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INFLUENCE OF FORMING IN THE T3 CONDITION ON PROPERTIES OF 2090-T8X, 2091-T8X AND 8090-T8X

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ABSTRACT

A forming sequence for Al-Li alloys in which T3 material is aged directly to T8 without an intervening solution treatment would be desirable. Such a sequence would allow forming in a relatively formable condition, provide the deformation necessary for highest strength, and eliminate quenching distortion problems. In order to evaluate the feasibility of such a sequence, we have subjected samples of 2090-T3E27, 2091-T3 and 8090-T3 to various amounts of stretching, aged them for various lengths of time and measured their tensile strength and corrosion resistance, and characterized their precipitate microstructures. The results of these tests show some differences in response between the alloys but indicate that the proposed sequence is feasible.

I. INTRODUCTION

A general characteristic of current Al-Li alloys is the need for plastic deformation after solution treatment and before aging in order to develop high strength. This requirement places restrictions on the production sequences that can be used for forming of sheet metal parts. For instance, a typical sequence in which forming is done in the annealed condition, with subsequent solution treatment and aging, would result in a final strength significantly less than that of a T8 temper. This may not be acceptable for some applications. However, some Al-Li alloys have been shown to have good formability in the T3 condition [1]. Bend radii of 1.5 t for 1.6 mm (0.063 in.) sheet in the T3 condition are not uncommon. Thus, if the part could be formed in the T3 condition and subsequently aged directly to T8 without a solution treatment, high strength may be attainable. This production sequence is attractive because it avoids the necessity for quenching the formed part, thus eliminating attendant problems of distortion.

A complicating factor in the use of this sequence, however, is the non-uniform nature of the deformation in formed parts. Typical parts may have regions of very high strain, such as in the outer fibers of a small radius bend, adjacent to regions of little or no strain, such as flat webs. This non-uniformity of plastic deformation may lead to gradients in the strength of the formed part. Such strength gradients could cause unpredictable behavior of the part in service and would lower the design allowable strength. In addition, local gradients in deformation during forming may cause significant variations in the local state of precipitation. In addition to causing strength gradients, this may lead to locally enhanced corrosion or stress corrosion susceptibility.

To investigate the feasibility of this forming sequence, we have evaluated the effects of various amounts of deformation in the T3 condition on the subsequent precipitation, strength and corrosion resistance of several Al-Li alloys. Strength was evaluated by simple tension tests, corrosion resistance by the Modified ASTM Acetic Acid Salt Intermittent Spray (MASTMAASIS) test and precipitation by Differential Scanning Calorimetry (DSC). These tests were performed on samples that had been stretched by various amounts while in the T3 temper. For each condition, samples were under-aged, peak-aged and over-aged in order to determine the sensitivity of the material to variations in the aging parameters and to evaluate the applicability of the recommended aging parameters to samples deformed before aging.
II. EXPERIMENTAL METHOD

Three commercially available Al-Li alloys were used. 2090-T3E27, 1.27 mm (0.05 in.) thick was obtained from ALCOA; 2091-T3, 1.6 mm (0.063 in.) thick from Pechiney; and 8090-T3, 1.6 mm (0.063 in.) thick from Alcan. The chemical compositions in weight percent are listed below.

<table>
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<th></th>
<th>Li</th>
<th>Cu</th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Ti</th>
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<td>2090</td>
<td>1.6</td>
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<td>0.06</td>
<td>0.05</td>
<td>0.02</td>
<td>0.19</td>
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<tr>
<td>2091</td>
<td>1.8</td>
<td>2.1</td>
<td>1.6</td>
<td>0.03</td>
<td>0.04</td>
<td>0.02</td>
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<tr>
<td>8090</td>
<td>2.45</td>
<td>1.18</td>
<td>0.66</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>0.11</td>
</tr>
</tbody>
</table>

These analyses were supplied by the manufacturer except for 2090, which was analyzed by Grumman. All of the materials were used in the as-received condition.

Strips for stretching, 150 mm (6 in.) x 485 mm (19 in.), were sheared with the 485 mm direction parallel to the rolling direction. These strips were stretched a predetermined amount, (typically 3, 6 and 9%) on a Cyril Bath V21 stretch-draw press. Blanks for tensile samples, 150 mm (6 in.) x 12.5 mm (0.5 in.), were sheared from the stretched sheets in a longitudinal orientation. A reduced center section approximately 6.25 mm (0.25 in.) x 31.25 mm (1.25 in.) was machined in each specimen with a Tensilikut router. Three specimens were prepared for each test condition. Similarly, blanks for corrosion testing, 100 mm (4 in.) x 150 mm (6 in.), were also sheared from the stretched sheets. Some bend samples, 25 mm (1 in.) x 50 mm (2 in.), were sheared from unstretched sheet with the 50 mm dimension parallel to the longitudinal direction. They were bent 90° in a three point air bending press brake. The various samples were then aged in air furnaces. The peak aging temperatures employed were those recommended by the manufacturer to develop damage tolerant properties that match 2024-T3. Other aging treatments can be used to attain higher strengths.

A. Tensile Properties

The yield strength and elongation to failure of 2090-T3E27 after stretching and aging to a modified T8 temper are shown in Figure 1. Numerical values are also tabulated in Table 2. Each data point represents the mean of three tests. The elongations listed represent only plastic strain. The data show a strong effect of stretching on the yield strength in the under- and peak-aged condition. At peak aging (20 h), a 3% stretch in the T3E27 condition increases the T8X yield strength by 55 MPa from 495 MPa (72 ksi) to 550 MPa (80 ksi). Increasing the amount of stretch to 5 or 8%, however, has little additional effect on the yield strength. The ultimate strength responded to stretching in a similar manner, but the difference between 0 and 3% stretch was less. The elongation to failure did not show any systematic trends and generally varied between 3 and 5%.

For a given level of stretch, the effect of under-aging was pronounced and resulted in lower strengths. Over-aging had less of an effect but did result in a noticeable drop in both yield and ultimate strengths in stretched material. Un-stretched material did not overage, while stretched material did. Unlike the under- or peak-aged condition, when the samples were over-aged, stretching had little effect on the yield or ultimate strengths.

The effects of stretching in the T3 and subsequent aging on the yield and elongation of 2091 are shown in Figure 2. Tabulated data for this alloy are not given because of lack of space. This alloy behaved like 2090 in that the first 3% of stretch had the largest effect, but in this case, subsequent stretching continued to increase the yield strength. The behavior of the ultimate strength was similar, but the amount of increase was less. The peak aged UTS rose from 438 MPa (63.5 ksi) at 0% stretch to 451 MPa (65.4 ksi) at 3% and 464 MPa (67.3 ksi) at 9%. The peak-aged elongation to failure decreased as the amount of stretching increased, falling to 11% at 9% stretch from 15% with no stretch. The behavior of this alloy was rather insensitive to aging time. For a 3% stretch, the ultimate increased from 435 MPa (63 ksi) after 3 h to 470 MPa (68 ksi) after 48 h. This behavior is probably a consequence of the choice of a low aging temperature where the alloy does not attain peak strength. This time/temperature was recommended by the manufacturer to develop damage tolerant properties that match 2024-T3. Other aging treatments can be used to attain higher strengths.
The yield strength and elongation of 8090 are shown in Figure 3. The yield strength of this alloy responded well to stretching, with most of the increase coming after the initial 3% stretch. The behavior of this alloy was more like 2091 than 2090, however, because additional stretching caused additional strengthening. The ultimate tensile stress was not as greatly affected as the yield; it increased from 530 MPa (77 ksi) at 0% stretch to 565 MPa (82 ksi) at 7% stretch. The elongation decreased with stretching, falling to under 2% after 7% stretch. The elongation of 8090 was the lowest of the three alloys, both in the T3 and T87X conditions. In fact, difficulty was experienced due to premature failure of the T3 material during the initial stretching operation, and the 7% stretch was performed on reduced section tensile samples. The maximum elongation obtainable in the T3 was approximately 9%. The manufacturer's certificate of conformity showed 18% elongation for the lot, thus it is possible that this piece of material was non-representative. The yield and ultimate strengths were insensitive to over-aging but were somewhat reduced when under-aged.

Limited testing was performed on 2024 in order to provide a basis for comparison. The results are shown in Figure 4. With 2024, there was practically no effect of stretch on the peak aged or over aged T8 properties, but in an under-aged condition stretching caused a marked increase in the yield and ultimate strengths and a decrease in the elongation. Thus, stretching accelerated the precipitation kinetics in 2024 more than in the Al-Li alloys.

B. Corrosion Behavior

Corrosion testing of 2091 and 8090 after various amounts of stretching and subsequent under-, peak- or over- aging showed an overall insensitivity to these parameters. The observed corrosion behavior did not appear to be a sensitive function of alloy, stretch or aging practice. Alloy 2090 was not corrosion tested. The primary form of corrosion observed was pit blistering, which was relatively common on most of the samples. The occurrence of pit blistering is indicative of an exfoliation resistant material. Although there was no pronounced trend, alloy 2091 appeared to show more susceptibility to corrosion as the aging time increased.

Exfoliation was not expected in these tests because neither alloy had a lamellar grain structure. 8090 had a fine sub-grain structure while 2091 had a recrystallized structure except near the center of the sheet where some lamellar grains were observed. This residual lamellar structure appeared to lead to some cracking on edges which had been sheared and where the lamellar grain structure was exposed. This cracking was thought to be stress initiated and corrosion driven and its existence implies that 2091 with a lamellar grain structure in this state of aging might be susceptible to stress corrosion cracking. The amount of shear cracking observed in 2091 was similar to what would be expected in a 7075-T6 or 2024-T3 sample and thus did not indicate any enhanced susceptibility of Al-Li alloys.

The bend samples of 8090 did not show any difference in the severity of corrosion between the bend areas and the flat areas. 2091, however, showed somewhat deeper pitting in the bend areas.

C. Precipitate Microstructures

Thermograms from the 2090 alloy are shown in Figure 5. The solid line represents the precipitate microstructure in the T3E27 condition with 5% stretch. The data show the dissolution at about 150°C of the pre-existing GP zones and the subsequent formation at 250°C of the main strengthening precipitates, \( \delta' \), \( \delta \), and \( \delta_2 \) [3]. The effects of subsequent aging of this microstructure for 5, 20 and 80 h at 163°C are shown by the dotted and dashed lines in Figure 5. In the peak aged (20 h) condition, the GP zone phases are completely dissolved and the 250°C formation peak has been eliminated indicating a complete transformation of the precipitate microstructure. After only 5 h aging, however, there is still a significant 250°C formation peak present, indicating that the intermediate precipitate phases have not completely formed during this aging treatment. The over-aged microstructure is characterized by the absence of a 250°C formation peak and also the slight broadening and displacement to higher temperatures of the intermediate phase dissolution peak (approximately 225°C). This data correlates well with the tensile results which showed that the under- and over-aging treatments resulted in lower strengths.

There are two effects of stretching on the T3E27 microstructure, as shown in Figure 6. Stretching causes an increase in the GP zone peak enthalpy (area) and displaces it towards higher temperatures. This shows that the dislocations introduced during the stretch allow for additional precipitation of GP zones at room temperature and that these zones can grow slightly larger, indicating that complete precipitation had not occurred at room temperature. The major effect of stretching, however, is the acceleration of the intermediate phase formation reaction. Stretching caused the formation peak to shift from 262°C down to 246°C and to become sharper. This shows that the presence of the dislocations introduced during the
stretch causes a significant acceleration of the intermediate phase formation kinetics. It is also apparent from these curves that increasing the stretch from 5% to 8% had little additional effect on the precipitation kinetics, explaining why there was little additional strengthening observed after the greater stretch. The data in Figure 7 confirm this observation. They show the microstructures from Figure 6 after aging. These data show that 5% stretch caused a significant reduction in the enthalpy of the intermediate phase formation peak (262°C), but that additional stretch had little further effect.

DSC data from 2091 are shown in Figure 8. In this case, the aging temperature was low enough to avoid formation of the 270°C phase, and the primary effects of aging were to cause a transformation of the GP zone phase to a more stable strengthening phase which dissolves at approximately 225°C. Continued aging caused an increase in the volume fraction and stability of this phase, in agreement with the gradually increasing tensile results. Comparisons such as shown in Figures 6 and 7 for 2090 were also made for 2091. They show similar effects particularly with respect to acceleration of the 270°C formation peak.

The equivalent DSC data from 8090 are shown in Figure 9. This alloy is unlike the other two in that it has a small formation peak at approximately 175°C when in the T3 condition. Aging at 166°C completes this reaction, dissolves the GP zone phase and causes the appearance of a large dissolution reaction between 200 and 300°C. This represents the dissolution of the strengthening phases. In addition, it can be seen that aging at 166°C causes a systematic decrease in the enthalpy (area) of the 310°C formation peak. This is in contrast to the behavior of 2091, where the aging temperature was low enough to avoid formation of the higher temperature phase.

IV. DISCUSSION

The results of this study show that a production sequence in which T3 material is formed into parts and subsequently aged directly to a T8 condition without solution treatment appears to be feasible. The strengths obtained after a minimum amount of stretch are as high as the best obtainable in a mill T8 treatment and there does not appear to be any unusual increase in the exfoliation corrosion susceptibility.

The 2090 alloy appears to be particularly well suited to this sequence because its strength reaches a plateau after a minimum amount of stretch and is insensitive to further deformation. In this study, 3% was the least amount of stretch used, so it is not yet known if less stretch would suffice. To take advantage of the higher strength induced by deformation during forming in the T3 condition, the entire part would have to be deformed. This leads to a requirement for a minimum amount of stretch throughout the part. This will restrict this sequence to parts that have no undeformed areas, or will require the introduction of an additional stretching operation.

Under-aging of this material caused a significant decrease in strength. The effects of over-aging were not as pronounced and tended to minimize the differences between the strength of differently stretched areas.

The behavior of the 2091 alloy was generally similar to that of 2090 except that additional stretching caused some additional strengthening throughout the range examined. This alloy was the least sensitive to aging practice and could be under- or over-aged with little penalty. It was also the weakest and had much better ductility than 2090 or 8090.

The 8090 data showed this material to be less affected by the initial stretching operation and it also continued to become stronger with increasing stretch. Thus, it does not appear to have the “plateau like” behavior of 2090, but changes its strength with additional increments of stretch. It was somewhat sensitive to under-aging and insensitive to over-aging. The ductility of this material was very low, indicating that there may have been some unknown problems with this particular sheet.

The data from 2024 highlight the basic difference between it and the Al-Li alloys. 2024 was totally insensitive to stretching when it was peak- or over-aged. In the under-aged condition, however, high strength was attainable after stretching. This indicates that a different aging schedule would be desirable if 2024 were to be processed using this forming sequence in order to avoid over-aging due to the cold work. This difference in behavior between 2024 and Al-Li alloys is thought to be a consequence of the sluggish response of Al-Li alloys to room temperature aging and to the high aging temperature employed for 2024.

The DSC data show that the observed strengthening effects are readily interpretable in terms of the state of precipitation. These data are also expected to be useful in quality control or diagnostic situations where tensile tests cannot be made.
V. SUMMARY

Forming parts from 2090, 2091 and 8090 in the T3 condition and aging directly to a T8 condition is a feasible procedure.

The strengths developed are similar to those of typical T8 tempers, and gradients in the strength between heavily and lightly deformed areas are not excessive. A minimum amount of deformation throughout the entire part will, however, be desirable.

Exfoliation corrosion resistance is not adversely affected by this sequence and appears to be similar to that of other high strength alloys.

The microstructures developed by this process correlate well with the observed mechanical properties.

VI. ACKNOWLEDGMENTS

It is a pleasure to acknowledge technical discussions with P.N. Adler (Grumman Corp.) and K.R. Hasse (Kaiser Aluminum Corp.). The assistance of H. Baker for DSC, L. Burgess for heat treatment and P. Power for mechanical testing is greatly appreciated. This work was performed as part of the Independent Research and Development program at Grumman Corp.

VII. REFERENCES


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Figure 1. The effects of stretching 2090-T3E27 various amounts and subsequently aging to T8X.

Figure 2. The effects of stretching 2091-T3 various amounts and subsequently aging to T8X.

Figure 3. The effects of stretching 8090-T3 various amounts and subsequently aging to T8X.

Figure 4. The effects of stretching 2024-T3 various amounts and subsequently aging to T8X.
Figure 5. Effect of aging on 2090 with 5% stretch.

Figure 6. Effect of 5 & 8% stretch on 2090-T3E27.

Figure 7. Effect of stretching on 2090-T8X.

Figure 8. Effect of aging on 2091 with 3% stretch.

Figure 9. Effect of aging on 8090 with 3% stretch.