Heat treatment is an integral part of aluminum alloy processing. The full potential of high strength and medium strength aluminum alloys can be realized only after the adoption of proper heat treatment practices.

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Due to its limited strength, unalloyed aluminum is used in applications where only limited strength is required. Increasing the strength of aluminum can be achieved in a moderate way by work hardening and, to a substantial extent, by precipitation hardening combined with mechanical and thermal treatments. This type of processing has resulted in a series of tempers in which commercial aluminum alloys are available. The same alloy in different tempers has varied mechanical properties. The principal drawbacks for high strength heat-treatable aluminum alloys are reduced ductility and fracture toughness in the short transverse direction and enhanced stress corrosion cracking (SCC) susceptibility. To overcome these drawbacks, various thermal-mechanical treatments have been devised to provide these alloys in various tempers such as T73, T76, T39, etc. High strength non-heat treatable alloys of the 5XXX series also have a series of H2 and H3 tempers to enhance corrosion resistance. Strategic materials applications are those that involve national security and/or national interests such as defense and aerospace. Heat treatable aluminum alloys to be used in such applications are broadly classified as high strength aluminum alloys of the 7xxx (7075-T6), medium strength with moderate corrosion and fracture resistance of the 7xxx and 2xxx (7075-T76, 7075-T73, 2014-T6, 2214-T6, and 2219-T87), medium strength, high fracture-resistant alloys (2024-T3 and 2219-T39), and superplastic-forming alloys (7475).

In addition, aluminum alloys also find use in armor plating applications where high strength-to-weight ratios are mandatory. Non-heat treatable alloys of the 5xxx series (Alclad 5056, 5156, 5256, 5356-H321, 5456, and 5083) are widely used in naval applications due to their excellent corrosion resistance. Development of aerospace grade aluminum in India was hampered over the years due to several reasons including unavailability of 99.85% purity primary metal with strict control of iron and silicon, dissolved gases, and alkali metals; unavailability of proper sized extrusion and forging presses; and possibly most important, the lack of demand for these alloys from the domestic aerospace industry, as most airplanes (civil and military) and space vehicles were imported.

Aluminum alloys 7475 and 2219
Alloy 7475 was the result of a successful alloy development program...
36

HEAT TREATING PROGRESS • MAY/JUNE 2008

of the 7xxx series to develop an alloy having high resistance to stress corrosion cracking. The 7xxx series alloys are extremely sensitive to structure property co-relationships, and, therefore, a wide range of chemical compositions and thermomechanical processes are available that improve some specific property such as fracture toughness, ductility, notch, and stress corrosion cracking. Alloy 7475 has the distinction of being the first aluminum alloy to provide high, controlled fracture toughness. It is available in T6, T76, and T73 tempers.

Alloy 2219, developed in 1954, is the material of choice for use in cryogenic applications. It has excellent mechanical properties above 230°C. Additions of 0.18 Cr, 0.10 V and 0.3 Mn help in the formation of extremely fine dispersoids, which contribute to high temperature strength. The alloy also has excellent weld characteristics and weld strength together with good corrosion resistance. It is used widely in the T8 temper. A high-purity version of this alloy (2419) is used in B1B military aircraft. Magnesium additions to the basic 2219 composition impart improved strength to this alloy.

Military fighter planes such as the F16 and F18 have lower wing materials of 7475 alloy. Nonetheless, over the years the airplane wing box structure has, for the most part, in commercial jet aircraft included a 7000 series alloy (2419) is used in B1B military aircraft. Magnesium additions to the basic 2219 composition impart improved strength to this alloy.

Homogenization plays a significant role in the physical metallurgy of these high-strength alloys in the generation of fine dispersoids. The size, shape, distribution, and density of these particles control a variety of effects such as mechanical recovery, dynamic recrystallization, propensity to fracture, texture and anisotropy, and stress corrosion resistance[2].

Homogenization of 7475 alloy results in the formation of extremely fine (0.03 to 0.20 μm) Cr-rich insoluble compounds above 400°C. These Cr-rich compounds have been identified as the E phase (Al18Cr2Mg3), as shown in Fig. 1. The heating rate to, or steeped or interrupted heating prior to, the homogenization temperature is critical in determining the size and shape of the E phase formed during thermal exposure. Although the dendrite cell peripheries develop a fine, dense E phase distribution after homogenization, the cell core E phase distribution is controlled by the heating sequence. The sequences most conducive for cell core fine dispersoid formation, in increasing order of effectiveness are:

- Heat at 37°C/h, hold at 200°C for 24 h, heat at 37°C/h to 450°C.
- Flash heat to 470°C, hold for 10 minutes, quench, reheat at 37°C/h to 470°C.
- Heat at 37°C/h to 470°C, quench, reheat at 37°C/h to 470°C.

After 470°C, 24-hour thermal exposure, most dense, fine dispersoid distribution is obtained by the last sequence. A simple heating sequence of 37°C/h to 470°C yields a relatively coarse precipitate, which dissolves during the 470°C soak, leaving a refined fine dispersoid distribution after 24 hours.

The first sequence is most successful in suppressing dynamic recrystallization during the subsequent hot rolling. A fine, dense E-phase distribution and the absence of a precipitate free zone (PFZ) in the area adjacent to the cell boundaries are effective in suppressing dynamic recrystallization (Fig. 2). Therefore, Cr additions in the amount of 0.22% in 7475 (5.7Zn-2.3Mg-1.5Cu-0.22Cr) alloy effectively inhibits recrystallization during hot rolling.

**Solution Treatment**

For effective heat treatment practices, the solution treatment is the
necessary first step to produce a solid solution in which the maximum practical amounts of soluble hardening elements are taken into solid solution in the alloy. The process consists of soaking the alloy at a temperature high enough and for sufficient duration to achieve a nearly homogeneous solid solution.

For alloy 2219 (6.3Cu-0.3Mn-0.18Zr-0.10V-0.06Ti), complete solid solubility of Cu cannot occur. Therefore, the solution temperature is established as close to the eutectic temperature as possible using existing equipment taking care to avoid overheating.

The rate of heating to the solution treatment temperature also is important. The heating rates used should ensure that no nonequilibrium melting occurs, and the best check for this is to use hot-stage microscopy to avoid this phenomenon. Alternatively, if lower temperatures are used, under-heating of components may result in realizing the full potential of the heat treatment practices.

The soak time is the time required for the alloy to be held at the solution temperature long enough to achieve homogeneity of the solid solution. This time varies from a few minutes for thin sheets to several hours for thicker product forms. Soak times for Alclad sheets or products should be minimal, because diffusion of alloying elements from the core into the cladding reduces the corrosion protection for which the cladding is intended.

Both 7475 and 2219 are susceptible to high-temperature oxidation during elevated temperature exposures. Protective fluoborate compounds are used in solution heat treatment furnaces to ensure that the aesthetics of components made of these alloys are not unduly affected by high-temperature oxidation.

**Quenching**

Quenching from the solution treatment temperatures to room temperature to produce a supersaturated solid solution, a prerequisite for artificial aging is perhaps the most critical step in the heat treatment process. A rapid quench from the solution heating temperature is imperative to form an effective supersaturated solid solution. The cooling rate between 400 and 260°C is most critical, and should be extremely high for both 2219 and 7475, because it is the critical range in which precipitation may occur should the cooling rate slow down. Suitable agitation of the quench media plays an important role in breaking up the insulating blanket of steam formed on the hot metal and improves quenching. Proper racking of parts for quenching also minimizes the possible distortion and residual stress (Fig. 3).

After quenching, a forming or straightening operation is conducted to remove residual stresses. For most 2xxx series alloys including 2219, cold working of freshly quenched material is beneficial as the material responds well during the subsequent aging treatment.

**Artificial Aging**

Aging of solution treated and quenched alloy is the final step in the heat treatment operation for most aluminum alloys. Artificial aging involves holding the alloy at a slightly elevated temperature (120 to 175°C for 7475, and 165 to 190°C for 2219) for sufficient duration to induce hardening through controlled precipitation of microstructurally favorable constituents. Typical heat treatment temperatures for alloys 2219 and 7475 are listed in Table 1.

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**Table 1 — Heat treatment parameters for 2219 and 7475 aluminum alloys**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Annealing temp., °C</th>
<th>Solution temp., °C</th>
<th>Aging temp., °C</th>
<th>Duration, h</th>
</tr>
</thead>
<tbody>
<tr>
<td>2219</td>
<td>415</td>
<td>535</td>
<td>190</td>
<td>18-36</td>
</tr>
<tr>
<td>7475</td>
<td>415</td>
<td>510-515(a)</td>
<td>120-175</td>
<td>3-26</td>
</tr>
</tbody>
</table>

(a) Soak at 465-477°C

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This article is adapted from the paper presented at 24th ASM Heat Treating Society Conference, September 17-19, 2007, Detroit, Mich., USA.
It is usual practice to complete forming and straightening operations before aging changes the mechanical properties of these alloys appreciably. When scheduling on the shop floor makes this impractical, certain alloys require refrigeration prior to forming operations. It is common practice to pack full-size aircraft wing plates in dry ice prior to forming and machining operations. Alloys in the T6 temper have the highest achievable strengths, whereas T7 represents an overaged temper, where some degree of strength has been sacrificed to improve one or more other characteristics, such as dimensional stability at elevated temperatures or reduction in residual stresses. The T7 temper is based on the fact that selective corrosion at grain boundaries is reduced with increased overaging. Aging temperatures in the range of 160 to 175°C are used following a controlled exposure at lower temperatures to allow the formation of a large number of GP (Guinier-Preston) zones that are stable at higher temperatures. These tempers are attained either by using a two-stage isothermal precipitation treatment or by heating at a controlled rate to a single treatment temperature[4].

### Thermochemical Aging (TMA) Treatments

Between quenching and aging operations, alloy 2219 responds well to cold working operations. Thermochemical treatment implies deforming the alloy after quenching and before aging. These treatments improve strength due to strain-induced precipitation of additional fine precipitates that strengthen the substructure of these alloys. Typical mechanical properties of 2219 and 7475 are tabulated in Table 2.

#### Conclusions

Alloy 2219-T8 is widely used by the Indian aerospace industry for cryogenic applications due to its excellent weldability and strength. Alloy 7475 in T73 and T76 tempers is used in military aircraft. Both the production and processing under indigenous conditions are challenging operations, and various agencies and R&D institutions have contributed to their development.

### References


### For more information:

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#### Table 2 — Mechanical properties of 2219 and 7475 Al alloys in commonly used tempers

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temper</th>
<th>YS, MPa</th>
<th>UTS, MPa</th>
<th>Elong., %</th>
<th>HBN 500 kg, 10 mm</th>
<th>Shear Strength, MPa</th>
<th>Fatigue limit, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>2219</td>
<td>O</td>
<td>70</td>
<td>170</td>
<td>18</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>T6</td>
<td>290</td>
<td>415</td>
<td>10</td>
<td>115</td>
<td>255</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>T81, T85</td>
<td>350</td>
<td>455</td>
<td>10</td>
<td>130</td>
<td>285</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>T87</td>
<td>395</td>
<td>475</td>
<td>10</td>
<td>130</td>
<td>280</td>
<td>105</td>
</tr>
<tr>
<td>7475</td>
<td>T6</td>
<td>496</td>
<td>552</td>
<td>12</td>
<td>—</td>
<td>296</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>T73</td>
<td>435</td>
<td>505</td>
<td>14</td>
<td>—</td>
<td>269</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>T76</td>
<td>462</td>
<td>524</td>
<td>12</td>
<td>—</td>
<td>269</td>
<td>—</td>
</tr>
</tbody>
</table>

Quenching from the solution treatment temperatures to room temperature to produce a supersaturated solid solution, a prerequisite for artificial aging, is perhaps the most critical step in the heat treatment process. A rapid quench from the solution heating temperature is imperative to form an effective supersaturated solid solution.