HEAT TREATING ALUMINUM FOR AEROSPACE APPLICATIONS

It is of low weight. Its alloys can be heat treated to relatively high strengths. It is of reasonable cost, and it is easy to bend and machine. Because of these advantages, aluminum is the most common material used in aerospace today.

This article discusses typical applications of aluminum heat treating in the aerospace industry. An overview of the physical metallurgy of the various alloys is given, as is a description of common heat treating defects in aluminum. The benefits and advantages of polymer quenchants are also examined.

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In the aerospace industry, the most common aluminum alloys used are 7XXX wrought products. The thickness of parts used range from 0.6 mm to 250 mm. Aluminum alloy 7075, 7050 extrusions are used extensively for stringers, and other structural components. Some extrusions of 2024, and 2014 are used. Sheet, both clad and non-clad, of 2024, 7475 and 7075 is used for wing and fuselage skins. Sheet is also formed and built-up to use in bulkheads and other structural components. For heavy loading, large forgings of 7050 and 7040 are typical, particularly in military aircraft.

Aluminum Heat Treating

Aluminum Solution Heat Treating — Aluminum alloys are classified as either heat treatable or not heat treatable, depending on whether the alloy responds to precipitation hardening. In heat treatable alloy systems like 7XXX, 6XXX, and 2XXX, the alloying elements show greater solubility at elevated temperatures than at room temperature. This is illustrated for the Al-Cu phase diagram (Figure 1).

The Al-Cu phase diagram shows that holding a 4.5% alloy at 515 to 550°C will cause all the copper to go completely into solution. This is typically known as the "solution heat treating temperature.” If the alloy is slowly cooled, then the equilibrium structure of Al + CuAl2 will form. The CuAl2 that forms is large, coarse, and incoherent. However, if the alloy is cooled rapidly, there will be inadequate time for the CuAl2 to precipitate. All the solute is held in a supersaturated condition. Controlled precipitation of the solute in finely dispersed particles at room temperature (natural aging) or at elevated temperatures (artificial aging) is used to develop the optimized mechanical and corrosion properties of these alloys.

Solution heat treatment develops the maximum amount of solute into solid solution. This requires heating the material near the eutectic temperature and holding it there long enough to allow nearly complete solid solution. After solution heat treatment, the material is quenched to maintain the solute in supersaturated solid solution. Because the solution heat treatment temperature is so close to the eutectic melting temperature, temperature control is critical. This is especially true for 2XXX series alloys. In this alloy group, the initial eutectic melting temperature is only a few degrees above the maximum recommended solution heat treatment temperature.

Solution heat treating and quenching of these alloys is typically accomplished in large high temperature furnaces. Aluminum is also commonly heat treated in salts. In some applications, the furnace is supported above the quench tank, which moves under the furnace on rails. Sometimes there is more than one quench tank, each containing a different quenchant.

Quenching — An understanding of heterogeneous precipitation during quenching can be understood by nucleation theory applied to diffusion controlled solid-state reactions. The
kinetics of heterogeneous precipitation occurring during quenching depends on the degree of solute supersaturation and the diffusion rate, as a function of temperature. As an alloy is quenched, there is greater supersaturation (assuming no solute precipitates). But the diffusion rate increases as a function of temperature, become greatest at elevated temperatures. When either the supersaturation or the diffusion rate is low, the precipitation rate is low. At intermediate temperatures, the amount of supersaturation is relatively high, as is the diffusion rate. Therefore, the heterogeneous precipitation rate is greatest at intermediate temperatures. This is shown schematically in Figure 2. The amount of time spent in this critical temperature range is governed by the quench rate.

The amount of precipitation formed during quenching reduces the amount of subsequent possible hardening. This is because solute precipitated from solution during quenching is unavailable for any further precipitation reactions. This results in lower tensile strength, yield strength, ductility and fracture toughness.

Natural Aging — Some heat treatable alloys, especially 2XXX alloys, harden appreciably at room temperature to produce the useful tempers T3 and T4. Alloys that have been naturally aged to T3 or T4 tempers exhibit high ratios of ultimate tensile strength/yield strength. They also have excellent fatigue and fracture toughness properties.

Natural aging and the increase in properties occur by the rapid formation of GP (Guinier-Preston) Zones from the supersaturated solid solution and from quenched-in vacancies. Strength increases rapidly, with properties becoming stable after approximately 4-5 days. The T3 and T4 tempers are based on natural aging for 4 days. For 2XXX alloys, improvements in properties after 4-5 days are relatively minor, and become stable after one week.

The Al-Zn-Mg-Cu and Al-Mg-Cu alloys (7XXX & 6XXX) also harden by the mechanism of GP Zone formation. However, the properties from natural aging are less stable. These alloys still exhibit significant changes in properties even after many years.

Natural aging characteristics change from alloy to alloy. The most notable differences are the initial incubation time for changes in properties to be observed, and the rate of change in properties. Aging effects are suppressed with lower than ambient temperatures. In many alloys, such as 7XXX alloys, natural aging can be almost completely suppressed by holding at -40°C.

Because of the very ductile and formable nature of as-quenched alloys, retarding natural aging increases scheduling flexibility for forming and straightening operations. It also allows for uniformity of properties during the forming process, contributing to a quality part. However, refrigeration at normal temperatures does not completely suppress natural aging. Some precipitation still occurs.

Table 2 shows typical temperature and time limits for refrigerated parts stored in the as-quenched condition.
cooling (quenching) results in a supersaturated solid solution and is the driving force for precipitation.

This phenomenon was discovered by Wilm, who found the hardness of aluminum alloys with minute quantities of copper, magnesium, silicon, and iron increased with time, after quenching from a temperature just below the melting point. In general, the sequence of precipitation occurs by the clustering of vacancies, formation of GP Zones; nucleation of a coherent precipitate; precipitation of an incoherent precipitate; and the coarsening of the precipitates.

Precipitation hardening (aging) involves heating the alloyed aluminum to a temperature in the 200º- 450ºF range. At this temperature, the supersaturated solid solution created by quenching begins to decompose. Initially there is a clustering of solute atoms near vacancies. Once sufficient atoms have diffused to these vacancy clusters, coherent precipitates form. Because the clusters of solute atoms are a mismatch to the aluminum matrix, a strain field surrounds them. As more solute diffuses to the clusters, eventually the matrix can not accommodate the matrix mismatch and a semi-coherent precipitate forms.

Heating the quenched material in the range of 95-205°C accelerates precipitation in heat treatable alloys. This acceleration is not completely because of changes in reaction rate. Structural changes occur that are dependent on time and temperature. In general, the increase in yield strength that occurs during artificial aging increases faster than the ultimate tensile strength. This means the alloys lose ductility and toughness. T6 tensile properties are higher than T4 properties, but ductility is reduced. Over-aging decreases the tensile strength and increases the resistance to stress-corrosion-cracking. It also enhances resistance to fatigue crack growth and imparts dimensional stability to the part.

Precipitation hardening curves have been developed for all the most common alloys. Figure 3 shows aging curves for 2024 and 6061. Both alloys show evidence of reversion of GP Zones by initial reductions in hardness. This is caused by the destruction of small GP Zones that are below the critical size. Similar aging curves have been developed for 7075 and casting alloys.

Generally, the higher the aging temperature the shorter the time required to attain maximum properties.

Defects Occurring During Heat Treatment

Defects can occur during a part’s production. These may come from operations before heat treatment, such as midline porosity, inclusions formed as the ingot is cast. Further defects can form during homogenization of the ingot, such as segregation — the formation of hard intermetallics and second phase particles.
Most thermally induced aluminum defects occur during solution heat treatment or during quenching. Solution heat treating defects include oxidation, incipient melting, and under-heating. Quenching defects are typically distortion or inadequate properties caused by a slow quench, which result in precipitation during quenching, and inadequate supersaturation.

**Oxidation** — If parts are exposed to temperature too long, high temperature oxidation can become a problem. The term high temperature oxidation is really a misnomer. The culprit is actually moisture in the air during solution heat treatment. The moisture is a source of hydrogen, which diffuses into the base metal. Voids form at inclusions or other discontinuities. The hydrogen gas gathers and forms a surface blister on the part. In general, 7XXX alloys are the most susceptible (particularly 7050), followed by the 2XXX alloys. Extrusions are most prone to blistering, followed by forgings. An example of surface blistering that can occur is shown in Figure 4.

Eliminating moisture minimizes the surface blistering problem. This is accomplished by the sequencing of the door over quench tanks, and thoroughly drying and cleaning furnace loads prior to solution heat treatment. It is also important to be sure load racks are also dry. However, it is not always possible to eliminate high humidity in the air to prevent surface blistering. Often, the ambient relative humidity is high, so other measures may have to be taken.

Ammonium fluoroborate is typically used to prevent blistering on 7XXX extrusions and forgings. An amount equivalent to 5g/m³ of work-load space is used. This is applied as a powder in a shallow pan hanging from the furnace load rack. The material is corrosive and requires operators to wear appropriate personal protective equipment. Additionally, because the material is corrosive at temperature, it is recommended the furnace’s inside panels be of stainless steel.

Anodizing parts prior to solution heat treatment is an alternative to ammonium fluoroborate. This is generally practical for larger extrusions and forgings, where the cost of anodizing is small compared with the cost of the part. However, for small parts, the additional added cost does not generally justify the possible benefit of anodizing prior to solution heat treatment.

**Incipient Melting** — Non-equilibrium conditions occur because of localized solute concentrations, which can decrease the eutectic temperature and cause localized melting. This is often called incipient melting. An example is shown in Figure 5. When this occurs, significant decreases in properties result. Toughness, ductility, and tensile properties are most affected.

Local melting can also occur if the part is heated too quickly. This is particularly true of 2XXX alloys. In this alloy system, there are local concentrations of Al₂Cu. At slow heating rates, the Al₂Cu dissolves slowly into the matrix. At high heating rates, there is inadequate time for the Al₂Cu to dissolve. Local concentrations cause the local eutectic temperature to drop, resulting in localized melting. If inadequate time is allowed for this metastable liquid to dissolve into the matrix there is generally no decrement in properties.

**Under-heating** — Under-heating during solution heat treatment can
cause problems by not allowing enough solute to go into solid solution. This means less solute is available during subsequent precipitation hardening reactions. As an illustration of this, Figure 6 shows the effect of solution heat-treating temperature on yield strength and ultimate tensile strength. As the temperature is increased for both alloys, the tensile strength is also increased. For 2024-T4, it can be seen that there is a change in slope and rapid rise in properties as the temperature is increased past about 488°C.

**Distortion during Quenching**

Of all possible defects occurring during heat treatment, distortion during quenching is the most common. It is probably responsible for most of the non-value added work (straightening) and costs associated with aluminum heat treating. An extreme case of distortion is shown in Figure 7.

Distortion during quenching is caused by differential cooling and differential thermal strains developed during quenching. These strains can occur center-to-surface, or surface-to-surface. Differential cooling can be caused by high quench rates, so that the center is cooled much slower than the surface (non-Newtonian cooling), or by non-uniform heat transfer across the surface of the part.

Aluminum is more prone to quenching distortion than steel because solution heat treating temperatures are so close to the liquidus temperature. Aluminum exhibits less strength and greater plasticity than steel at the solution heat-treating temperature (or austenitizing temperature for steel). Much higher quench rates are necessary in aluminum to prevent premature heterogeneous precipitation occurring during quenching, and to maintain supersaturation of the solute.

In steel, there is a coupled phase transformation of austenite to martensite, which causes a 3% volume change during quenching. There is no coupled phase transformation in aluminum that can cause cracking or distortion. However, the coefficient of linear expansion of aluminum is approximately twice that of steel. This causes much greater changes in length or volume as a function of temperature, and increases the probability that distortion will occur.

Racking of the parts is critical. The parts should be fully supported, with the loads spread out over a large area since the creep strength of aluminum is poor. The effect of this is illustrated in Insert Figure 8. Parts should be wired loosely to prevent them from hitting each other during solution heat treatment. If wired too tightly, the wire could cut the parts. The use of pure aluminum wire minimizes this problem.

Because of the poor strength of the heat treated aluminum parts, distortion can occur as they enter the quenchant. As a general rule, parts should enter the quenchant aerodynamically to avoid distorting the part before it even enters the bath. It should enter smoothly – it should not “slap” the quenchant. This is shown in Figure 9.

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*Figure 7 — Distortion of a large aerospace rib resulting from improper quenching and racking practice.*

*Figure 8 — Distortion from inadequately supporting the workload.*

*Distortion during quenching is caused by differential cooling and differential thermal strains developed during quenching.*
Racking a part so that it enters the quenchant smoothly makes it more likely to have uniform heat transfer across the part. Distortion is more likely to occur because of horizontal changes in heat transfer than by vertical differences in heat transfer.

Polyalkylene glycol (PAG) polymer quenchants are used in the aerospace industry to control and minimize quenching distortion. Typically, quenchants are governed by AMS 3025, and are either Type I or Type II. Type I quenchants are single polyalkylene glycol polymers. Type II quenchants are multiple molecular weight polyalkylene glycol polymers. Each offers different benefits. Because of the higher molecular weight of the Type II quenchants, lower concentrations can be used. However, Type II polymers have a lower cloud point temperature, which can cause higher drag-out if parts are removed from the quenchant before they reach the quenchant temperature (typically 80-100°F). The benefit of quenching aluminum in a PAG quenchant is shown in Figure 10.

Polyalkylene glycols exhibit inverse solubility in water — they are completely soluble in water at room temperature, but insoluble at elevated temperatures. The inverse solubility temperature can range from 60°C to 90°C depending on the molecular weight and structure of the polymer. Inverse solubility modifies the conventional three-stage quenching mechanism and provides great flexibility in controlling the cooling rate.

When a component is first immersed, the solution in the immediate vicinity of the metal surface is heated to above the inverse solubility temperature. The polymer becomes insoluble and a uniform polymer-rich film encapsulates the surface of the part. The stability and duration of this film is dependent on the temperature, concentration, and level of agitation present. The stable polymer-rich film eventually uniformly collapses, and cool quenchant comes into contact with the hot metal surface. Nucleate boiling re-
results, with its attendant high heat extraction rates, as shown in Figure 11.

The cooling rate of these polymers can be varied to suit the specific application by changing the concentration, quenchant temperature, and the amount of agitation. Typically, for most applications, the agitation is usually fixed, while the concentration is changed.

The polymer concentration influences the thickness of the polymer film deposited on the surface of the part during quenching. As the concentration increases, the maximum rate of cooling, and the cooling rate in the convection phase decrease.

Agitation has an important effect on the quenching characteristics of the polymer quenchant. It ensures uniform temperature distribution within the quench tank, and it also affects the quench rate. As the severity of agitation increases, the duration of the polymer-rich phase decreases and eventually disappears, and the maximum rate of cooling increases. Agitation has comparatively little effect on the cooling rate during the convection stage.

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