Characterization of Mechanical Properties and Formability of Cryorolled Aluminium Alloy Sheets

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Abstract

Al-Mg alloys are extensively used in aerospace and marine industries due to their high strength to weight ratio and excellent corrosion resistance. Cryorolling is one of the important severe deformation processes to produce sheets with high strength. But low formability of cryorolled sheets limits their use in automotive industry. In the present work, formability of cryorolled AA5083 alloy sheets was characterized. Sheet samples were cryorolled and cold rolled with 80% reduction in thickness and mechanical properties were compared. Formability was determined in biaxial stretching mode through limiting dome height test. Partial annealing in the range of 150° C to 300° C was done on cryorolled AA5083 alloy samples to improve formability without significant loss of strength. Heat treatment in the range 200-250° C was found to be the optimum temperature for achieving a good combination of strength and formability.

Keywords: Cold rolling, Cryorolling, Annealing, Formability.

1 Introduction

Aluminum alloys with a wide range of mechanical properties are used in various engineering applications. Due to their lower weight and excellent corrosion resistance, Al alloys are extensively used in aerospace industry. In the automotive industry, there is a continuing trend towards use of aluminum alloys in vehicle construction. However, one of the limitations of aluminum alloys is lower strength and formability.

Improvement of mechanical properties of aluminum alloys has been an area of interest to material scientists. For ductile materials, enhancement of strength can be done by severe plastic deformation processes. These processes are typical metal forming processes where parent materials are subjected to very high strain in order to generate Ultra Fine Grain Structure (UFGS) with greater strength at the cost of ductility of the material [Naka & Yoshida, 1999]. Some of these are: Equal Channel Angular Pressing (ECAP), Accumulative roll-Bonding (ARB), High Pressure Torsion (HPT) and Cryogenic rolling (CYR) [Azushima et al., 2008].

Cryogenic rolling, also known as cryorolling, is one of the potential techniques to produce nanostructured bulk materials from its bulk counterpart at cryogenic temperatures which is nearly -196° C or liquid nitrogen [Gopi et al., 2012]. The majority of these methods require large plastic deformations (strains much larger than unity). In the case of cryorolling, the deformation in the strain hardened metals is preserved as a result of the suppression of the dynamic recovery [Sarma et al., 2008]. Figure 1 shows a schematic diagram of conventional cold rolling and cryogenic rolling processes using a two high rolling mill. In conventional cold rolling (CCR), the sheets are rolled at room temperature in number of passes to achieve the final thickness.
Aluminum alloys strengthened by cold or cryorolling exhibit reduction of ductility which would make the material unsuitable for forming applications. Therefore, a suitable heat treatment was given to the cold rolled (CLR) and cryorolled (CYR) sheets to improve ductility without sacrificing too much on strength. A partial annealing (recovery annealing) with temperature in the range 150-300°C (below the recrystallization temperature) for 30 min was done to achieve the desired combination of strength and ductility.

3 Material Characterization

3.1 Microstructure

The microstructures of the initial as received material is shown in Figure 2 (a) which reveals coarse equiaxed grains. The microstructures in cryorolled and coldrolled condition with 70% reduction are shown in Figure 2 (b) and 1 (c) respectively. The substructure formation with an unclear cell network has been found. But the microstructure of cryorolled sample after 70% reduction shows ultra fine grain structure possibly with grain size less than 1 micron. The grain refinement and increased dislocation density contribute to improved mechanical properties such as higher strength and hardness as compared to that of their bulk materials. The microstructure of cryorolled sample annealed at 250°C after 80% reduction is shown in Figure 2 (d). It reveals bigger grains than in cryorolled condition but much finer than in the initial as received microstructure.
Figure 2: Optical micrographs of AA5083 alloys in different conditions (a) as fully annealed; (b) after cryorolling at 70% reduction, (c) after coldrolling at 70% reduction and (d) partial annealing at 250°C after 80% reductions in cryorolling.

3.2 Hardness

Hardness tests were done using Vicker Micro hardness testing machine. 10 to 15 readings were taken and the average values have been plotted (Figure 3) as a function of annealing temperature for both coldrolled and cryorolled samples.

Figure 3: Variation of hardness with annealing temperature of cold rolled and cryorolled samples.

The hardness values in as rolled condition are also shown for comparison. The hardness values of as cryorolled material after 80% reduction are 12% higher than that of the cold rolled sheets. The enhancement of hardness of cryorolled sheets is due to higher dislocation density [Panigrahi & Jayaganthan, 2008]. The rolling of pure metals and alloys at cryogenic temperatures suppresses dynamic recovery and the density of accumulated dislocations reaches higher levels with the increasing number of cryorolling passes [Wang et al., 2003]. The hardness decreased with annealing temperature, the rate of reduction being greater beyond 250°C.

3.3 Tensile properties

Tensile samples of CLR and CYR sheets were tested on an Instron Machine at a constant crosshead speed of 2.5mm/min at room temperature. The samples were prepared by laser cutting according to ASTM Standards E8/E8M–11 (sub-size specification) as shown in Figure 4.
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Figure 4: Dimensions of subsize rectangular tension test specimens.

The load elongation data was obtained from the tensile tests on cryorolled and cold rolled specimens. Based on the load-elongation data, engineering stress - engineering strain were plotted and shown in Figure 5. The standard tensile properties such as YS, UTS and percentage elongation were calculated from these plots. Yield strength is taken as the stress at 0.2% offset strain.

Figure 5: Engineering stress vs engineering strain for rolled and annealed conditions of Al 5083 alloy.

From the results obtained, it can be observed that due to severe plastic deformation in cryogenic conditions, the yield stress and ultimate stress have increased substantially.

The cryo-rolled sheets were heat treated at four different temperatures, 150°C, 200°C, 250°C and 300°C for half an hour in the furnace and then allowed to cool inside the furnace. With increase in annealing temperature, the yield stress decreases as internal stress in the material is relieved, and it starts deforming at a much lower stress than in cryorolled condition. During recovery, the strain hardening ability is improved as rearrangement of dislocations inside the grains takes place during recovery without formation of new grains. Partial annealing, i.e. heating to a temperature range below the recrystalisation temperature and holding for some time is expected to soften the material by recovery process without significant loss of strength and hardness unlike in full annealing, where complete recrystallization would reduce hardness and improve ductility. The internally stored energy decreases with decrease in dislocation density and hence hardness and ultimate tensile stress values decrease with increase in annealing temperature.

The variation of YS and UTS and percentage elongation with annealing temperature of cryorolled and cold rolled samples are shown in Figure 6 and Figure 6 respectively. The results are summarized in Table 1 and Table 2 respectively.
Figure 6: Variation of strength and ductility of rolled AA5083 alloys with annealing temperature.

Table 1: Mechanical Properties of cryorolled-samples of AA5083 alloy

<table>
<thead>
<tr>
<th>Ann.Tem. (°C)</th>
<th>Hardness (VHN)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>%Elong.</th>
</tr>
</thead>
<tbody>
<tr>
<td>As rolled (80% reduction)</td>
<td>148</td>
<td>391</td>
<td>431</td>
<td>5.5</td>
</tr>
<tr>
<td>150° C</td>
<td>139</td>
<td>301</td>
<td>338</td>
<td>10.3</td>
</tr>
<tr>
<td>200° C</td>
<td>127</td>
<td>240</td>
<td>305</td>
<td>13.4</td>
</tr>
<tr>
<td>250° C</td>
<td>116</td>
<td>227</td>
<td>289</td>
<td>15.5</td>
</tr>
<tr>
<td>300° C</td>
<td>94</td>
<td>117</td>
<td>246</td>
<td>26.07</td>
</tr>
</tbody>
</table>

Table 2: Mechanical Properties of cold rolled-samples of AA5083 alloy

<table>
<thead>
<tr>
<th>Ann.Temp. (°C)</th>
<th>Hardness (VHN)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>%Elong.</th>
</tr>
</thead>
<tbody>
<tr>
<td>As rolled (80% reduction)</td>
<td>130</td>
<td>308</td>
<td>388</td>
<td>6.7</td>
</tr>
<tr>
<td>150° C</td>
<td>130</td>
<td>256</td>
<td>318</td>
<td>9.8</td>
</tr>
<tr>
<td>200° C</td>
<td>124</td>
<td>230</td>
<td>289</td>
<td>12</td>
</tr>
<tr>
<td>250° C</td>
<td>110</td>
<td>217</td>
<td>283</td>
<td>13</td>
</tr>
<tr>
<td>300° C</td>
<td>90</td>
<td>109</td>
<td>232</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Increase in annealing temperature increases percentage elongation of the material under tensile load. The maximum ductility was observed for specimens annealed at 300° C but it was associated with a sharp reduction in strength from 250° C to 300° C. Therefore, it is necessary to choose annealing temperature at which an optimum combination of strength and ductility can be obtained. In the annealing temperatures used in this study, a good combination of yield strength and ductility has been obtained in the temperature range 200-250°C (YS~230-240MPa and elongation ~15%).

4 Formability study

To characterize formability in case of deformation in bi-axial tension mode, Limiting Dome Height tests were conducted on a 100-ton hydraulic press and the dome height at the point of necking/failure was measured by a coordinate measuring machine. A schematic of the experimental set up used for LDH tests is shown in Figure 7.

![Figure 7 Diagram of LDH test set up with standard dimensions.](image)

The tested samples after annealing at different temperatures are shown in Figure 8. The LDH values of coldrolled and cryorolled samples for different annealing temperatures are summarized in Table 3.

![Figure 8: LDH test samples annealed at different temperatures.](image)
### Table 3 Limiting Dome Height (mm) for different samples

<table>
<thead>
<tr>
<th>Annealing Temperature</th>
<th>LDH for cold rolled</th>
<th>LDH for cryorolled</th>
</tr>
</thead>
<tbody>
<tr>
<td>200°C</td>
<td>5.22</td>
<td>6.18</td>
</tr>
<tr>
<td>250°C</td>
<td>8.38</td>
<td>8.96</td>
</tr>
<tr>
<td>300°C</td>
<td>11.08</td>
<td>12.14</td>
</tr>
</tbody>
</table>

It was found that experimentally the samples of both cryorolled and cold rolled sheets have very poor formability in the as rolled condition. No appreciable dome height was observed in LDH tests and hence it could not be measured. After the low temperature annealing, significant improvement in formability has been achieved. The LDH increased with increasing annealing temperature for both CYR and CLR samples due to increased ductility. Formability of CYR samples has been found to be higher than CLR samples. Formability improves with increasing strain hardening ability due to reduced dislocation density. Though LDH was maximum for samples annealed at 300°C, the best combination of strength and formability has been achieved with annealing temperature in the range of 200°-250°C.

### 5 Conclusions

Cryorolling is one of the potential routes to produce Al alloy AA 5083 sheets with ultrafine-grained structure. The suppression of dynamic recovery and accumulation of higher dislocation density contribute to improved mechanical properties. The CLR AA5083 alloy sheets exhibit higher strength and hardness than CLR alloys after 80% reduction. It is possible to improve formability of the CLR Al-Mg alloy sheets by partial annealing without significant loss of strength. The limiting dome height increased with increase in annealing temperature. Annealing in the range 200°-250°C has been found to give a good combination of strength and formability.

### 6 References


