Heat Treating Aluminum for Aerospace Applications
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Abstract
Aluminum has been used in the aerospace industry since the original Wright Flyer. While there have been inroads made by composites and plastics, the primary structural material for aerospace is heat treated aluminum. In this paper, a brief overview of the application of aluminum to aerospace will be discussed. A short review of aluminum physical metallurgy will also be provided. Common defects observed during aluminum heat-treating will be shown, with possible corrective actions.

Introduction
Aluminum in many forms has been used in aircraft since the early beginning. This is because aluminum alloys can be heat-treated to relatively high strengths, while maintaining low weight. It is easy to bend and machine, and cost of material is low. Because of these advantages, it is the most common material used in aerospace today. It is used in the manufacture of advanced commercial aircraft such as the Boeing 777, Airbus 380, and military aircraft such as the Boeing UCAV (Figure 1) or the Boeing F/A-18 E/F (Figure 2).

Figure 1 – Artist conception of the Boeing UCAV (Unmanned Combat Air Vehicle).

Figure 2 - Boeing F/A-18F during sea trials.

Typically, the aluminum alloys used in aerospace structures are the heat treatable grades, such as 2XXX, 6XXX, and 7XXX. 7XXX alloy grades such as 7075, 7040, and 7050 predominate in aerospace structures. Some of the Al-Li alloys such as 2090 and 8090 have also found application. These alloys are commonly used because they are commonly available and readily formed and heat-treated to high, corrosion resistant strengths.

Most commonly, the 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 requirements. Some extrusions of 2024, and 2014 are also used. Sheet, both clad and non-clad sheet of 2024, 7475 and 7075 is used for wing and fuselage skins. Sheet is also formed and built-up to form bulkheads and other structural requirements. For heavy loading, large forgings of 7050 and 7040 are commonly used, particularly in military aircraft.
 Recently, there has been much interest in the use of heat treated 7050 and 7040 plate to eliminate the cost of forgings. In this case, the plate (heat treated at the aluminum mill) is supplied to the airframe manufacturer. There the plate is heavily machined to fabricate large ribs and bulkheads. The advantage of this is that it avoids heat-treating small parts and may have better distortion and residual stress control. Unfortunately, there is a significant property variation through the thickness of thick plate. This variation has been studied in detail, and the microstructure development in thick sections has been extensively studied [1].

Because of affordability, the use of castings has also been used. However, the use of castings has been limited because of design factors and the limited ductility of castings. Typically casting alloys such as A356, and A357 are used. Applications of castings are simple, non-flight critical applications, such as door handles and avionics cabinets.

Heat-treating of aluminum requires stringent controls. These controls are in place to avoid melting the alloy during solution heat treatment, and to insure that a safe and durable product is manufactured and created. Temperature uniformity requirements inside furnaces are tight (±5ºF) to prevent eutectic melting, and ensure uniform properties throughout the workload. Because of the sensitivity of aluminum to process variations, and to achieve repeatable results, and to provide a quality product, the airframe manufacturers, suppliers, and heat-treaters have developed a series of specifications. The most widely used specification is AMS-2770 “Heat Treatment of Aluminum Parts” [2]. This specification details solution heat treating times, temperatures, quenchants, quenchant concentrations, and aging practices. It also details the required documentation for heat treat lot traceability. Furthermore, this specification details the quality assurance provisions needed to insure that a quality product is provided to the airframe manufacturer.

**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 the 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 [3] (Figure 3).

**Table 1 - Solution heat treatment temperature range and eutectic melting temperature for 2XXX alloys.**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Solution Heat Treatment Temperature Range, ºC</th>
<th>Initial Eutectic Melting Temperature, ºC</th>
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</thead>
<tbody>
<tr>
<td>2014</td>
<td>496-507</td>
<td>510</td>
</tr>
<tr>
<td>2017</td>
<td>496-507</td>
<td>513</td>
</tr>
<tr>
<td>2024</td>
<td>488-507</td>
<td>502</td>
</tr>
</tbody>
</table>

**Figure 3 – Partial aluminum-copper phase diagram (after Van Horn [4])**

The Al-Cu phase diagram shows that holding a 4.5% alloy at 515 to 550ºF will cause all the copper to go completely into solution. This is the typically know as the “solution heat treatment 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 involves heating the aluminum and alloys to a temperature slightly below the eutectic melting temperature. Solution heat treatment develops the maximum amount of solute into solid solution. This requires heating the material close to near the eutectic temperature and holding the material at temperature long enough to allow close to 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 (Table 1).

Solution heat treating and quenching of these alloys is typically accomplished in large high temperature ovens. In some applications, the furnace is supported above the quench tank. The quench tank moves under the furnace on rails. Sometimes there is more than one quench tank, with each tank containing a different quenchant. A typical solution heat-treating furnace and quench tank used for heat-treating aluminum aerospace components is shown in Figure 4.

**Figure 4 - Large drop-bottom furnace used to solution heat-treat and quench aluminum alloys.**

**Quenching.** An understanding of heterogeneous precipitation during quenching can be understood by nucleation theory applied to diffusion controlled solid-state reactions [5]. The kinetics of heterogeneous precipitation occurring during quenching is dependent on the degree of solute supersaturation and the diffusion rate, as a function of temperature. So, as an alloy is quenched, there is greater supersaturation (assuming no solute precipitates). But the diffusion rate increases as a function of temperature. The diffusion rate is greatest at elevated temperature. 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 the greatest at intermediate temperatures. This is shown schematically in Figure 5. The amount of time spent in this critical temperature range is governed by the quench rate.

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

**Figure 5 - Schematic showing the interrelationship between the amount of solute supersaturation and diffusion rate on the amount of heterogeneous precipitation occurring during quenching.**

Quantifying quenching, and the cooling effect of quenchants have been extensively studied [6] [7] [8] [9]. The first systematic attempt to correlate properties to the quench rate in Al-Zn-Mg-Cu alloys was performed by Fink and Wiley [10] for thin (0.064") sheet. A Time-Temperature-Tensile Property curve was created and was probably the first instance of a TTT diagram for aluminum. It was determined that the critical temperature range for 75S (7075) is 400°C to 290°C. This is similar to the critical temperature range found for Al-Zn-Mg-Cu alloys [11]. At quench rates exceeding 450°C/sec., it was determined that maximum strength and corrosion resistance were obtained. At intermediate quench rates of 450°C to 100°C/sec., the strength obtained is lowered (using the same age treatment), but the corrosion resistance was unaffected. Between 100°/sec and 20°C/sec, the strength decreased rapidly, and the corrosion resistance is at a minimum. At quench rates below 20°C/sec, the strength decreases rapidly, but the corrosion resistance improved. However, for a given quenching medium, the cooling rate through the critical
temperature range was invariant no matter the solution heat treat temperature.

One method that quantifies the quench path and material kinetic properties is called the “Quench Factor” and was originally described by Evancho and Staley [12]. This method is based on the integration of the area between the Time-Temperature-Property Curve and the quench path. Wierszykowski [13] provided an alternative explanation of the underlying principles of the Quench Factor. However, his discussion is more generally applied to the thermal path prior to isothermal transformation. The procedures for developing the Quench Factor have been well documented [14] [15] [16] [17] [18] [19]. This procedure could be used to predict tensile properties [20], hardness [21] and conductivity [15]. It was found that the Quench Factor could not be used to predict elongation because of its strong dependence on grain size [15]. This method tends to overestimate the loss of toughness [19]. This method also can be used to determine the critical quench rate for property degradation [22].

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

Natural aging, and the increase in properties occurs 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), harden by the same 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.

The 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 nearly 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. This contributes 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 refrigeration.

### Table 2 Typical time and temperature limits for refrigerated parts stored in the as-quenched condition.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Maximum Delay Time after Quenching</th>
<th>Maximum Storage Time for Retention of the AQ Condition</th>
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<tbody>
<tr>
<td></td>
<td>Maximum Storage Time</td>
<td>-12°C (10°F)</td>
</tr>
<tr>
<td></td>
<td>(10°F) Max.</td>
<td>Max.</td>
</tr>
<tr>
<td>2014</td>
<td>15 minutes</td>
<td>1 day</td>
</tr>
<tr>
<td>2024</td>
<td>15 minutes</td>
<td>1 day</td>
</tr>
<tr>
<td>2219</td>
<td>15 minutes</td>
<td>1 day</td>
</tr>
<tr>
<td>6061</td>
<td>30 minutes</td>
<td>7 days</td>
</tr>
<tr>
<td>7075</td>
<td>30 minutes</td>
<td>7 days</td>
</tr>
</tbody>
</table>

**Artificial Aging.** After quenching, most aerospace aluminum alloys are artificially aged. This is a complex process, and requires an understanding of vacancies, and the interaction of precipitation and metastable phases. In general, the sequence of precipitation occurs by clustering of vacancies, formation of GP Zones; nucleation of a coherent precipitate; precipitation of an incoherent precipitate, and finally the coarsening of the precipitates.

Precipitation hardening is the mechanism where the hardness, yield strength, ultimate strength dramatically increase with time at a constant temperature (the aging temperature) after rapidly cooling from a much higher temperature (solution heat treat temperature). This rapid cooling or quenching results in a supersaturated solid solution, and provides the driving force for precipitation. This phenomenon was first discovered by Wilm [23], who found that 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 temperature.
Precipitation hardening (aging) involves heating the alloyed aluminum to a temperature in the 200°-450°F range. At this temperature, the supersaturated solid solution created by quenching from the solution heat-treating temperature, begins to decompose. Initially there is a clustering of solute atoms near vacancies. Once sufficient atoms have diffused to these initial vacancy clusters, coherent precipitates form. Because the clusters of solute atoms have a mismatch to the aluminum matrix, a strain field surrounds the solute clusters. As more solute diffuses to the clusters, eventually the matrix can no longer accommodate the matrix mismatch. A semi-coherent precipitate forms.

Finally, after the semi-coherent precipitate grows to a large enough size, the matrix can no longer support the crystallographic mismatch, and the equilibrium precipitate forms. This is shown in Figure 6 for 7050, showing the structural changes that occur from the formation of GP Zones, to the final overaged equilibrium precipitate.

Heating the quenched material in the range of 95-205°C accelerates precipitation in heat treatable alloys.
This acceleration is not completely due to changes in reaction rate. As was shown above, 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 that the alloys lose ductility and toughness. T6 properties are higher than T4 properties, but ductility is reduced. Overaging decreases the tensile strength, and increases the resistance to Stress-Corrosion-Cracking. It also enhances the resistance to fatigue crack growth. It also imparts dimensional stability of the part.

Precipitation hardening curves have been developed for all the most common alloys. Figure 7 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.

![Aging curves for 2014 and 6061.](image)

The aging curves for the different alloys vary; however, generally the higher the aging temperature, the shorter the time required to attain maximum properties. When high aging temperatures are used, properties are reached very rapidly with time. For this reason, aging temperatures are usually lower to assure that the entire load is brought to the required aging temperature without risk of reduced properties caused by over-aging of the fastest rising aluminum.

**Defects Occurring During Heat Treatment**

During the production of a part, defects can occur. These can come from operations before heat treatment, such as midline porosity, inclusions that are formed during casting the ingot. Further defects can form during homogenization of the ingot, such as segregation, the formation of hard intermetallics and second phase particles.

Most defects associated with heat treatment of aluminum occur either during solution heat treatment, or during quenching. Solution heat treating defects include oxidation, incipient melting and under-heating. Defects occurring during quenching are typically distortion or inadequate properties caused by a slow quench, resulting in precipitation during quenching, and inadequate supersaturation.

![Oxidation evident on a 7050 extrusion that has been exposed to extended times at the solution heat-treating temperature.](image)

**Oxidation.** If parts are exposed to temperature too long, high temperature oxidation could become a problem. The term high temperature oxidation is really a misnomer. The culprit is actually moisture in the air during solution heat treatment. This 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 the most prone to blistering, followed by forgings. An example of surface blistering that can occur is shown in Figure 8.

Eliminating the moisture will minimize the problem of surface blistering. This is accomplished by sequencing of door over quench tanks, and thoroughly drying and cleaning furnace loads prior to solution heat treatment. It is also important to make sure that the load racks used for solution heat treatment 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 that other measures may have to be taken.

The use of ammonium fluoroborate is typically used to prevent blistering on 7XXX extrusions and forgings. An amount equivalent to 5 g per m$^3$ of workload space is usually used to prevent surface blistering. This is applied as a powder in a shallow pan hanging from the furnace load rack. This material is very corrosive and requires operators to wear the appropriate personal protective safety equipment. Because the material is corrosive at temperature, it is recommended that the inside panels in the furnace be manufactured with stainless steel. This will reduce corrosion and maintenance.

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 to 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 can occur because of localized solute concentrations. Because of the increased concentration of solute, the eutectic temperature could be decreased, causing localized melting. This is often called *incipient melting*. An example is shown in Figure 9. When this occurs, significant decreases in properties. Properties most affected include toughness, ductility and tensile properties.

Local melting can also occur if it is heated too quickly. This is particularly true of 2XXX alloys. In this alloy system, there are local concentrations of Al$_2$Cu. At slow heating rates, the Al$_2$Cu dissolves slowly into the matrix. At high heating rates, there is inadequate time for the Al$_2$Cu 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, then in general, there is no decrement in properties.

![Figure 9 - Incipient melting observed in a 2024 alloy.](image)

**Under-heating.** Under-heating during solution heat treatment can causes problems by not allowing enough solute to go into solid solution. This means that less solute is available during subsequent precipitation hardening reactions. As an illustration of this, Figure 11 shows the effect of solution heat-treating temperature on the 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.

Figure 11 - Tensile strength as a function of solution heat-treating temperature for 6061 and 2024 (after Hatch [5]).

Distortion during Quenching. Of all the possible “defects” occurring during the heat treatment of aluminum, 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 12.

Figure 12 - Distortion of a large aerospace rib resulting from improper quenching and racking practice

Distortion during quenching is caused by differential cooling, and differential thermal strains developed during quenching. These thermal strains could be developed center-to-surface, or surface-to-surface. This differential cooling can be caused by large 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. This is 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. This 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 ($2.38 \times 10^{-5}$ mm/mm compared to $1.12 \times 10^{-5}$ mm/mm). 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 Figure 13. Parts should be wired loosely to prevent the parts 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.

Figure 13 - Distortion from racking. The part was inadequately supported over a large area.

Because of the poor strength of the heat-treated aluminum parts, distortion of the parts can occur as they enter the quenchant. As a general rule, parts should enter the quenchant aerodynamically to avoid distortion the part before it even enters the quenchant. It should enter the quenchant smoothly – it should not “slap” the quenchant. This is shown in Figure 14.

Racking a part so that it enters the quenchant smoothly also offers the benefit that it is 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 polymer quenchants are used in the aerospace industry to control and minimize the distortion occurring the quenching of aluminum. Typically these quenchants are governed by AMS 3025, and are either Type I or Type II. Type I quenchants are single polyalkylene glycol polymers, while Type II quenchants are multiple molecular weight polyalkylene glycol polymers. Each offers different benefits. Because of the higher molecular weight of the Type II PAG 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 benefits of quenching aluminum in the PAG quenchants is shown in Figure 15.

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 of the polymer, and the structure of the polymer.

This phenomenon of inverse solubility modifies the conventional three-stage quenching mechanism [24] and provides great flexibility to control 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 the duration of this polymer film is dependant on the temperature, concentration and amount of agitation present.

The stable polymer-rich film eventually uniformly collapses, and cool quenchant comes into contact with the hot metal surface. Nucleate boiling results, with attendant high heat extraction rates.

As the period of active boiling subsides, cooling occurs by conduction and convection into the quenchant. When the surface temperatures fall below the inversion temperatures, the polymer dissolves, forming a homogeneous solution again. These stages are illustrated in Figure 16.

The cooling rate of these polymers can be readily 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.

Figure 14 - Typical racking procedures for aerospace parts. Note that the parts are racked vertically so that heat transfer occurs evenly on all sides.

Figure 15 - Comparison of the distortion occurring when quenching in cold water and in a 20% Type I Polyalkylene Glycol quenchant.
The concentration of the polymer influences the thickness of the polymer film that is 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.

**Conclusions**

In this short paper, typical applications of aluminum heat-treating in the aerospace industry have been shown. A brief overview of the physical metallurgy of the various alloys used in aerospace was detailed. Finally, a description of typical heat-treating defects observed was illustrated. The benefits and advantages of polymer quenchants for aluminum were shown.

**References:**


[9] Dakins, M., Central Scientific Laboratory, Union Caribe, Report CSL-226A.


[23] Wilm, A., Metallurgie, 8 (1911) 225.


**Figure 16 - Various stages during the quenching process using a PAG based polymer quenchant.**