Significant Increase in Tensile Strength and Hardness in 2024 Aluminum Alloy by Cryogenic Rolling

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Abstract

Because of high strength to weight ratio and good resistance to corrosion, 2024Al alloy has attracted a high attention in the aerospace and shipbuilding industries. Most of the research activities to grain refinement lead to decrease in ductility. In this article, the researchers have developed a novel approach in achieving both high strength and good ductility in 2024 Al alloy. The approach involves Solid solution-treating, rolling at cryogenic temperature (containing a high density of dislocations) and artificial aging treatment to generate bimodal structure and nanosized S’ precipitates (Al2CuMg). Under optimal processing conditions, tensile strength (653 MPa), ductility (11% tensile elongation) and hardness (170 HV) were obtained.

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Keywords: Cryogenic rolling; Ultrafine grain size; Nanostructure; 2024 Al alloy; Precipitation; Aging; Mechanical properties.

1. Introduction

High strength in age hardenable alloys is caused by Precipitates. The major alloying elements in the 2024Al containing copper and magnesium. The major precipitates in this alloy are Al2CuMg and Al2Cu, Cheng et al. (2007).

According to Hall-Petch equation, the reduction of grain size results in increase of yield stress. However, the mechanical properties of ultra-fine structured materials can be further improved via improvement in dislocations density and precipitation, Sabirov et al. (2008).

Ultrafine grained and nanostructured materials (UFGNSM) were produced through severe plastic deformation (SPD) processes such as equal channel angular pressing (ECAP), and severe torsional straining. Utilization of these techniques in age hardenable alloys due to formations of precipitates and GP zones are very difficult to achieve UFGNSM. In other words, precipitates and GP zones in the microstructure can reduce dislocations movement. Therefore, ductility is reduced and moreover the material will be cracked during this process, Chinh et al. (2009).
On the other hand, the formation of UFGNSM by SPD methods are due to large deformations under very high pressures. The majority of these methods require large plastic deformation. However, Cryogenic Rolling (CR) relatively requires less force and in addition the low temperature in this approach prevents the dynamic recovery during deformation. Therefore a high density of defects will remain which can act as a potential recrystallization sites for precipitates, Doppalapudi et al. (2010).

The processing steps in Cryogenic Rolling include: (1) Solid solution-treating (SST); (2) rolling at cryogenic temperature; and (3) artificial aging treatment.

The current work focuses on the evolution of the mechanical properties in 2024Al alloy by Cryogenic Rolling. The goal is to improve strength, ductility, and hardness.

2. Experimental procedure

2.1. As received 2024Al alloy

A commercial 2024Al alloy sheets of 8mm thick was chosen for this investigation. The chemical composition of the material is given in table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Sn</th>
<th>Ti</th>
<th>Sb</th>
<th>V</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt %</td>
<td>4.089</td>
<td>1.443</td>
<td>0.425</td>
<td>0.123</td>
<td>0.013</td>
<td>0.039</td>
<td>0.015</td>
<td>0.010</td>
<td>Balance</td>
</tr>
</tbody>
</table>

2.2. Processing steps

The samples were cut with dimensions of 60mm (length) × 40mm (breadth) × 8mm (thickness). The as-received alloy samples were first solid-solution treated at a temperature 495 °c for 55 minutes and then quenched in water. Solutionized samples were immersed in a cryogenic-bath (liquid nitrogen). After that, samples were rolled along the longitudinal at liquid nitrogen temperature with a total reduction ratio of 85%. After each pass, the samples was immersed in liquid nitrogen. To optimize the strength - ductility combination, these CR materials were artificially aged.

2.3. Characterization tests

Specimens with a gage length of 25 mm, a thickness of ~1.2 mm and a width of 6 mm were used for uniaxial tensile testing. Specimens were machined as per ASTM E-8 specifications. Vickers hardness was measured to keep track of the hardness variation. Scanning electron microscopy (SEM) analysis had been conducted in a sample with optimum conditions.

3. Result and discussions

3.1. Experimental and Characterization results

Table 2 shows the tensile properties of 2024Al at different processing states. According to table, solutioning - cryogenic rolling and aging at 160 °c for 24h reveals the highest strength and elongation. The ultimate tensile strength increased about 1.39 times with reduction in ductility of 0.55 times as compared to as received samples. As the results show, the artificial aging treatment after Cryogenic Rolling not only increase the strength but also the elongation.
The reason for this phenomenon is two folds:

1. Formation of nano-sized $S'$ ($\text{Al}_2\text{CuMg}$) precipitates.
2. Production of an ultrafine grained and nanostructured bulk material (Bimodal structure)

The former, definitely increases the strength and hardness. The latter, not only improves the strength, but also due to the existence of ultrafine grained structure improves ductility, D. Doppalapudi et al. (2010). As a result, after aging treatment, a good combination of strength and ductility will be achieved.

Table 2. Tensile properties of 2024Al at different processing states.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Ultimate tensile strength MPa</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>As received</td>
<td>467 ± 10</td>
<td>20 ± 2</td>
</tr>
<tr>
<td>SST- CR</td>
<td>525 ± 20</td>
<td>3 ± 1</td>
</tr>
<tr>
<td>SST- CR- Aging (160 $^\circ$C - 1h)</td>
<td>539 ± 10</td>
<td>6 ± 3</td>
</tr>
<tr>
<td>SST- CR- Aging (160 $^\circ$C - 3h)</td>
<td>541 ± 15</td>
<td>8 ± 3</td>
</tr>
<tr>
<td>SST- CR- Aging (160 $^\circ$C - 6h)</td>
<td>648 ± 10</td>
<td>9 ± 4</td>
</tr>
<tr>
<td>SST- CR- Aging (160 $^\circ$C - 12h)</td>
<td>645 ± 12</td>
<td>10 ± 2</td>
</tr>
<tr>
<td>SST- CR- Aging (160 $^\circ$C - 24h)</td>
<td>653 ± 10</td>
<td>11 ± 3</td>
</tr>
<tr>
<td>SST- CR- Aging (160 $^\circ$C - 27h)</td>
<td>528 ± 15</td>
<td>6 ± 1</td>
</tr>
</tbody>
</table>

Figure 1 indicates the hardness variation with aging time at 160 $^\circ$C. In contrast to the alloy conventional T6 or T8 heat treatment, Cryogenic Rolling have led to higher alloy hardness and moreover, the ageing kinetics are much sooner (160 $^\circ$C - 24 h as compared to 190 $^\circ$C - 24 h for T8), T. Shanmugasundaram et al. (2006). This could be attributed to the formation of high-density dislocations introduced by the Cryogenic Rolling, which significantly accelerates heterogeneous nucleation of precipitates, Huang et al. (2011).
Figure 1 indicates the Vickers hardness variation of 2024 Al with different processing states in Cryogenic Rolling. The results show a significant increase in hardness as compared to as received samples.

Figure 2 shows fracture surface morphology of tensile sample of the SST- CR- Aging (160 °C - 24h). By applying aging treatment, soft to brittle fracture ratio in material increases. As it has been illustrated, there is a combination of fine and coarse dimples (yellow and green arrow). Decreasing grain size and increasing dislocations density can be due to the reduction of dimples’ size. This confirms the presence of the bimodal structure in SST- CR- Aging (160 °C - 24h) sample.
4. Conclusions

- 2024 Al alloy with a bimodal structure (ultrafine grained and nanostructured) was successfully produced via cryogenic rolling. The alloy had an increased ultimate tensile strength of 653 MPa, and a good ductility, 11%. The ultimate tensile strength increased about 1.39 times as compared to as received samples.
- In comparison to the as received samples, cryogenic rolling resulted an increased hardness (170 HV as compared to 128).
- In comparison to the alloy conventional T8 heat treatment, cryogenic rolling resulted a reduced ageing temperature (160°C as compared to 190°C).

References


Fig. 3. Fracture surface morphology of tensile sample of the SST- CR- Aging (160 °C - 24h).