12	945	Water	...	...
122—T61	12	945	Water	10-12	310
142—T21	...	...	...	2-4	650
142—T4	6	965	Water	...	...
142—T571	...	...	...	22-26	340
142—T77	6	965	Water	1-3	650
195—T4	12	955	Water	...	...
195—T6	12	955	Water	3-6	310
195—T62	12	955	Water	12-20	310
220—T4	18	810	Water	...	...
319—T4	12	935	Water	...	...
319—T6	12	935	Water	1-6	315
355—T4	12	975	Water	...	...
355—T51	...	...	...	7-9	440
355—T6	12	975	Water	3-5	310
355—T61	12	975	Water	8-10	310
355—T7	12	975	Water	3-5	440
355—T71	12	975	Water	4-6	475
356—T4	12	995	Water	...	...
356—T51	...	...	...	7-9	440
356—T6	12	995	Water	2-5	310
356—T7	12	995	Water	3-5	400
356—T71	12	995	Water	2-4	475
40E—T51	...	...	...	9-11	355

- (1) Soaking time periods, after load has reached specified temperature, required for average casting. Time can be decreased or may have to be increased, depending on particular castings, as demonstrated by experience.
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FOR SAND, PERMANENT-MOLD AND DIE CASTINGS**

TREATMENT	APPLICATION	PURPOSE	TEMP.° F.	TIME-HRS.	TYPE OF QUENCH
Annealing	Sand and P.M. castings	To stress relieve & reduce growth	700	2	Air cooled
Stress Relieving	Die castings	To reduce internal stresses	350-500	4-6	Cooled in still air
Annealing	Die castings	To increase ductility	500-700	4-6	Furnace cooled or cooled in still air