The *Heat Treatment* of *Aerospace Fasteners*

by Daniel H. Herring

Aerospace applications include aircraft (manned and unmanned, fixed and flex wing), rotorcraft (helicopters, gyrocopters), and space vehicles (shuttles, space stations, satellites).

Fasteners are one of the most critical components used in all of these applications and are required to meet the most demanding performance characteristics (Table 1). The types of fasteners in the aerospace industry include screws, rivets, bolts, nuts, pins, collars, and washers.

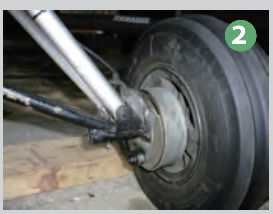
Fasteners account for a significant number of parts in aircraft and directly affect strength characteristics and weight of structural assemblies. According to The Boeing Company, the 747 includes over six million parts, half of which are fasteners. On average, for example, 2.4 million (2,400,000) fasteners are used to assemble a Boeing 787 aircraft. On average, 22% are structural bolts (mostly titanium), and the rest are aluminium rivets.

As the Industry evolves to incorporate newer, more exotic materials, fasteners continue to figure prominently in the manufacturing and assembly processes. Fasteners play a critical role in defining the longevity, structural integrity, and design philosophy of most metallic aircraft structures.

Table 1 Typical Mechanical Properties of Aircraft Fastener Materials Produced from Sheet

Material [a]	Tensile Strength mm (in)	Yield Strength MPa (ksi)	Elongation (%)
2024	345 (50)	290 (42)	13
6061	462 (67)	400 (58)	5
7075	503 (73)	427 (62)	8

Typical aerospace fastener materials include aluminium, steel (e.g. A286, H-11) superalloys (e.g., Waspaloy, Hastalloy, Inconel 718), nickel alloys (e.g. Monel, K-Monel) and titanium.



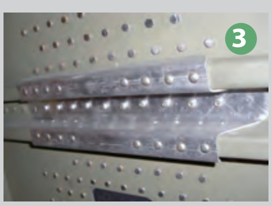


Figure 1: Fasteners Holding Laser Guided Bomb Delivery System

Figure 2: Wheel Attachment on Aircraft Landing Gear

Figure 3: Interior of a Riveted Fuselage Skin Patch

Common Aluminium Alloys in the Aerospace Industry

2024 is widely used in aircraft structures, especially wing and fuselage structures under tension and for various types of fasteners. The mechanical properties of 2024 depend greatly on the temper of the material. Since the material is susceptible to thermal shock, 2024 is used in qualification of liquid penetrant tests outside of normal temperature ranges.

6061 is one of the most versatile of the heat-treatable alloys but its use in fastening applications is limited since it is less strong than most of the 2xxx or 7xxx series alloys. This material poses good formability and corrosion resistance, with medium strength. Alloys in this heat-treatable group may be formed in the T4 temper (solution heat-treated but not artificially aged) and then reach full T6 properties by artificial aging.

7075 is a major aluminium alloy for aerospace fasteners having zinc as the primary alloying element. It is strong, with strength comparable to many steels, and has good fatigue strength and average machinability. 7075 has less resistance to corrosion than many other aluminium alloys. 7075 is often used in transport applications, including aviation, marine and automotive due to its high strength-to-density ratio.

Heat Treatment of Aluminium

Heat treating of aluminium and aluminium alloys are precision processes. They must be carried out in furnaces and ovens properly designed and built to provide very precise thermal conditions, and be equipped with adequate control instruments to insure the desired uniformity and repeatability of temperature-time cycles. To insure that the final properties are achieved, heat treat process details must be carefully established, controlled, and documented for each type of product. Let's learn more.

Types of Heat Treatment

The types of heat treatments applied to aluminium and its alloys are:

- Preheating or homogenizing, to reduce chemical segregation of cast structures and to improve their workability.

• Annealing, to soften strain-hardened (work-hardened) and heat treated alloy structures, to relieve stresses, and to stabilize properties and dimensions.

•Solution heat treatments, to improve mechanical properties by putting alloying elements into solution.

•Precipitation heat treatments, to provide hardening by precipitation of constituents from solid solution.

Homogenization (Ingot Preheating Treatments)

The initial thermal operation applied to castings or ingots (prior to hot working) is referred to as homogenization, which has one or more purposes depending upon the alloy, product, and fabricating process involved. One of the principal objectives is improved workability since the microstructure of most alloys in the as-cast condition is quite heterogeneous. This is true for alloys that form solid solutions under equilibrium conditions, and even for relatively dilute alloys.

Annealing

Annealing can be used for both heat treatable and non-heat treatable alloys to increase ductility with a slight reduction in strength. There are several types of annealing treatments dependent to a large part on the alloy type, initial structure, and temper condition. In annealing it is important to ensure that the proper temperature is reached in all portions of the load. The maximum annealing temperature is also important in achieving good results.

The distorted, dislocated structure resulting from cold working of aluminium is less stable than the strain-free annealed state, to which it tends to revert. Lower-purity aluminium and commercial aluminium alloys undergo these structural changes only with annealing at elevated temperatures. These changes occur in several stages, according to temperature or time, and have led to the concept of different annealing mechanisms or processes.

Full annealing (temper designation "O") produces the softest, most ductile, and most versatile condition. For both heat treatable and non-heat treatable aluminium alloys, reduction or elimination of the strengthening effects of cold working is accomplished by heating at temperature from about 260ºC to 440ºC (500ºF to 825ºF). The rate of softening is strongly temperature dependent; the time required can vary from a few hours at low temperature to a few seconds at high temperature.

Table 2 Process Description

Process	Solution Heat Treating	Quenching	Aging (Age Hardening)
Goal	To take into solid solution the maximum practical amount of soluble hardening elements (e.g. Cu, Si, Mg) in the alloy.	To preserve as nearly intact as possible the solid solution formed at elevated (solution treat) temperatures.	To cause precipitation to occur (the degree of stable equilibrium for a given grade is a function of time and temperature).
Purpose	To take advantage of the precipitation hardening reaction (aging) it is first necessary to produce a solid solution.	To cool rapidly enough to produce a "super saturated" solution.	To create a change in which the structure recovers from an unstable or "meta" stable condition (produced by quenching or cold working)

Stress relief annealing can be used to remove the effects of strain hardening in cold worked alloys. No appreciable holding time is required after the parts have reached temperature. Stress relief annealing of castings provides maximum stability for service applications when elevated temperatures are expected.

Partial annealing (or recovery annealing) is done on non-heat treatable wrought alloys to obtain intermediate mechanical properties. Recovery annealing involves a reduction in the number of dislocations and is greatest at the center of individual grains, producing a sub-grain structure with groups of dislocations at the sub-grain boundaries. With increasing time and/or temperature, the sub-grain size gradually increases. Complete recovery from the effects of cold working however, is obtained only with recrystallization.

Recrystallization is characterized by the gradual formation and appearance of a microscopically resolvable grain structure. The new structure is largely strain-free, with few, if any, dislocations within the grains and no concentrations at the grain boundaries. Heating after recrystallization may produce grain growth (coarsening) in one of several forms.

Principles of Precipitation Hardening

The heat treatable alloys contain amounts of soluble alloying elements that exceed the equilibrium solid solubility limit at room and moderately higher temperatures. The amount present may be less or more than the maximum that is soluble at the eutectic temperature.

In most precipitation hardenable systems, a complex sequence of time-dependent and temperature-dependent changes is involved (Table 2). The relative rates at which solution and precipitation reactions occur with different solutes depend upon the respective diffusion rates, in addition to solubility and alloy contents. Bulk diffusion coefficients for several of the commercially important alloying elements in aluminium have been determined by experimental methods.

The formation of zones can occur in an essentially continuous crystal lattice by a process of homogeneous nucleation. The nucleation of a new phase is greatly influenced by the existence of discontinuities in the lattice. Since in polycrystalline alloy grain boundaries, sub-grain boundaries, dislocations, and interphase boundaries are locations of greater disorder and higher energy than the solid-solution matrix, they are preferred sites for nucleation of precipitates.

Solution Heat Treating

The purpose of solution heat treatment is the dissolution of the maximum amount of soluble elements in the alloy into solid solution. The process consists of heating and holding the alloy at a temperature sufficiently high and for a long enough period of time to achieve a nearly homogenous solid solution in which all phases have dissolved.

Care must be taken to avoid overheating or underheating. In the case of overheating, eutectic melting can occur with a corresponding degradation of properties such as tensile strength, ductility and fracture toughness. If underheated, solution is incomplete, and strength values lower than normal can be expected. In certain cases, extreme property loss can occur. In general, a temperature variation of ± 5.5ºC (± 10ºF) from control setpoint is allowable but certain alloys require much tighter tolerances. The time at temperature is a function of the section thickness of the material and may vary from several minutes to many hours. The time required to heat a load to the treatment temperature also increases with section thickness and loading arrangement and thus the total cycle time must take into consideration these factors.

Quenching

Rapid and uninterrupted quenching in water or polymer is, in most instances, required to avoid precipitation detrimental to mechanical properties and corrosion resistance. The solid solution formed by solution heat treatment must be cooled rapidly enough to produce a supersaturated solution at room temperature which provides the optimal condition for subsequent precipitation hardening.

Quenching is in many ways the most critical step in the sequence of heat treating operations. The objective of quenching is to preserve as nearly intact as possible the solid solution formed at the solution heat treating temperature, by rapidly cooling to some lower temperature, usually near room temperature.

The fundamentals involved in quenching precipitation-hardenable alloys are based on nucleation theory applied to diffusion-controlled solid state reactions. The effects of temperature on the kinetics of isothermal precipitation depend principally upon degree of supersaturation and rate of diffusion.

Water is not only the most widely used quenching medium but also the most effective. In immersion quenching, cooling rates can be reduced by increasing water temperature. Conditions that increase the stability of a vapor film around the part decrease the cooling rate; various additions to water that lower surface tension have the same effect.

Figure 4

Typical Aluminium Solution Heat Treating Furnace

(Photograph Courtesy of Wisconsin Oven Corporation)

Aging (Age Hardening)

Age hardening is achieved either at room temperature (natural aging) or with a precipitation heat treatment (artificial aging) cycle. The same general rules used in solution heat treatment (temperature uniformity, time at temperature) apply for precipitation hardening.

Aging at Room Temperature (Natural Aging)

Most of the heat treatable alloys exhibit age hardening at room temperature after quenching, the rate and extent of such hardening varying from one alloy to another. No microstructural changes can be seen metallographically during room-temperature aging, since the hardening effects are attributable solely to the formation of a zone structure within the solid solution.

Since the alloys are softer and more ductile immediately after quenching than after aging, straightening or forming operations should be performed in the as quenched condition. The process window for forming after quenching can be enlarged by keeping the alloy refrigerated prior to forming.

Aging At Elevated Temperature (Artificial Aging)

The effects of precipitation on mechanical properties are greatly accelerated, and usually accentuated, by reheating the quenched material to about 100ºC - 200ºC (212ºF - 424ºF). The effects are not entirely attributable to a changed reaction rate; as mentioned previously, the

Figure 5 Typical Aging Oven (Photograph Courtesy of Nutec-Bickley)

structural changes occurring at the elevated temperatures differ in fundamental ways from those occurring at room temperature. These differences are reflected in the mechanical characteristics and some physical properties. A characteristic feature of elevated-temperature aging effects on tensile properties is that the increase in yield strength is more pronounced than the increase in tensile strength. Also ductility, as measured by percentage elongation, decreases. Thus, an alloy in the T6 temper has higher strength but lower ductility than the same alloy in the T4 temper.

In certain alloys, precipitation heat treating can occur without prior solution heat treatment since some alloys are relatively insensitive to cooling rate during quenching, thus they can be either air cooled or water quenched. In either condition, these alloys will respond strongly to precipitation heat treatment.

In general, the principles and procedures for heat treating wrought and cast aluminium alloys are similar. For cast alloys however, soak times and quenching media are often different due to the section sizes involved. Typically, soak times are longer and quenchants such as boiling water are used to reduce quenching stresses in complex shapes.

The mechanical properties of permanent mold, sand, and plaster castings of most aluminium alloys are greatly improved by solution heat treating, quenching, and precipitation heat treating, using practices analogous to those employed for wrought products.

In Summary

Aerospace fastener failures are not an option. As such, the fabrication and heat treatment of these critical components is paramount. Challenges include the large production volumes and assurance that each individual fastener is suitable for its intended application.

References

Herring, Daniel H., Understanding Aluminum Heat Treatment, Industrial Heating, February 2005.