# A STUDY OF THE FRACTURE BEHAVIOR, DEFORMATION MECHANISMS, MICROSTRUCTURES, AND DUCTILITY OF PRECIPITATION STRENGTHENED ALUMINUM-LITHIUM ALLOYS

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ABSTRACT

The effect of microstructure as a consequence of precipitation aging on the fracture behavior, deformation mechanisms, mechanical properties, and microstructures of aluminum-lithium was studied. The alloy studied was an aluminum-lithium-zirconium alloy. The precipitation response with aging time and temperature was studies in order to correlate the deformation response to the alloys to the heat treating, microstructure, and fracture surface characteristics and features. The primary focus of this study was to relate the variation in ductility with aging to the microstructural parameters and fracture mechanisms. An aluminum alloy containing 2.6wt.%Li and 0.09wt.% Zr exhibited very low tensile ductility consistently prior to the peak-aged strength independent of thermal treatment. A transition was characterized by very low ductility in the slightly underaged condition up to the near peak-aged condition, then followed by a substantial increase in ductility with aging after the peak-aged treatment. Based on the quantitative microscopy of the size of the precipitates, it was proposed that the increase in the ductility of the alloy after aging was a consequence of particle coarsening with aging and resulting in Orowan looping due to the transition from dislocation particle shearing to dislocation particle bypassing with increasing precipitate size. As the interparticle spacing increased with overaging, and the dislocations were impeded by and thus bypassed the larger particles, the amount of plastic deformation increased as was reflected by the strength and ductility experimental data.

## 1 INTRODUCTION

The precipitation hardening response of an aluminum alloy containing lithium and zirconium was studied in order to correlate the deformation response of the alloy to heat treating, microstructure, and fracture surface characteristics. The primary focus of this study was the relationship between strength, ductility microstructural parameters and fracture mechanisms. The brittle behavior of the aluminum-lithium alloy differed substantially from ductility response of various other precipitation strengthened aluminum alloys. Material in the slightly underaged and near peak-aged condition exhibited very low ductility, but a transition was observed on aging beyond the peak strength condition when ductility increased substantially. However, in many aluminum alloys, the ductility does not reach such a low value which is because the dislocations can cross-slip due to the high stacking fault energy of aluminum. However, in aluminum-lithium alloys, cross-slip has not been seen since the dislocations move in pairs thus reducing the probability of cross-slip [1], and also because the coherency strains are small around the particles [2]. The cross-slip process will tend to reduce the tendency toward slip planarity. The planarity of slip in Al-Li alloys is thus more pronounced than that observed in non lithium containing aluminum alloys such as the Al-Cu and Al-Zn alloy systems [3]. A planar slip distribution thus often occurs with heat treated Al-Li alloys containing ordered coherent precipitates. In order to better understand the deformation behavior of the alloy, surface features and fracture morphology were analyzed by scanning electron microscopy. Samples with different extrusion geometries, extrusion ratios, and extrusion temperatures were examined. The objectives were to characterize the fracture surfaces according to aging time, to identify the microstructural features which play a role in the fracture behavior, and to provide an explanation for the prominent fracture mechanisms. The scanning electron micrographs of the tensile fracture surfaces revealed predominately transgranular fracture below and around peak-aging. In addition, transmission electron microscopy (TEM) was performed on thin foil samples from several different aging conditions to study the internal structure of the precipitation hardened alloy. Both the size distribution of particles and the dislocation subgrain structure were studied. The underaging, peak-aging, and overaging thermal treatments of the alloy were analyzed with transmission electron microscopy, and quantitative particle size measurements were performed to determine the size, distribution, morphology, and coarsening rate for both δ' ($Al_3Li$) precipitates and for composite, $Al_3Li/Al_3Zr$, particles. Quantitative measurements of the precipitate particle were performed directly from TEM micrographs. From this study, it was determined that the ductility was directly related to the size, distribution, and spacing of the intermetallic precipitate particles. It was also found that subgrain size had a negligible effect on the tensile properties.

For aluminum-lithium alloys which are strengthened by coherent deformable particles, the dislocations often shear the precipitates in the underaged condition and usually bypass the precipitates in the overaged condition. The thermal treatment resulted in the nucleation, growth, and coarsening of intermetallic particles that could only be seen at very high magnifications with a transmission electron microscope. In the peak-aged condition, a combination of dislocation particle shearing and particle bypassing can sometimes occur simultaneously due to a distribution of both large and small particle sizes. For the Al-Li alloy, the plastic deformation is controlled by δ'($Al_3Li$) particles randomly distributed throughout the microstructure which impede dislocation motion. The δ' particle size, spacing, volume fraction, and distribution are a direct consequence of the aging practice and composition, and control the extent of plastic deformation. The aluminum-lithium alloy involved in this research was solution heat treated and artificially aged in order to obtain a microstructure containing a uniform distribution of δ'($Al_3Li$) precipitates. The aluminum-lithium alloy also contained a small amount of zirconium as an alloying element. Zirconium has been shown [1] to be a beneficial alloy addition to refine ingot grain size and control recrystallization.

## 2. DUCTILITY AND BRITTLE FRACTURE BEHAVIOR

As seen from Figure 1, the ductility reaches a minimum before the maximum peak-aged strength condition is obtained for the 185$^oC$ heat treatment, and occurs around the peak-aged condition for the 193$^oC$ aging practice This minimum in the ductility can be attributed to a large extent on the planar deformation and strain localization of this alloy. The ductility of the alloy becomes very brittle, to approximately 0.1% elongation, and thus the influence of planar deformation in controlling the ductility is reflected in this elongation response to heat-treatment. The scanning electron micrographs of the tensile fracture surfaces revealed predominately transgranular fracture mechanism below and around peak-aging associated with the low ductility. However, after this brittle behavior, the ductility improved past the peak-aged heat treatment into the overaged condition. After the peak aged condition and longer aging times the ductility continued to increase as the strength continued to decrease. The strength ductility behavior shown in Figure 2, was driven by the intensity of planar deformation. However, the ductility recovered with further heat treating due to the growth and coarsening of the δ' particle to sizes larger than the minimum Orowan looping radius ($r_{loop}$). Once the particles have achieved sizes larger than $r_{loop}$, the particles become bypassed and looped by the dislocations rather than cut or sheared by the dislocations, and hence the slip planarity and strain localization mechanisms become less and eventually no longer dominate or even contribute in the overaged condition. Sainfort and Guyot [4] reported observations of dislocation loops around particles in the peak-aged heat treatment of an Al-Li-Cu alloy, thus, suggesting that the planar slip mechanism may not be the most dominate process controlling the ductility. Due to the given distribution of particle sizes around the peak-aged condition, some of the particles are sheared while other larger particles are looped by the dislocations. Thus, there is a competition between the strain localization and Orowan looping mechanisms influencing the ductility. In the underaged conditions, where all of the particles are small in size, and thus less than $r_{loop}$, the strain localization controls the ductility due to the successive cutting of the precipitates by the dislocations. There is a definite average particle size below which particles are sheared by dislocations and above which dislocations pass around the particles and form a loop [5,6]. In the severely overaged heat treatment where all of the particles have matured and increased to sizes greater than the critical Orowan looping size, the particles are no longer successively sheared by the dislocations and thus the strain localization no longer dominates. A transition was characterized by very low ductility in the slightly underaged condition up to the near peak-aged condition, then followed by a substantial increase in ductility with aging after the peak-aged treatment. The ductility decreased to less than one percent elongation in the slightly below peak-strength, and then substantially increased with continued precipitation after the peak-strength. However, in many aluminum alloys, the ductility does not reach such a low value which is because dislocations can cross-slip due to the high stacking fault energy of aluminum. However, in aluminum-lithium alloys cross-slip does not usually occurs due to because the dislocations travel in pairs and the coherency strains around the particles are small. In order to better understand the deformation and fracture, a scanning electron microscopy study of the fracture surfaces of Al-2.6wt.%Li-0.09wt.%Zr tensile samples solution heat treated and artificially aged was performed to relate the mechanical behavior to microstructure in the precipitation hardened Al-Li alloy. Scanning electron microscopy (SEM) analysis of the surface features and fracture morphology of the alloy was performed to understand the mechanisms of fracture in relation to the ductile to brittle transition that resulted in the alloy from precipitation hardening. Transmission electron microscopy (TEM) analysis was also performed to characterize the deformation behavior, and revealed the distribution of precipitates (both $Al_3Li$ ($\delta'$) precipitates and $Al_3Zr$-$Al_3Li$ precipitates) in the microstructure at very high magnifications as well as the dislocation subgrain structure of the alloy at lower magnification. Microstructural variables that influence the ductility, strength and toughness include the grain size, the size and distribution of the precipitate particles, grain boundaries, and dislocations. The strengthening response of the alloy was a consequence of ordered coherent $Al_3Li$ precipitates in the microstructure which impeded the dislocation glide motion during plastic deformation. Quantitative microscopy was performed to characterize the deformation behavior, and revealed the distribution of $Al_3Li$ and $Al_3Zr$-$Al_3Li$ precipitates in the microstructure at very high magnifications as well as the dislocation subgrain structure of the alloy at lower magnification. It was proposed from this study that the presence of $\delta'$ particles in the matrix promotes intense planar slip which was believed to be responsible for the ultra-low ductility prior to the peak-aged temper. The strengthening was found to be controlled by dislocation shearing $Al_3Li$ particles in the underaged condition, and dislocation bypassing $Al_3Li$ particles in the overaged condition. Based on a detailed quantitative microscopy study, it was proposed that the increase in the ductility of the alloy after peak-aging was a consequence of particle coarsening with aging resulting in the Orowan process during plastic deformation due to the transition from dislocation particle shearing to dislocation particle bypassing. Thus, from this study it was found that the ductility was directly related to the size, distribution, and spacing of the intermetallic precipitate particles. The $\delta'$ particle size, spacing, volume fraction, and distribution are a direct consequence of the aging practice and composition, and control the extent of plastic deformation. It was also found from the TEM analysis that the subgrain size had a negligible effect on the tensile properties.

Based on SEM analysis of the fractured surfaces on the aluminum-lithium-zirconium alloy, transgranular shear type fracture mode occurred in the underaged and peakaged conditions. However, the severely overaged condition exhibited a primarily intergranular fracture, most likely due to the formation of precipitate free zones at the grain boundaries. The SEM of the solution heat-treated condition exhibited a dimpled ductile fracture mode with dimpled microvoid. The alloy exhibited extremely brittle behavior, with very low elongation, immediately prior to and around the peakaged heat-treatments. The proposed factors controlling the ductility of the Al-Li alloy were planar deformation and subsequent localization in the underaged and peak-aged conditions. At the peak-aged condition and longer aging times, the ductility began to increase as the strength decreased. The strength ductility behavior appeared to the peak-aged condition, appeared to be driven by the intensity of planar deformation. The extent of planar deformation in controlling the ductility is reflected in the very low elongation response to the heat treatments. Planar deformation or inhomogeneous planar slip creates stress concentrations at the end of slip bands. Planar slip deformation is associated with strain localization in the form of intense slip bands of deformation. It was also found thought that the Orowan process, and microvoid growth at grain boundary precipitates, were important factors in the overaged conditions with respect to the improved ductility of the alloy with further artificial aging after the peakaged heat treatment. Based on the TEM quantitative microscopy of the size of the precipitates, it was proposed that the increase in the ductility of the alloy after aging was a consequence of particle coarsening with aging and resulting in Orowan looping due to the transition from dislocation particle shearing to dislocation particle bypassing with increasing precipitate size. As the interparticle spacing increased with overaging, and the dislocations were impeded by and thus bypassed the larger particles, the amount of plastic deformation increased as was reflected by the strength and ductility experimental data.

## 3. SUMMARY AND CONCLUSIONS

An experimental study of the consequence of the thermal processing schedule on the thermomechanical behavior and microstructural evolution of an Al-2.6wt.%Li-0.09wt.%Zr alloy. This alloy was solution heat treated and artificially aged for a series of aging times and temperatures was performed at various thermally heat treated conditions. Both the solution heat treating and artificial aging steps of the thermal processing were directly followed by a cold water quench. The thermal treatment resulted in the nucleation, growth, and coarsening of intermetallic particles. The growth and coarsening kinetics were strongly dependent on the thermal processing parameters such as temperature and time. The average particle size, distribution, spacing, and volume fraction of the intermetallic precipitates directly related to the heat treating practice and composition, and correlated to the overall deformation behavior. For all of the heat treating times and temperatures studied the composite $Al_3Li/Al_3Zr$ particles were much larger than the δ', $Al_3Zr$ –free, particles. The particle coarsening rate which was a function of the aging temperature, for the composite $Al_3Li/Al_3Zr$ particles was more rapid than that of the δ' $Al_3Li$ precipitates. Increasing the aging temperature and the presence of the $Al_3Zr$ phase was found to accelerate the aging kinetics of the alloy. Therefore, a small increase in the temperature and or a small amount of zirconium in the alloy resulted in a faster particle coarsening rate of the overall combined particle size distribution, and thus caused the alloy to age more rapidly. Based on SEM analysis of the fractured surfaces of the Al-Li-Zr research alloy, the transgranular shear type fracture mode occurred in the underaged and peak-aged conditions. However, the severely overaged condition exhibited a primarily intergranular fracture, most likely due to the formation of precipitate free zones at the grain boundaries. The SEM of the solution heat-treated condition revealed a dimpled ductile fracture mode with dimpled microvoids. The alloy exhibited extremely brittle behavior, with very low elongation, immediately prior to and around the peak-aged heat-treatments. The proposed factors controlling the ductility of the binary Al-Li alloy were planar deformation and subsequent strain localization in the underaged and peak-aged conditions. At the peak aged condition and longer aging times the ductility began to increase as the strength decreased. The strength ductility behavior up to the peak-aged condition, appears to be driven by the intensity of planar deformation. It was also proposed that the Orowan mechanism, and microvoid growth at grain boundary precipitates, where important factors in the overaged conditions with respect to the improved ductility of the alloy with further artificial aging after the peak-aged heat-treatment. Based on the TEM quantitative microscopy of the size of the precipitates, it was proposed that the increase in the ductility of the alloy after aging was a consequence of particle coarsening with aging and resulting in the Orowan process due to the transition from dislocation particle shearing to dislocation particle bypassing with increasing particle size.

## 4. REFERENCES


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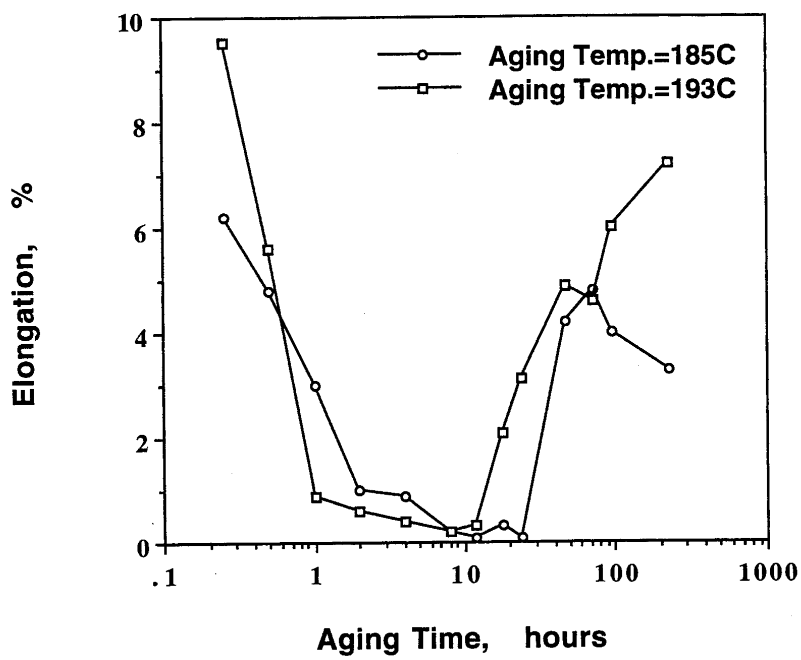


Figure 1: Comparison Between the Ductility Elongation Percent of the 185°C and the 193°C Aging Practices for the Al-2.6wt.%Li-0.09wt.%Zr Alloy.

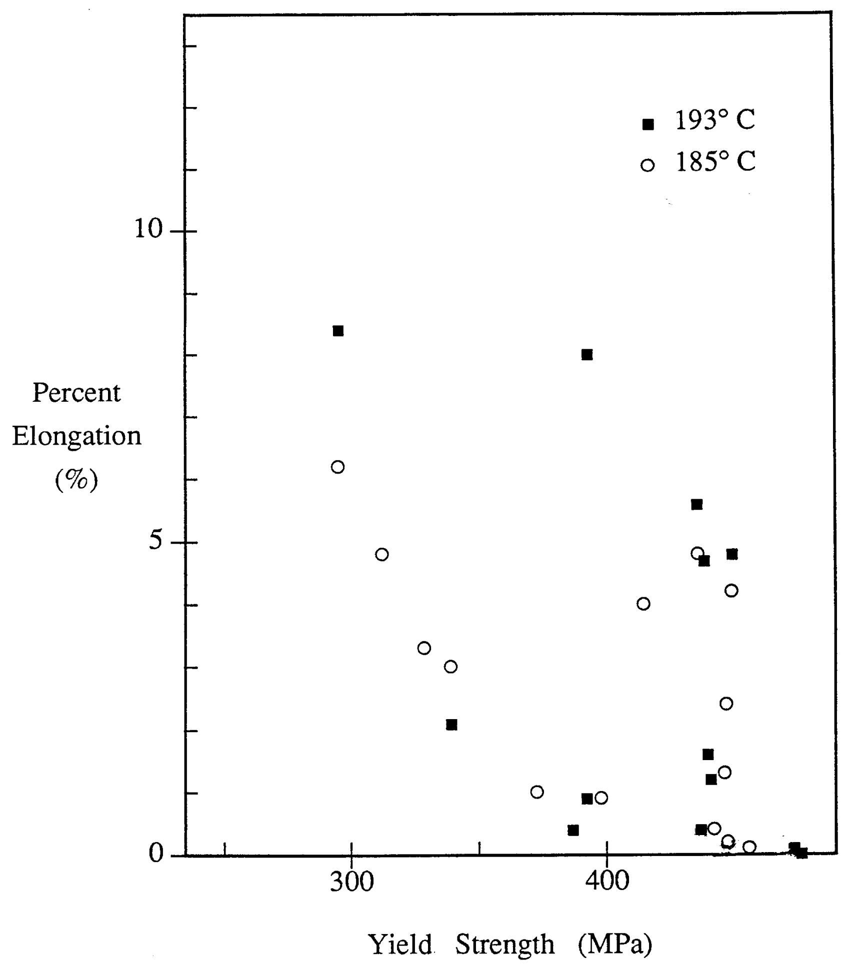


Figure 2: Comparison Between the Elongation versus the Yield Strength for the Al-2.6wt.%Li-0.09wt.%Zr Alloy Artificially Aged at 185$^{o}$C and 193 $^{o}$C and Solution Heat Treated at 550$^{o}$C for 1 Hour.