ALUMINUM-LITHIUM ALLOY RESEARCH

E.A. STARKE, JR
A.A. CSONTOS

TECHNICAL MANAGEMENT CONCEPTS, INC.
P.O. BOX 340345
BEAVERCREEK, OH 45434-0345

JUNE 1997

FINAL REPORT FOR SEP 1995 – JAN 1997

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

MATERIALS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7750

DTIC QUALITY INSPECTED 4
NOTICE

USING GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA INCLUDED IN THIS DOCUMENT FOR ANY PURPOSE OTHER THAN GOVERNMENT PROCUREMENT DOES NOT IN ANY WAY OBLIGATE THE US GOVERNMENT. THE FACT THAT THE GOVERNMENT FORMULATED OR SUPPLIED THE DRAWINGS, SPECIFICATIONS, OR OTHER DATA DOES NOT LICENSE THE HOLDER OR ANY OTHER PERSON OR CORPORATION; OR CONVEY ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY RELATE TO THEM.

THIS REPORT IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS, IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

KUMAR V. JATA, Project Engineer
Metals Development & Materials Processing Branch

KATHERINE A. STEVENS, Actg Chief
Metals Development & Materials Processing Branch

WALTER M. GRIFFITH, Asst Chief
Metals, Ceramics & NDE Division
Materials Directorate

Do not return copies of this report unless contractual obligations or notice on a specific document requires its return.
A recent Air Force program was focused on developing an isotropic aluminum-lithium alloy, having greater than two weight percent lithium. The addition of two weight percent lithium can reduce the density of aluminum by six percent and increase the modulus by twelve percent, thus offering significant benefits for weight savings in aerospace systems. The Air Force program was successful in that the difference between the longitudinal and 45 degree yield strengths of the experimental alloy was significantly reduced that previously observed for alloys containing greater than two weight percent lithium, i.e., only a 10% variation compared with 20-25% for commercially available alloys. The alloy, designated AF/C-498 has the composition of Al-2.7Cu-2.1Li-0.6Zn-0.3Mn-0.3Mg-0.5Zr and the standard aging treatment was to solution heat treatment, quench, stretch 6% and age for 24 hours at 150 degrees C. Unfortunately the elongation after this aging treatment is lower than the minimum of five percent that is desirable for aerospace applications.

The research under this contract was concerned with examining aging treatments that would improve the elongation with no sacrifice in strength or isotropic properties. The material studied was received from the Air Force Materials as 0.5 inch plate. The plate was marked that it had been solutionized at 540 degrees C, quenches, stretched 6%, and aged at 300 degrees F (149 degrees C) for 24 hours (T8).
Introduction

Aluminum-lithium alloys offer attractive properties for aerospace applications due to their low density, good strength, and fatigue crack growth resistance. However, these alloys have higher levels of anisotropy in their mechanical properties than conventional aerospace aluminum alloys. The anisotropy of Al-Li alloys is due, in part, to the very sharp textures that are developed during rolling and the precipitation of the strengthening particles on specific habit planes.

A recent Air Force program was focused on developing an isotropic aluminum-lithium alloy, having greater than two weight percent lithium. The addition of two weight percent lithium can reduce the density of aluminum by six percent and increase the modulus by twelve percent, thus offering significant benefits for weight savings in aerospace systems. The Air Force program was successful in that the difference between the longitudinal and 45° yield strengths of the experimental alloy was significantly reduced over that previously observed for alloys containing greater than 2 weight percent lithium, i.e. only a 10% variation compared with 20-25% for commercially available alloys. The alloy, designated AF/C-489 has the composition of Al-2.7Cu-2.1Li-0.6Zn-0.3Mn-0.3Mg-0.05Zr and the standard aging treatment was to solution heat treat, quench, stretch 6% and age for 24 hours at 150°C. Unfortunately the elongation after this aging treatment is lower than the minimum of five percent that is desirable for aerospace applications.

The research under this contract was concerned with examining aging treatments that would improve the elongation with no sacrifice in strength or isotropic properties. The material studied was received from the AF Materials Dir. as 0.5” plate. The plate was marked that it had been solutionized at 540°C, quenched, stretched 6% and aged at 300°F (149°C) for 24 hours (T8).

Experimental Results and Discussion

Initial examination of the plate revealed that it was not in the T8 temper, but was in the T36 temper. Figure 1 shows bright field transmission electron micrographs and the (011) selected area diffraction pattern (SADP) of the as-received material. The SADP has spots from the aluminum matrix and Al₅Li (δ⁺) precipitates and the bright field micrographs show the dislocation structure associated with the pre-age stretch. Figure 2 is a bright-field/dark-field pair, the dark field using a diffraction spot from the δ⁺ precipitates. The very fine δ⁺ is indicative of a naturally aged Al-Li alloy having approximately 2 wt.% Li. Figure 3 shows bright field micrographs of the as-received material using a (001) zone axis. These micrographs contain two types of dispersoids; the small ones are probably Al₂Zr and the larger ones are possibly Al₅CuMn. We haven’t confirmed the composition of the dispersoids at this time but will accomplish this on the follow-on contract. Also note that the larger particles create deformation zones during the pre-age stretch, Figure 3-f.

Figure 4 presents the SADP, bright-field and centered dark-field transmission electron micrographs from the (001) zone axis of the AF/C-489 after aging for 24 hours at 150°C. These micrographs illustrate the presence of both Al₅CuLi (T₁) and Al₅Cu (θ⁺) as well as δ⁺. Some of the precipitates are composites, probably Al₅Li and Al₂Zr. Figure 5 presents the SADP, bright-field, and centered dark-field TEM’s from slightly off the (011) zone axis
of AF/C-489 in the T8 temper and illustrates the “puckering” caused by θ⁺ along the subgrain boundaries. At this time, we do not have corresponding TEM’s of a high angle grain boundary.

The aging response at three different temperatures, 100°, 120°, and 150°C, of the as-received T36 plate was determined from hardness measurements, Figure 6. The lower aging temperatures, i.e. 100° and 120°C, were used in a two step aging study. Figure 7 shows the hardness curves as a function of aging at 150°C for samples given a first step aging treatment at 100°C for various times. Two step aging treatments for tensile tests were selected that produced similar hardness to the single 24 hour/150°C treatment. Similar hardness data for a 120°C first step aging are shown in Figure 8.

Both longitudinal and transverse tensile samples were machined from the as-received plate using ASTM standard E8 sub-sized tensile bars. They had a one inch gauge length and a nominal diameter of 0.25 inches. All samples were representative of the midplane of the plate. The thermal treatments and the results of the tensile tests are presented in Table I. It is obvious that the hardness results do not accurately predict the tensile properties, i.e. even though the hardness values were the same for the single-age and the selected treatments for the double-aged samples, the strengths were not always the same. However, one double-age treatment, 120°C for 8 hours followed by 21 hours at 150°C produced an almost equivalent strength to the 24 hour/150°C age, but with a 38% improvement in elongation, 7.43% versus 5.37%.

Scanning electron micrographs of the 150°C/24hr and 120°C/8hr/150°C/21hr are shown in Figure 9. The fracture surface for the single-aged sample is essentially perpendicular to the stress axis and primarily intergranular while the fracture surface for the double-aged sample is at approximately 45° to the stress axis and primarily transgranular. It is obvious that there is a difference in grain boundary structure, i.e. precipitate size and distribution and precipitate free zone width.

This preliminary study shows that a significant improvement in ductility can be obtained by modifying the heat treatment of this alloy from that originally used, i.e. 24 hours at 150°C. We believe that we can still improve the strength/elongation combination by optimizing the pre-age stretch and the double-age treatment and these studies are continuing under our new contract with TMC and with a grant from the Air Force Office of Scientific Research.
Figure 1: a) Selected area diffraction pattern (SADP) and b) Bright-field TEM micrographs (BFTEM) of the (011) zone axis for the as-received AF/C-489 alloy along the stretch direction.

Note that the (011) SADP indicates the presence of only the Al matrix and δ' precipitate spots while the BFTEM micrographs demonstrate the dislocation structure associated with the pre-age stretch.
Figure 2) Off (011) zone axis SADP for the as-received AF/C-489 alloy along the stretch direction and bright-field and dark-field TEM micrographs utilizing the transmitted and δ' precipitate diffracted beams, respectively.

Note the extremely fine δ' precipitate size and distribution in the dark-field TEM micrograph which is indicative of the T36 natural aging temper.
Figure 3: a) SADP of the (001) zone axis for the as-received AF/C-489 alloy in the through thickness direction. b/c) Low-magnification BFTEM micrographs demonstrating the varying disperoid sizes & distribution. d & e-g) BRTEM micrographs illustrating the dislocation structure associated with the pre-age stretch in the Al matrix and across various disperoids, respectively.
Figure 4:  SADP, bright-field, and centered dark-field TEM micrographs from the (001) zone axis of the AF/C-489 alloy with a T8 temper at 150°C for 24 hours which illustrate the presence of both T₁ and θ'' plates as well as δ' spheres and coatings along the interface between the precipitate plates and the matrix.
Figure 5: SADP, bright-field, and centered dark-field TEM micrograph series from slightly off the (011) zone axis for the AF/C-489 alloy with a T8 temper at 150°C for 24 hours which illustrate the puckering of θ" plates along the subgrain boundaries
Figure 6: Rockwell B hardness versus aging time at various temperatures for AF/C 489-T36.
Double Aging 100°C 24/48/72 hrs and 150°C X hrs

Figure 7: Rockwell B hardness versus aging time after various pre-aging treatments for AF/C 489.
Double Aging 120°C 8/12/24/48 hrs and 150°C X hrs

Figure 8: Rockwell B hardness versus aging time after various pre-aging treatments for AF/C 489.
Figure 9:  

a, c, & e) SEM micrographs of the fracture surfaces for the AF/C 489-T36 alloy aged at 150°C for 24 hrs.

b, d, & f) SEM micrographs of the fracture surfaces for the AF/C 489 alloy pre-aged at 120°C for 8 hrs 20 minutes with a final age at 150°C for 21 hrs.
<table>
<thead>
<tr>
<th>Annealing Condition</th>
<th>Direction</th>
<th>$\sigma_{YS}$</th>
<th>$\sigma_{UTS}$</th>
<th>% El</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Received</td>
<td>Longitudinal</td>
<td>37.7 Ksi 260 Mpa</td>
<td>48.7 Ksi 337 Mpa</td>
<td>18%</td>
</tr>
<tr>
<td>$150^\circ$C 24 hrs</td>
<td>Longitudinal</td>
<td>68.54 Ksi 473 MPa</td>
<td>79.96 Ksi 551 MPa</td>
<td>5.37%</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>57.88 Ksi 399 MPa</td>
<td>76.15 Ksi 525 MPa</td>
<td>4.25%</td>
</tr>
<tr>
<td>$100^\circ$C 24 hrs / $150^\circ$C 16.5 hrs</td>
<td>Longitudinal</td>
<td>64.02 Ksi 441 MPa</td>
<td>77.54 Ksi 535 MPa</td>
<td>7.43%</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>52.10 Ksi 359 MPa</td>
<td>74.87 Ksi 516 MPa</td>
<td>6.76%</td>
</tr>
<tr>
<td>$100^\circ$C 24 hrs / $150^\circ$C 18 hrs</td>
<td>Longitudinal</td>
<td>63.41 Ksi 437 MPa</td>
<td>76.24 Ksi 526 MPa</td>
<td>7.28%</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>51.95 Ksi 358 MPa</td>
<td>73.49 Ksi 507 MPa</td>
<td>5.95%</td>
</tr>
<tr>
<td>$100^\circ$C 48 hrs / $150^\circ$C 18 hrs</td>
<td>Longitudinal</td>
<td>61.88 Ksi 427 MPa</td>
<td>76.01 Ksi 524 MPa</td>
<td>6.68%</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>51.80 Ksi 357 MPa</td>
<td>74.49 Ksi 514 MPa</td>
<td>6.16%</td>
</tr>
<tr>
<td>$100^\circ$C 72 hrs / $150^\circ$C 18 hrs</td>
<td>Longitudinal</td>
<td>60.50 Ksi 417 MPa</td>
<td>76.09 Ksi 525 MPa</td>
<td>8.14%</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>51.95 Ksi 358 MPa</td>
<td>73.64 Ksi 508 MPa</td>
<td>5.81%</td>
</tr>
<tr>
<td>$120^\circ$C 8 hrs 20 min / $150^\circ$C 21 hrs</td>
<td>Longitudinal</td>
<td>66.85 Ksi 461 MPa</td>
<td>77.79 Ksi 536 MPa</td>
<td>7.43%</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>56.72 Ksi 391 MPa</td>
<td>75.16 Ksi 518 MPa</td>
<td>6.37%</td>
</tr>
<tr>
<td>$120^\circ$C 12 hrs / $150^\circ$C 21 hrs</td>
<td>Longitudinal</td>
<td>65.90 Ksi 454 MPa</td>
<td>77.56 Ksi 535 MPa</td>
<td>6.67%</td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td>55.79 Ksi 385 MPa</td>
<td>74.56 Ksi 514 MPa</td>
<td>5.32%</td>
</tr>
</tbody>
</table>