MULTIPLE $n$ BEHAVIOR IN AN AL-LI 2090 ALLOY

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Abstract

Clausing plane stress/plane strain specimens were used to study the work hardening behavior of a commercial 2090 Al-Li alloy. A single $n$ behavior was observed for the solution treated and underaged specimens. For the peak aged and slightly overaged specimens, a double $n$ behavior was noted. A mechanistic explanation for such behavior based on the effectiveness of the precipitate strengthening is provided.

Introduction

The concept of a multiple $n$ behavior, where $n$ is the work hardening coefficient is not accepted widely for describing the stress-strain behavior of polycrystalline materials. However, both double-$n$/1-4/ and triple-$n$/5-10/ behaviors have been reported by various investigators. Reasons based on microstructural and geometric factors have been suggested. Also, all these studies have focused on steels and brass. One class of alloys that have been studied extensively in the past decade are aluminum-lithium alloys. Aluminum-Lithium alloys are particularly attractive to the aerospace industry because of their lower density and higher stiffness compared to conventional aluminum alloys. However, they have unattractive fracture behavior, poor fatigue crack growth resistance and especially poor ductility compared to traditional high strength aluminum alloys/11/. This poor ductility is a prominent disadvantage in deformation processing of these alloys where planar plastic flow fields are frequently encountered. Such fields are of...
technical interest because of the adverse effects that planar flow has on the mechanical properties of metals. In this paper, the deformation behavior of a 2090 Al-Li commercial alloy in plane stress/plane strain is presented with a focus on the continuum work hardening behavior.

**Experimental Procedure**

The commercial 2090 Al-Li alloy was machined from a 50mm thick plate into Clausing specimens (Fig. 1). The loading axis was parallel to the rolling direction. The Clausing(plane stress/plane strain) specimen/12/ has come to be frequently used in experimental studies involving plane strain sensitivity/13/, shear localization/14/ and hydrogen embrittlement/15,16/. This specimen is well suited for both mechanistic and simple phenomenological studies because of its capability of producing a limited volume of essentially planar flow near its centerline without the complicating effects of large stress and strain gradients or hydrostatic stress while providing a flat gage section for easy surface

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**Nominal Dimensions (mm)**
- $L_0 = 75$
- $T = 6.3$
- $W_0 = 25.4$
- $t_0 = 2$
- $l_0 = 6.3$
- $r = 2.0$

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Fig. 1. Geometry and dimensions of the Clausing specimen.
observations. The machined specimens were then solution treated at 527°C for 2 hours. Two specimens were retained in the solutionized condition for mechanical testing. The other specimens were then aged at 200°C for 8, 16, 24 and 32 hours, two specimens being heat treated for each aging time. Thus for every heat treatment condition two specimens were mechanically tested. That is, for each condition of heat treatment, one specimen was continuously loaded to fracture while the other was incrementally tested. The following is the incremental testing procedure. The specimen was first loaded to just beyond the yield point, corresponding to a small plastic strain and then unloaded. The relevant dimensional (thickness, width and longitudinal) changes were measured. After this, the specimen was reloaded to another small strain increment and the above procedure repeated in several small strain increments till the specimen fractured. This incremental loading procedure allows close monitoring of the deformation behavior of the specimen during mechanical testing and also provides the capability of measuring changes in specimen dimensions during the process making it possible to experimentally determine true stress and true strain values. The continuous tests mentioned earlier were performed as a check to ensure that no aberrations occurred during incremental testing which would result in erroneous data or be different from the results for the specimens that were continuously loaded to fracture.

Results and Discussion

The stress-strain curves from, both, the continuous and the incremental tests were very similar, hence the data plotted here are taken only from the incremental test data. A simple power law \( \sigma = K\varepsilon^n \), where \( n \) and \( K \) are the work hardening and strength coefficients respectively was used to fit the mechanical test data for the various specimens aged for different times. Figures 2 and 3 show the true stress-strain and the double logarithmic plots for the incrementally tested specimens. Each data point corresponds to an increment of strain during the testing process. Extremely good fits (\( r^2 = 0.97-0.99 \)) were obtained for the solution treated
specimen and the specimens that were aged for 8 and 16 hours. However, the fits were not as good ($r^2=0.85$) for the specimens aged for 24 and 32 hours. Attempts were made to fit other constitutive equations such as the Ramberg-Osgood equation to the experimental data, but with little accuracy. Hence a double $n$ model was applied for the specimens aged for 24 hours and 32 hours to improve the accuracy of fit for these two specimens.

![True stress-strain plots](image1)

**Fig. 2.** True stress-strain plots for the various specimens.

![Double logarithmic stress-strain plots](image2)

**Fig. 3.** Double logarithmic stress-strain plots for the specimens. The arrow indicates the slope discontinuity.
Table 1 summarizes the values of the work hardening coefficients and the corresponding strain ranges for which they are valid for all specimens. It is quite clear from the stress-strain data that there is an effect of the heat treatment on the value of the work hardening coefficient. It is also interesting to note that the change in slope or slope discontinuity of the logarithmic stress-strain curves for the specimens aged for 24 and 32 hours occurs at a strain of 0.025 approximately. Even though the second linear segment after this change in slope is based on only a few data points, it can be seen from the stress-strain data that these are the trends that would be followed.

TABLE 1. η values and corresponding strain ranges for the specimens.

<table>
<thead>
<tr>
<th>Heat Treatment</th>
<th>Work Hardening Coefficient, n</th>
<th>Strain Range</th>
<th>Fracture Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solutionized</td>
<td>0.31</td>
<td>-</td>
<td>0.157</td>
</tr>
<tr>
<td>Aged 8h</td>
<td>0.16</td>
<td>-</td>
<td>0.067</td>
</tr>
<tr>
<td>Aged 16h</td>
<td>0.29</td>
<td>-</td>
<td>0.046</td>
</tr>
<tr>
<td>Aged 24h</td>
<td>0.17</td>
<td>ε &lt; 0.025</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>0.48</td>
<td>ε &gt; 0.025</td>
<td></td>
</tr>
<tr>
<td>Aged 32h</td>
<td>0.09</td>
<td>ε &lt; 0.025</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
<td>ε &gt; 0.025</td>
<td></td>
</tr>
</tbody>
</table>

As stated earlier, multiple η models are not widely accepted because of a dearth of convincing mechanistic explanations for their occurrence. What follows is a relevant mechanistic explanation based on experimental observations for the 2090 Al-Li alloy made during this research. No attempt is made to explain the microstructural aspects of the mechanism of deformation in these Al-Li alloys as this is already available in literature/17,18/. Suffice to say, that during the process of deformation in these alloys, the strengthening for the aged material is provided by the δ' (Al₃Li) precipitates which retain their coherency even after extended aging periods. The volume fraction of the δ' precipitate in
the 2090 alloy which is aged at 200 C is approximately 5%. Very importantly, it has also been shown that under the conditions of aging used in this study, composite precipitates consisting of a core of $\text{Al}_3\text{Zr}$ surrounded by a ring of $\delta'$ ($\text{Al}_3\text{Li}$) form after 24 hours of aging at 200 C /19/. It should also be noted that peak hardness for this 2090 Al-Li alloy under the heat treatment conditions described above occurs at about 32 hours of aging at 200 C /20/(also see Figure 4).

![Aging Time, h vs Hardness, HRK](image)

**Fig. 4.** Hardness as a function of aging time.

A mechanistic explanation for the observed single n values for the solution treated and the underaged material( 8 and 16 hours of aging) and the double n values for the peak aged and very slightly overaged tempers(24 and 32 hours of aging) is given below. The small-sized $\delta'$ ($\text{Al}_3\text{Li}$) precipitates which form at lower aging times(8 hours), are sheared by the dislocations/21/. This leads to planar slip and a low value of the work hardening coefficient(n=0.16). With increasing aging times(16 hours), the larger precipitates provide more resistance to the movement of the dislocations. The dislocations circumvent the particles by the Orowan mechanism. This results in the formation of dislocation tangles around the particles and promotes slip on secondary systems and causes strain hardening of the matrix manifested in a larger value of n=0.29. In
such cases, a single value of $n$ is sufficient to describe the work hardening behavior. For the 24h aged specimen, as a result of the formation of the composite $\text{Al}_3\text{Zr}\text{-Al}_3\text{Li}$ precipitate, the resistance offered to the movement of dislocations is high and cross slip becomes difficult/11/. Thus in the initial stages of deformation, the dislocations move freely in the matrix until they are blocked by the composite precipitate particles. Consequentially, the work hardening coefficient in this initial stage of deformation is low ($n=0.17$). The barrier to further movement of the dislocations results in the formation of dislocation pile-ups. These pile-ups exert a back stress on the dislocation sources which must be countered by larger applied stresses to overcome not only the back stress but also the interaction between the pile-ups and the geometrically necessary dislocations at the particle-matrix interface to cause further deformation. Thus, this second stage of deformation is characterized by an increase in the value of $n$. For this case, the deformation can be well described by a double $n$ model, where the initial deformation is characterized by a low $n$ value until saturation of the back stress due to the pile-ups at the composite particles occurs at a strain of approximately 0.025. After this a larger stress is necessary to cause deformation and this is manifested as a change in the value of $n$. This same behavior is representative of the specimen aged for 32h. For the solution treated specimen, the high value of the work hardening coefficient is an outcome of dislocation interaction as a result of multiple slip.

As stated earlier, such a triple $n$ behavior has been observed before in Clausing specimens for an AISI 1090 spheroidized steel and alpha brass/8,10/. In these cases, the multiple $n$ phenomenon has been attributed not only to the saturation of back stress as a result of dislocation pile-ups but also to the specimen geometry of the Clausing specimen. The Clausing specimen because of its geometry develops a plane stress/plane strain state when loaded uniaxially in tension. The plane strain state is produced when a constraint to deformation is created in the width direction of the gage section because of the rigid grip
sections of the specimen. This is true in ductile materials when necking is prominent in the width direction. For the aged Al-Li alloy which has low toughness, lateral necking is practically absent. Also, a double \( n \) behavior is not observed for the solution treated specimen which is relatively ductile compared to the aged specimens. Hence, the change in slope of the double logarithmic plot cannot be attributed to the effect of the constraint for the 24 h and 32 h aged specimens but rather to the barrier to dislocation cross slip provided by the \( \delta' \) composite precipitate.

**Conclusion**

The deformation behavior of a 2090 Al-Li was studied for different heat treatments using Clausing specimens which provide a plane stress/plane strain state when loaded uniaxially in tension. A mechanistic explanation based on phenomenological evidence is provided for the observed work hardening behavior in this alloy. A single \( n \) behavior was observed for the solution treated and specimens aged for 8 h and 16 h. The 24 h and 32 h aged specimens showed a double \( n \) behavior which is attributed to a two stage work hardening because of the effectiveness of the barrier provided by the \( \delta' \) composite precipitates to the movement of dislocations by cross slip.

**References**
