Heat treating of aluminum and aluminum alloys

**Abstract:**

The general types of heat treatments applied to aluminum 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 effect solid solution of alloying constituents and improve mechanical properties
- Precipitation heat treatments, to provide hardening by precipitation of constituents from solid solution.

Heat treating processes for aluminum are precision processes. They must be carried out in furnaces properly designed and built to provide the thermal conditions required, and adequately equipped with control instruments to insure the desired continuity and uniformity of temperature-time cycles. To insure the final desired characteristics, process details must be established and controlled carefully for each type of product.

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**INGOT PREHEATING TREATMENTS (HOMOGENIZING)**

The initial thermal operation applied to ingots prior to hot working is referred to as "ingot preheating", which has one or more purposes depending upon the alloy, product, and fabricating process involved. One of the principal objectives is improved workability. 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**

The distorted, dislocated structure resulting from cold working of aluminum is less stable than the strain-free, annealed state, to which it tends to revert. Lower-purity aluminum and commercial aluminum alloys undergo these structural changes only with annealing at elevated temperatures. Accompanying the structural reversion are changes in the various properties affected by cold working. These changes occur in several stages, according to temperature or time, and have led to the concept of different annealing mechanisms or processes.
Recovery. The reduction in the number of dislocations is greatest at the center of the grain fragments, producing a subgrain structure with networks or groups of dislocations at the subgrain boundaries. With increasing time and temperature of heating, polygonization becomes more nearly perfect and the subgrain size gradually increases. In this stage, many of the subgrains appear to have boundaries that are free of dislocation tangles and concentrations.

Recovery annealing is also accompanied by changes in other properties of cold worked aluminum. Complete recovery from the effects of cold working 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—there are few if any dislocations within the grains and no concentrations at the grain boundaries.

Grain Growth After Recrystallization. Heating after recrystallization may produce grain coarsening. This can take one of several forms.

PRECIPITATION HARDENING

General 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.

Nature of Precipitates and Sources of Hardening. Intensive research during the past forty years has resulted in a progressive accumulation of knowledge concerning the atomic and crystallographic structural changes that occur in supersaturated solid solutions during precipitation and the mechanisms through which the structures form and alter alloy properties. In most precipitation-hardenable systems, a complex sequence of time-dependent and temperature-dependent changes is involved.

Kinetics of Solution and Precipitation. The relative rates at which solution and precipitation reactions occur with different solutes depend upon the respective diffusion rates, in addition to solubilities and alloy contents. Bulk diffusion coefficients for several of the commercially important alloying elements in aluminum were determined by various experimental methods.

Nucleation. The formation of zones can occur in an essentially continuous crystal lattice by a process of homogeneous nucleation. Recent investigations provide evidence that a critical vacancy concentration is required for this process and that a nucleation model involving vacancy-solute atom clusters is consistent with certain effects of solution temperature and quenching rate.

The nucleation of a new phase is greatly influenced by the existence of discontinuities in the lattice. Since in polycrystalline alloys grain boundaries, subgrain 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.

Quenching

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.

Critical Temperature Range. 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.

Quenching Medium. Water is not only the most widely used quenching medium but also the most effective. It is apparent that 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.

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 discernible microstructural changes accompany the room-temperature aging, since the hardening effects are attributable solely to the formation of zone structure within the solid solution.

Since the alloys are softer and more ductile immediately after quenching than after aging, straightening or
forming operations may be performed more readily in the freshly quenched condition.

**Precipitation Heat Treating (Artificial Aging)**

The effects of precipitation on mechanical properties are greatly accelerated, and usually accentuated, by reheating the quenched material to about 100 to 200°C. The effects are not entirely attributable to a changed reaction rate; as mentioned previously, the 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.

**Precipitation Heat Treating Without Prior Solution Heat Treatment**

Certain alloys that are relatively insensitive to cooling rate during quenching can be either air cooled or water quenched directly from a final hot working operation. In either condition, these alloys will respond strongly to precipitation heat treatment.

**Precipitation Heat Treating Cast Products**

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