Fracture Behavior of Commercial Al-Li Alloys

R. C. DORWARD
Center for Technology, Kaiser Aluminum Pleasanton,
CA 94566, USA

ABSTRACT

The fracture characteristics of Al-Li-X alloys are reviewed, with specific reference to the effects of microstructure on toughness and the failure process. Fracture is strongly affected by grain structure, temper condition, and test temperature and orientation. Considerable work remains to elucidate the factors that appear to be associated with brittle grain boundary fracture in near-peak-aged conditions: strain localization, grain boundary precipitates, weak PFZ's, and alkali metal segregation.

KEYWORDS

Al-Li alloys, fracture, microstructure, cryogenic toughness, grain boundaries, aging effects.

INTRODUCTION

Until recently, a major impediment to the commercial utilization of Al-Li alloys was their relatively low ductility and toughness. This problem has been attributed to a number of factors, including tramp impurities such as Na, K, H, etc., strain localization and stress concentrations at grain boundaries due to planar slip, weak precipitate free zones, and coarse grain boundary precipitates (Starke et al, 1981; Vasudevan et al, 1985). Alloys with respectable properties have recently been developed by grain size and shape control, minimizing impurity contamination, utilizing underaged tempers, and most importantly, the addition of alloy elements such as copper and magnesium that result in co-precipitation of other age hardening phases (Sanders and Niskanen, 1981; Lewis, 1980; Miller et al, 1984; Peel et al, 1984). However, aging to peak and overaged tempers still generally leads to brittle intergranular (or intersubgranular) fracture (Vasudevan et al, 1985; Dorward, 1986a; Vasudevan and Doherty, 1987).

This paper addresses the specific effects of grain structure, aging conditions, and test direction and temperature on the fracture characteristics of Al-Li alloys, with most attention given to commercial alloy AA 2090 (nominally Al-2.7%Cu-2.2%Li-0.12%Zr).

EXPERIMENTAL OBSERVATIONS

Orientation Effects

Most commercial high-strength aluminum alloys have an elongated, "pan-cake" type of grain structure. This is intentional; compared to an equiaxed grain structure, it generally provides superior mechanical properties and stress corrosion cracking resistance in the more highly stressed longitudinal and long-transverse directions. Alloy 2090 is also normally unrecrystallized in all product forms. Since this grain structure has a strong mechanical texture, test direction has a dramatic effect on toughness. As shown in Figure 1, Charpy impact energies of near peak-aged 2090 plate in the L-S and T-L orientations differ by more than an order of magnitude. The L-S orientation is particularly tough due to the laminated nature of the material. However, a draw-back of this type of structure is its relatively low short-transverse (S-L and S-T) properties. For example, this particular plate had a T-L fracture toughness of 23 MPa$\sqrt{m}$ compared to an S-L value of 13 MPa$\sqrt{m}$.

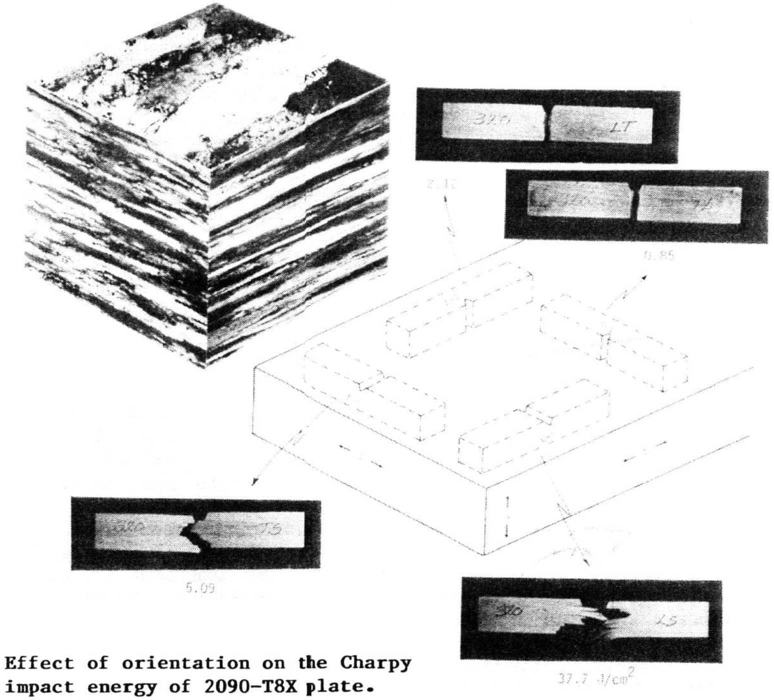


Fig. 1. Effect of orientation on the Charpy impact energy of 2090-T8X plate.

Orientation effects are also of special importance in products with non-uniform grain structures such as forgings and extrusions. The L-T Charpy impact energy near the edge of a 2090 bar extrusion, for example, is about twice that at the center.

Aging Effects

As with all heat-treatable aluminum alloy systems, the toughness and ductility of Al-Li alloys decrease with increasing aging time and/or temperature, i.e., as the yield strength increases (see Fig. 2). However, unlike conventional alloys, toughness does not recover upon overaging,

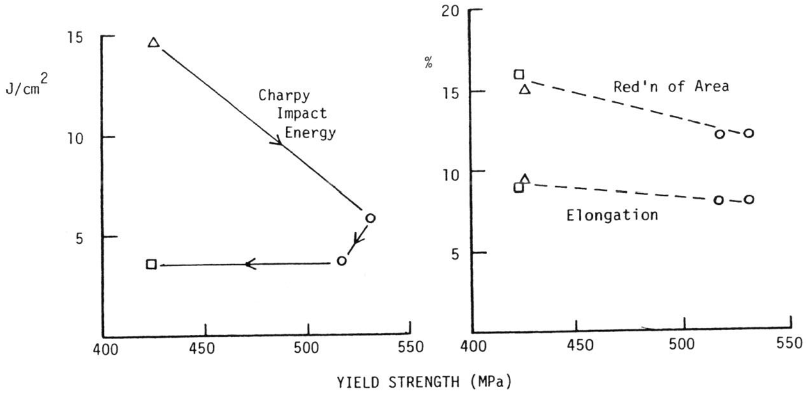


Fig. 2. Dependence of impact energy and ductility of 2090 extrusion on temper condition and strength (triangles-underaged, squared-overaged).

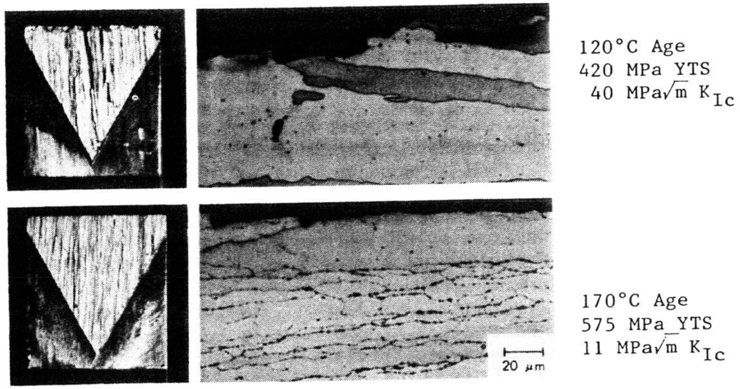


Fig. 3. Effect of temperature on S-L fracture of Al-2.1Li-2.0Cu-1.0Mg-0.1Zr alloy extrusion.

although ductility may. As shown in Figure 3, the S-L toughness of an experimental Al-2.1%Li-2.0%Cu-1.0%Mg-0.1%Zr alloy extrusion decreased from about 40 MPa$\sqrt{m}$ to 11 MPa$\sqrt{m}$ as the aging temperature was increased from 120°C to 175°C (and the yield strength increased from 420 to 575 MPa). Coincident with the decrease in toughness was a change in fracture morphology, which became smoother and more intergranular. The transition to intergranular fracture also coincided with extensive subgrain and grain boundary precipitation at the higher aging temperature.

SEM views of S-L fractures in near peak-aged 2090 plate clearly reveal inter-subgranular features (Fig. 4), and although the surface appeared macroscopically brittle, examination at high magnification showed evidence of local ductility, which was more actually pronounced than in the more ductile underaged condition. The local ductility is probably associated with PFZ's which become more pronounced in these alloys as the aging time/temperature is increased.

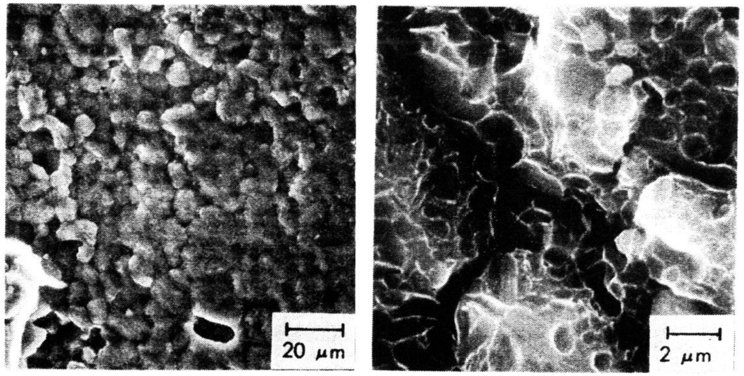


Fig. 4. SEM views of S-L fracture in peak-aged 2090 plate.

Microstructural Effects

As shown above, the fracture behavior of Al-Li-X alloys is strongly dependent on temper condition. The microstructural changes that occur upon artificial aging include coarsening of δ' (Al_3Li) and precipitation of copper and magnesium-containing phases such as θ' (Al_2Cu), T_1 (Al_2CuLi) and S' (Al_2CuMg). The copper-containing precipitates generally nucleate heterogeneously on dislocations and low angle sub-boundaries, and their aging response is therefore accentuated by prior deformation (stretching). In the peak-aged and overaged conditions, δ (AlLi) and T_2 (Al_6CuLi_3) phases precipitate on higher angle grain boundaries. The prevalence of ordered δ' in the underaged condition results in strong coplanar slip and strain localization, which were long associated with the poor ductility and toughness of Al-Li alloys. However, as noted earlier, the toughness of this temper condition is actually fairly respectable. Further aging results in precipitation of semicoherent T_1 and S' phases which promotes a more uniform strain distribution upon deformation, and provides a better strength-toughness combination than observed in the δ'-strengthened binary system. In peakaged and overaged materials, intergranular failure associated with grain boundary precipitates appears to be the major fracture mode (Suresh et al, 1987; Yin et al, 1987).

While the qualitative effects of aging on deformation, toughness and fracture morphology are well known, a complete mechanistic understanding is lacking. For example, what are the specific contributions of strain localization and grain boundary precipitation on fracture? Perhaps the two are inter-related. Figure 5 shows a slip band intersecting a T_2 precipitate at a grain boundary in peak-aged 2090 alloy. The high dislocation density at the site suggests that it could lead to fracture initiation by cavitation as shown by Kenik (1985). A similar mechanism has been proposed based on large $Al_6(CuFe)$ constituents (Butler et al, 1985), which are independent of the aging process.

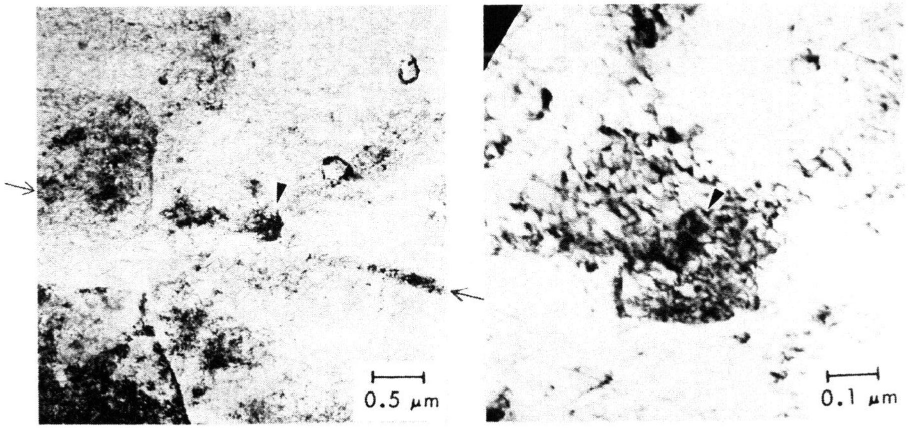


Fig. 5. TEM showing intersection of slip band and grain boundary T_2 pricipitate in peak-aged 2090 sheet.

In view of the apparent inter-relationships between precipitation, slip bands, and grain boundaries on the fracture of Al-Li alloys, one would expect an effect of grain (and subgrain) structure (recrystallized vs. unrecrystallized, shape, size) on fracture behavior. Today's semi-commercial alloys all contain zirconium as a grain stabilizing agent, the potential benefits of which have been recognized for many years (Fridlyander, 1969). That an unrecrystallized grain structure is preferable to a coarse-grained recrystallized alternative is not surprising, at least in perhaps all but the short-transverse (S-L) orientation. However, recent work indicates that a recrystallized, very fine-grain structure is most desirable, at least at relatively low strength levels (Miller et al, 1987).

Subgrain structure can also have a profound effect on toughness and fracture behavior (Dorward, 1986b). As shown in Figure 6, Kahn tear specimens machined from the surface of unrecrystallized 2090 sheet (well developed subgrains with a relatively high incidence of high angle boundaries) had lower toughness than the sheet center (less developed subgrains with lower angle boundaries) especially at higher strength levels. In the peak-aged condition, there were also distinct differences in the fracture morphologies between the two regions (Fig. 7). Center fractures were relatively featureless, traversing large numbers of grains without any significant deflection in direction; the surface morphology was microscopically rough, the fracture coinciding with subgrain boundaries. In the underaged condition, both fractures were largely trans-subgranular and similar in appearance.

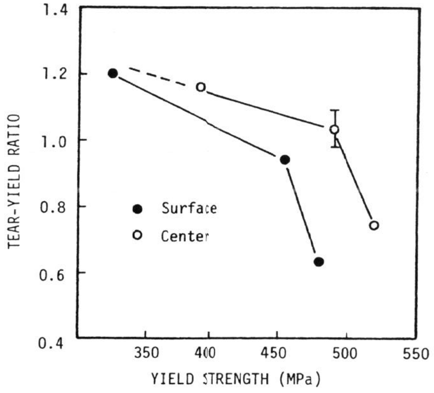
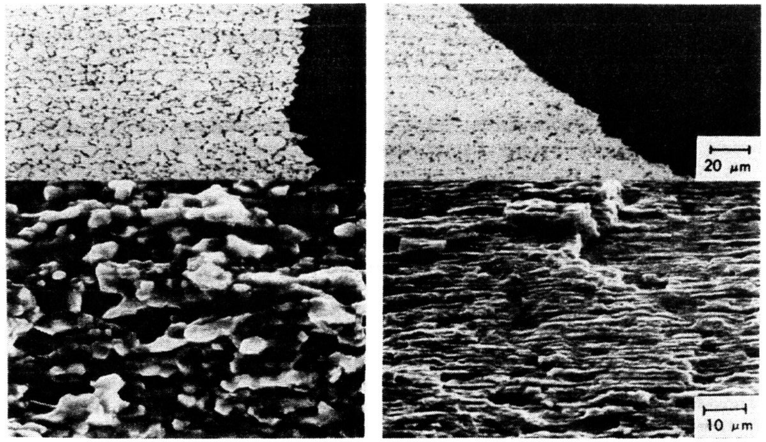


Fig. 6. Near-surface and center toughness of 2090 sheet as measured by Kahn tear strength.



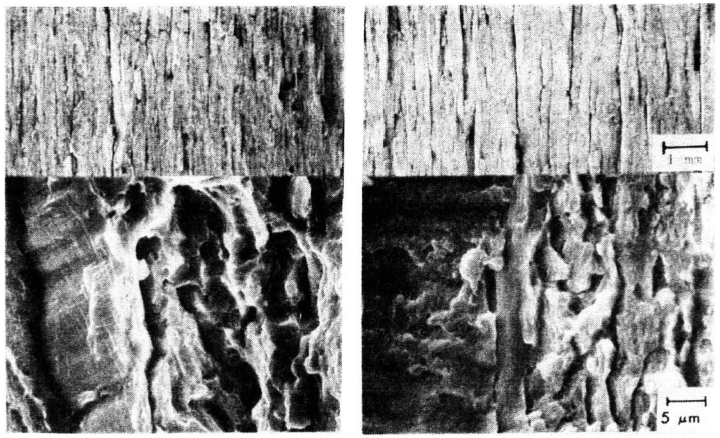
Near-Surface

Center

Fig. 7. Fracture cross sections and fractographs from near-surface and center regions of peak-aged 2090 sheet.

Cryogenic Effects

An unexpected benefit of aluminum-lithium alloys is an improved level of mechanical properties at cryogenic temperatures; the yield strength, ultimate tensile strength, elongation and fracture toughness generally increase as the test temperature is reduced to 4K. The mechanistic origin of improved cryogenic toughness is uncertain. Explanations to date have been based on (a) higher strain hardening rates associated with more homogeneous plastic deformation (Glaser et al, 1987), (b) solidification of low melting point liquid phases at grain boundaries (Webster, 1986), and (c) a greater tendency for short-transverse delamination perpendicular to the crack plane (Dorward, 1986)--see Figure 8. High magnification views show little effect of temperature except for striations at room temperature, which may relate to an increased incidence of planar slip (Starke et al, 1981).



295K (21.8 MPa√m)

88K (30.5 MPa√m)

Fig. 8. T-L fractures in 2090-T8X plate tested at room temperature and 88K.

The second mechanism is seemingly inconsistent with observations showing a slight reduction in short-transverse (S-L) toughness as the test temperature is decreased. The low melting point impurity rationale should apply to the S-L orientation as well--perhaps even more so since these fractures are almost entirely intergranular. The orientation dependence is more consistent with the delamination mechanism. Since the delamination cracks are at least as deep as the plastic zone size, they can promote plane stress conditions ahead of the crack tip concomitant with a larger measured stress intensity factor in the L-T and T-L cross grain orientations. A greater tendency for short transverse delamination at cryogenic temperatures is not only consistent with somewhat reduced S-L toughness, but will also be promoted by higher yield strengths at these temperatures, i.e., by a higher transverse stress (σ_z) ahead of the crack tip. As shown schematically in Figure 9, the fractured grain boundary frequency increases as toughness decreases and as the short transverse stress (yield strength) increases.

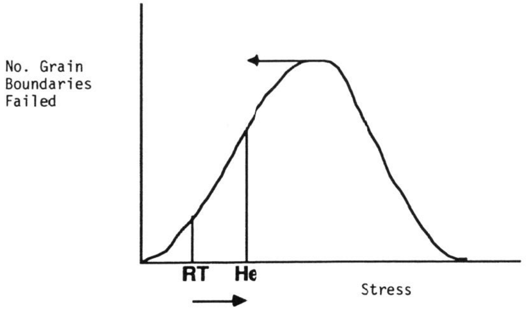


Fig. 9. Dependence of grain boundary failure frequency on stress (Verzasconi, 1987).

With regard to mechanism (a), it may be illustrative to consider a general model for strain-controlled fracture based on the expression (Glaser et al, 1987; Ritchie and Thompson, 1985).

$$J_{Ic} \quad r^* \sigma_y (\varepsilon_f)^{n+1}$$

where σ_y is the yield stress, n is the work hardening exponent, ε_f is the local fracture strain, and r^* is a material constant with dimensions of length. Since σ_y, n and ductility all increase at cryogenic temperatures(19), higher toughness would also be expected. Differentiation between this mechanism and the delamination theory might be accomplished by tests on (a) equi-axed recrystallized material, in which the delamination effect should be minimized, and (b) thinner specimens, which will be under plane stress conditions regardless of delamination effects.

CONCLUDING REMARKS

The fracture behavior of Al-Li-X alloys depends in a complex manner on a number of inter-related microstructural and test factors. Grain structure can have a pronounced effect, depending on test orientation: unrecrystallized materials have very high L-S and T-S fracture energies corresponding to laminated "ply-wood like" failure morphologies. Short transverse (S-L and S-T) fracture behavior, however, is compromised especially in near peak-aged temper conditions.

Fracture is largely transgranular in underaged conditions. As aging time/temperature is increased, fracture becomes more intergranular, with corresponding reductions in toughness. A number of explanations have been proposed to explain intergranular (and intersubgranular) failure, which involve

a) relatively weak PFZ's
b) impurity segregation of alkali metals
c) strain localization due to planar slip
d) coarse precipitates on grain boundaries.

Although evidence points to item (d) as a major factor in near peak-aged tempers, more work is required to isolate the specific contributions of strain localization and how it may be related to grain boundary precipitates.

There does not appear to be any simple correlation between fracture toughness and uniaxial mechanical properties in Al-Li alloys. This is probably due to the complex nature of the fracture process, and the manner in which it changes with aging conditions (and yield strength).

The strength-toughness combination of 2090 alloy plate improves dramatically in the L-T and T-L orientations at low test temperatures, making the material superior to any aluminum alloy currently used for cryogenic applications. The reason for this behavior has not been resolved; current explanations involve an increasing tendency for short-transverse intergranular delamination and higher strain hardening rates at low temperature.

REFERENCES

Butler, E. P., Owen, N. J. and Field, D. J. (1985). Void nucleation in a quaternary Al-Li alloy. Mater. Sci. and Tech., 1, pp. 531-536.
Dorward, R. C. (1986a). Fracture of Al-Li-Cu-(Mg) alloys: effect of subgrain structure and aging practice. J. Mater. Sci. Lett., 5, pp. 1015-1018.
Dorward, R. C. (1986b). Cryogenic toughness of Al-Cu-Li Alloy 2090. Scripta Metal., 20, pp. 1379-1383.
Fridlyander, I. N.. (1969). Aluminum-base alloy. Brit. Patent Spec. 1,172,736.
Glazer, J., Verazsconi, S. L., Sawtell, R. R. and Morris, J. W. (1987). Mechanical behavior of aluminum-lithium alloys at cryogenic temperatures. Metal. Trans., 18A, pp. 1695-1701.
Kenik, E. A. (1985). High voltage electron microscope in situ studies of strain localization in Al-Li alloys. In: Fracture: Measurement of Localized Deformation by Novel Techniques, pp. 125-135. AIME, Warrendale, PA.
Lewis, R. E. (1980). Advanced aluminum alloys from rapidly solidified powders. R&D Status Report, Contract F33615-78-C.
Miller, W. S., Cornish, A. J., Titchner, A. P. and Bennett, D. A. (1984). Development of Li-containing aluminum alloys for the ingot metallurgy production route. In: Aluminum-Lithium Alloys II, pp. 335-362, AIME, New York.
Miller, W. S., White, J., Reynolds, M. A., McDarmaid, D. S. and Starr, G. M. (1987). Al-Li-Cu-Mg-Zr alloys with high strength and toughness--solving the perceived dichotomy. Proc. 4th Int. Al-Li Conf., J. de Phys., pp. 151-162.
Peel, C. J., Evans, B., Baker, C. A., Bennett, D. A., Gregson, P. J. and Flower, H. M. (1984). The development and application of improved aluminum-lithium alloys. In: Aluminum-Lithium Alloys II, pp. 363-392, AIME, New York.
Ritchie, R.O. and Thompson, A. W. (1985). On macroscopic and microscopic analysis for crack initiation and crack growth toughness in ductile alloys. Met. Trans., 16A, pp. 233-248.
Sanders, T. H. and Niskanen, P. W. (1981). Microstructure, mechanical properties and corrosion resistance of Al-Li-X alloys--an overview. Res. Mech. Lett., 1, pp. 363-370.

Starke, E. A., Sanders, T. H. and Palmer, I. G. (1981). New approaches to alloy development in the Al-Li system. *J. Metals*, *33*, pp. 24-33.

Suresh, S., Vasudevan, A. K., Tosten, M. and Howell, P. R. (1987). Microscopic and macroscopic aspects of fracture in lithium-containing aluminum alloys. *Acta Metal.*, *35*, pp. 25-46.

Vasudevan, A. K., Ludwiczak, E. A., Baumann, S. F., Doherty, R. D. and Kersker, M. M. (1985). Fracture behavior in Al-Li alloys: role of grain boundary delta. *Mater. Sci. Eng.*, *72*, pp. L25-L30.

Verzasconi, S. L. (1987). Aluminum-lithium alloys and the effect of intergranular splitting on 2090-T81 alloy toughness. Charles Martin Hall Aluminum Technology Award Competition., Aluminum Association, Washington, DC.

Webster, D. (1986). Temperature dependence of toughness in various aluminum-lithium alloys. In: *Aluminum-Lithium Alloys III,* pp. 602-609, The Institute of Metals, London.

Yin, Z. M., Aust, K. T, Weatherly, G. C. and Lloyd, D. J. (1987). The deformation and fracture of two Al-Li based alloys. *Can. Metal. Quart.*, *26*, pp. 61-69.