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THE EFFECT OF TEMPERATURE ON THE FORMABILITY OF A HIGH STRENGTH ALUMINIUM AUTOMOTIVE ALLOY

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Abstract

The desire to reduce weight in automotive products is driven by a need to reduce CO$_2$ emissions. As such, to allow further weight reduction, higher performance aluminium alloys are in demand for sheet metal body structures. Due to their high strength to weight ratio 7xxx alloys are seen as an ideal candidate for this, however their use to date has been limited by poor formability. The formability of a 7xxx candidate alloy, 7021, has been assessed by way of tensile testing and deep drawing experimentation, both at room temperature and over an elevated temperature range. The formability of the alloy improved as the temperature was increased due to the lower flow stress experienced by the material during drawing. Microstructural analysis of samples post-forming showed a dimpled fracture surface with the dimple size increasing with temperature. Voids close to the fracture surface were shown to initiate at Fe-containing particles.

Introduction

Safety requirements, environmental restrictions, more advanced technological features and the desire for larger vehicles, has increased the weight of today's automobile. At the same time, the need for manufacturers to comply with ever increasingly stringent legislation, regarding CO$_2$ emissions and fuel consumption has resulted in the necessity to reduce the weight of cars [1]. The simplest and most effective way of reducing automobile weight is to make use of lighter materials for their structure[2]. Aluminium has been identified as a material which will allow such weight savings to be achieved whilst still maintaining the structural integrity of the final product [1–8]. Currently, the two alloy classes used in the automotive industry are the 5xxx and the 6xxx series aluminium alloys [6]. Due to their higher strength to weight ratio, 7xxx alloys are seen as an ideal candidate for further reducing vehicle weights without compromising structural integrity. However, to date, the use of 7xxx alloys in the automotive industry has been limited due to poor formability.
Due to the poor formability of high strength aluminium alloys at ambient temperature there has been a significant amount of research on forming at higher temperatures. Previous work has illustrated that by increasing temperature to above 300°C it is possible to improve the formability of alloys currently used within the automotive industry [9] and also newer 7xxx alloys [10]. Other work has illustrated that it may not be necessary to use such high temperatures to achieve good formability, and that temperatures in the range 150-250°C can lead to a significant improvement in formability[11]. Consequently, this study will focus on how the formability of a 7xxx candidate aluminium automotive alloy is affected at these temperatures.

**Experimental Methods**

An aluminium alloy 7021, provided by Constellium as 1.3mm thick sheet, was solution heat treated at 530°C for a period of one hour and water quenched prior to all testing. For the T4 temper condition the material was allowed to naturally age at room temperature for a period of seven days before testing. In the case of the T6 temper, after a period of seven days natural ageing, the material was artificially aged at 140°C, using a 20°C/hr ramp, and a hold time of 14 hours before being water quenched.

To assess the formability of the 7021 material, stress-strain curves were obtained by uniaxial tensile testing using an Instron 5885H uniaxial testing machine, fitted with a 30kN load cell. Elevated temperatures were achieved using an Instron environmental chamber (3119-408) and strain measurements were recorded using an Epsilon high temperature extensometer (Model: 3555BP-025M-050-HT) with a 25mm gauge length. A strain rate of 0.1s⁻¹ was used for all uniaxial tensile testing.

To investigate the influence of temperature on formability, deep drawing experiments were carried out at elevated temperatures up to 250°C using an Erichsen Sheet and Strip Metal Testing Machine (Model: 145/60), fitted with a 50mm diameter stainless steel punch. Both the clamp force (3.6kN) and punch speed (5mm/min) were controlled and maintained using the MES 3.35 software. Circular samples 110mm in diameter were used for deep drawing, leading to a drawing ratio of 2.2 in each successful draw. Elevated temperatures were obtained by heating the die using a digitally controlled heating stage (JUMO LR316). The punch was not heated during testing and graphite was used as lubricant in all cases.

**Results**

**Effect of Temperature on Uniaxial Tensile Testing**

Fig. 1 shows uniaxial tensile test results of the 7021 alloy in both T4 and T6 tempers, with the important data summarised in Table 1. In the T4 condition the yield stress and ultimate tensile strength (UTS) increased with temperature until 220°C after which point both fell. The strain to failure appeared relatively similar until 220°C above which it increased. Apparently anomalous strain to failure results were seen when tested at 170°C, with a significantly reduced strain to failure in all cases. Stable elongation (prior to necking), declined steadily with increasing temperature until 220°C, levelling off at this stage. In contrast the yield stress for the T6 temper only dropped noticeably above 220°C and then continued to decrease as temperature was increased. This same trend was seen for the UTS. However, the strain to failure of the T6 material increased steadily with temperature, unlike
the stable elongation which remained constant irrespective of temperature, until 250°C when it decreased. The stable elongation was similar in both the T4 and T6 materials when tested at 220°C.

![True stress strain curve](image)

Figure 1 - a) True stress strain curves for 7021 sheet tested over a range of temperatures; a) in T4 and b) T6 tempers.

Fracture Analysis of the 7021-T4 & T6 Tensile Specimens

When the fracture surfaces of both the 7021-T4 and 7021-T6 samples were analysed, as expected, a dimpled fracture surface was seen in all cases. The depth and width of the dimples increased with temperature. The samples at the lowest of the elevated temperatures showed very shallow dimples with serrated edges, in which it was possible to observe the presence of particles. For the T4 condition, when temperature was increased, the fracture
surface became uniformly covered in dimple sheets (Fig. 2a), whereas at lower temperatures the dimpled areas were dispersed between regions that showed evidence of a pure shear fracture (Fig. 2b). In the T6 condition the fracture surfaces did not show the same gradual transition from a homogeneously dimpled surface, at higher temperatures, to mixed dimple sheets and shear fracture, as in the T4 material. In contrast, in this temper the fracture surface only showed a fully dimpled ductile failure at 250°C (Fig. 2c) and at all lower temperatures the samples exhibited a mixed failure mode with regions exhibiting shear failure (Fig. 2d). From EDX measurements particles close to the fracture surface were found to contain Fe and Si. Fe-Si constituent particles were observed to be associated with void formation near to the fracture surface in each case. It was observed that the particles initiated voids by cracking at low temperatures (Fig. 2f), but as the temperature increased, the creation of voids was mainly caused by particle-matrix decohesion (Fig. 2e).

Table 1 - Summary of the uniaxial tensile data for 7021-T4 & T6 tested over a range of temperatures.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature °C</th>
<th>Yield Stress MPa</th>
<th>UTS /MPa</th>
<th>Strain to failure</th>
<th>Stable Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>7021-T4</td>
<td>150</td>
<td>120.1</td>
<td>187.2</td>
<td>0.23</td>
<td>0.127</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>145.1</td>
<td>192.6</td>
<td>0.14</td>
<td>0.104</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>187.1</td>
<td>220.7</td>
<td>0.22</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>205.3</td>
<td>221.3</td>
<td>0.28</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>165.9</td>
<td>177.4</td>
<td>0.24</td>
<td>0.046</td>
</tr>
<tr>
<td>7021-T6</td>
<td>150</td>
<td>247.8</td>
<td>269.8</td>
<td>0.19</td>
<td>0.056</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>256.0</td>
<td>279.1</td>
<td>0.20</td>
<td>0.056</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>245.3</td>
<td>267.7</td>
<td>0.20</td>
<td>0.056</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>222.5</td>
<td>246.5</td>
<td>0.22</td>
<td>0.053</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>179.4</td>
<td>189.4</td>
<td>0.23</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Figure 2 - Example fracture surfaces from the 7021 tensile specimens a) at 250°C and b) 220°C in T4 condition, c) at 250°C and d) 220°C in T6 condition. Fe-Si containing particles close to the tensile specimen fracture surface e) at 250°C and f) 150°C.
Effect of Temperature on Deep Drawability

In the T4 condition, a slight decrease in drawability was observed when the temperature was initially raised, probably as the result of a small amount of artificial ageing occurring during the heating stage. As temperature was further increased, drawability improved, with a fully drawn cup achieved at 190°C and 250°C, but with a reduction in drawability observed during testing at 220°C. In the samples that failed to produce a full draw, the point of fracture was independent of the rolling or transverse directions and failed in a variety of locations around the top of the cup. When a fully drawn cup was produced, earing was observed in both the rolling direction (RD) and 90° to the RD. In contrast, upon increasing temperature the drawability of the T6 samples gradually improved. The force required to draw the material also steadily decreased with temperature, as would be expected. When comparing the T6 material to the T4 it can be seen, that the T6 material was not as formable as in the T4 temper, but when 250°C was used as the forming temperature comparable drawability was observed, regardless of the temper condition.

![Figure 3 - Effect of temperature on the deep drawing displacement for the T4 and T6 temper conditions.](image-url)
Table 2 - Displacement and maximum force data from deep drawing tests over a range of elevated temperatures for 7021 in T4 and T6 starting tempers

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature /°C</th>
<th>Displacement /mm</th>
<th>Maximum force /kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>7021-T4</td>
<td>Room Temperature</td>
<td>21.7</td>
<td>68.9</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>20.3</td>
<td>52.3</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>22.1</td>
<td>55.5</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>Fully Drawn</td>
<td>55.8</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>21.4</td>
<td>54.7</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>Fully Drawn</td>
<td>51.1</td>
</tr>
<tr>
<td>7021-T6</td>
<td>Room Temperature</td>
<td>13.5</td>
<td>67.8</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>14.8</td>
<td>65.9</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>14.6</td>
<td>62.4</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>16.6</td>
<td>60.0</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>17.1</td>
<td>54.9</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>Fully Drawn</td>
<td>47.0</td>
</tr>
</tbody>
</table>

**Discussion**

The increase in yield stress and UTS seen in the 7021 alloy when tested in the T4 condition are likely to be due to the material artificially ageing during the heating period of the tensile test. At the lower temperatures the microstructure will only consist of primary particles, GP zones and solute clusters, whereas with increasing artificial ageing there will be an increased amount of η' and η particles present within the microstructure. Artificial ageing occurring during tests would explain the initial increase in yield stress and also the decrease in work hardening that was seen as the temperature increased. These changes in the microstructure could also explain the differences seen in the fracture surfaces of the materials. A heterogeneous dimpled surface, linked by areas of pure shear fracture at the lower temperatures, could be explained by void initiation at primary particles and shear failure between the voids. As the temperature is increased, a more homogeneously dimpled fracture surface is seen due to an increased density of coarser second phase particles. However upon increasing the temperature to 220°C and 250°C, the ductility of the T4 temper improved, primarily due to the reduced flow stress of the material, apart from these two instances at 220°C and 250°C in the T4 temper, the ductility of the material in the T4 and T6 temper was quite similar. The slight increase in yield stress initially observed with the T6 temper on testing at 170°C can be attributed to the material still artificially ageing to peak strength whereas the subsequent steady decrease in yield stress after 170°C could be attributed to the lower flow stress of the material at elevated temperatures. This could also explain the small increase in ductility seen over the higher temperature range, as the material could form a more stable neck at higher temperature.

As would be expected, the T4 temper shows better formability than the T6 at each temperature until 250°C, at which temperature the forming behaviour of the T6 samples converged with that of the T4, and both were able to fully draw a cup. However these results also show clearly that ductility alone is not a sufficient indicator for good formability of the alloy. In the T6 temper, the gradual increase in deep drawability can be attributed to the reducing flow stress as the temperature increases, which the tensile testing of the material highlighted. The increase in formability of the T4 temper material, from room temperature (RT) to 190°C can also be attributed to the lower flow stress of the material; yet increasing temperature further, to 220°C, led to a decrease in formability, indicating that it is not just the
lower flow stress that is controlling formability in this case. Indeed, the higher work hardening rate seen in the 190°C tensile test (Fig. 1) appears to ensure that the material is able to be drawn more effectively at the lower temperature, whereas at 220°C the material showed relatively little work hardening before the formability improves again at 250°C owing to the continued reduction in flow stress.

Conclusions

In this study the warm forming behaviour of 7021 has been investigated in both the T4 and T6 temper through tensile testing and deep drawing. In tensile testing the T4 temper exhibited increasing yield strength and UTS until above 220°C where it started to fall. The stable elongation also showed a steady decrease until the same temperature. In contrast the T6 temper showed a decrease in yield strength and UTS as temperature increased which coincided with a steady increase in strain to failure. Stable elongation in the T6 condition remained constant until 220°C at which point a drop was observed.

Fe-Si containing particles appeared to be responsible for the initiation of voids that lead to fracture. Void formation appeared to occur via two differing mechanisms, particle cracking and particle-matrix decohesion; the latter occurring mainly at higher temperatures. During deep drawing it was observed that with T6 material an increase in temperature lead to an increase in formability, with full drawability achieved at 250°C. However, full drawability was achieved in the T4 material at both 190°C and 250°C. At 190°C this was probably due to the material having the necessary work hardening ability to be able to withstand the stresses of a deep drawing operation and at 250°C the material became sufficiently soft to allow deep drawing.

This investigation will be further expanded upon by performing a full TEM and SEM analysis of the tensile and deep drawing samples, to allow the microstructural features leading to the changes in the formability to be elucidated fully. Microstructural analysis of the forming samples is necessary as the heating profile of the tensile test and the forming tests are slightly different, which could result in differing microstructures in the two tests, although they are not expected to be drastically different. Post-forming testing of the fully drawn cups will also be needed to discover which processing route will provide the best properties for industrial use.

References


