ADVANCES IN

FRACTURE RESEARCH

Editors

K. SALAMA, K. RAVI-CHANDAR,
D. M. R. TAPLIN, P. RAMA RAO

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Fracture Research

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IX. FRACTURE OF METALLIC MATERIALS

Fracture Behavior of Commercial Al-Li Alloys

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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$\sqrt{m}$.

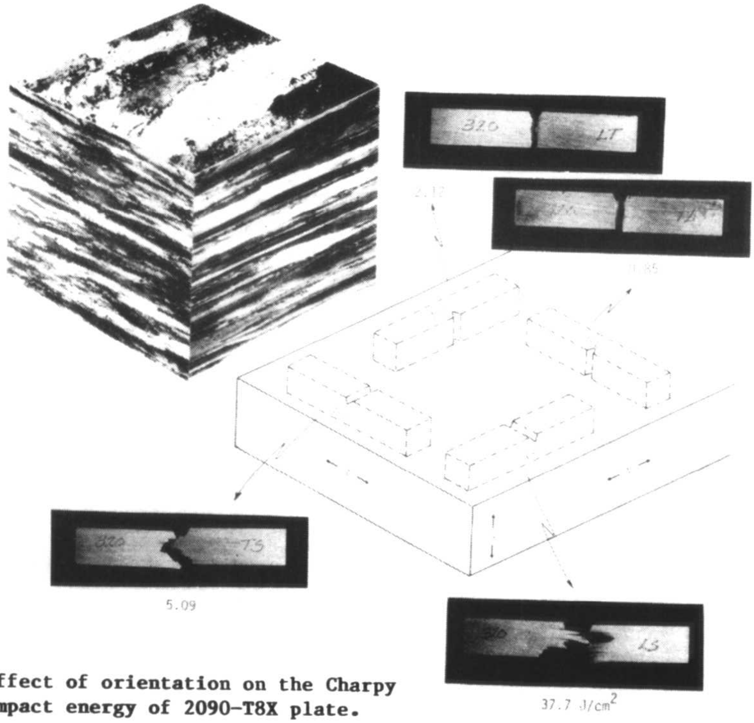

Fig. 1. Effect of orientation on the Charpy impact energy of 2090-T8X plate.

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,

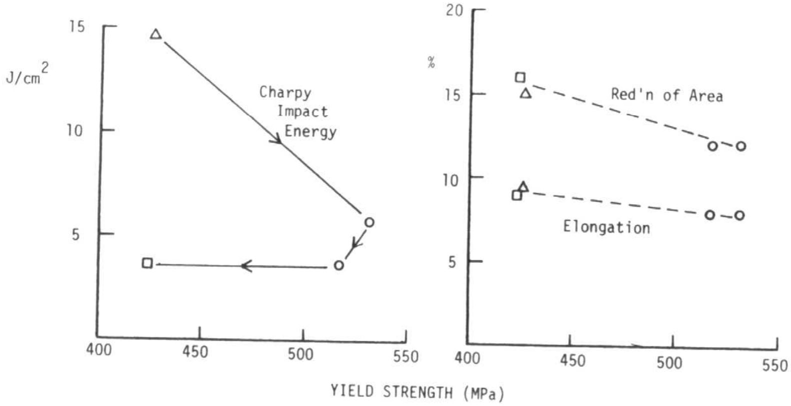

Fig. 2. Dependence of impact energy and ductility of 2090 extrusion on temper condition and strength (triangles-underaged, squared-overaged).

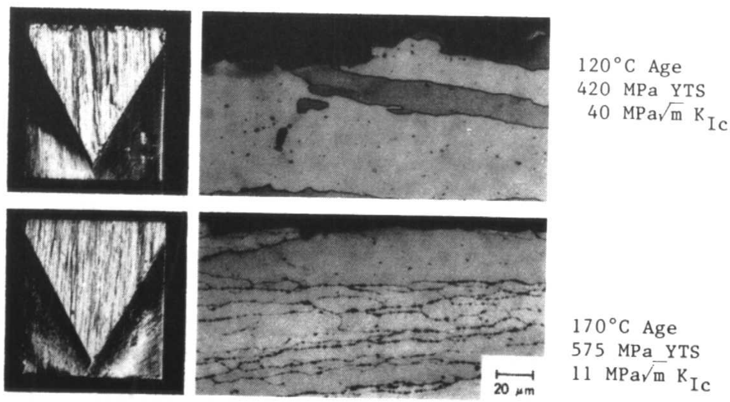

Fig. 3. Effect of temperature on S-L fracture of Al-2.1Li-2.0Cu-1.0Mg-0.1Zr alloy extrusion.

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.

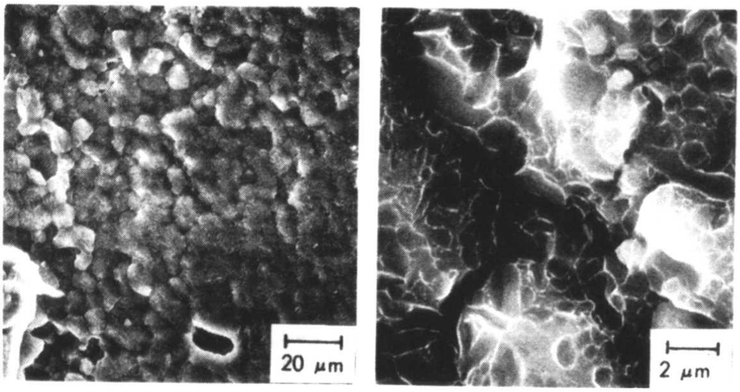

Fig. 4. SEM views of S-L fracture in peak-aged 2090 plate.

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.

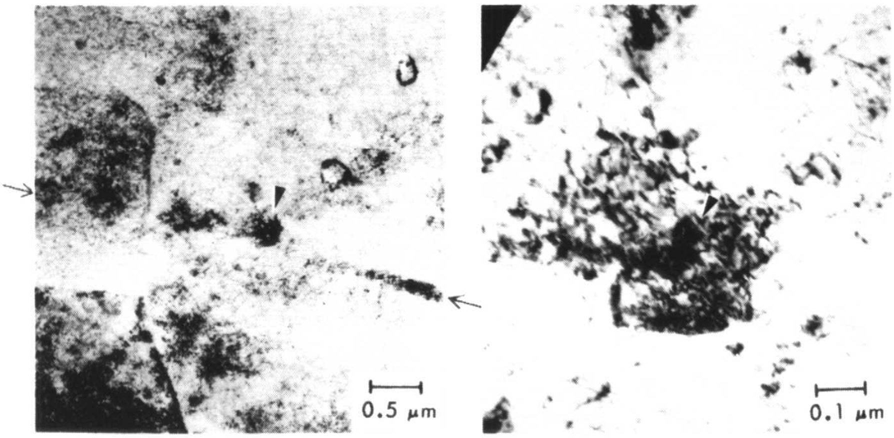

Fig. 5. TEM showing intersection of slip band and grain boundary T_2 pricipitate in peak-aged 2090 sheet.

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.

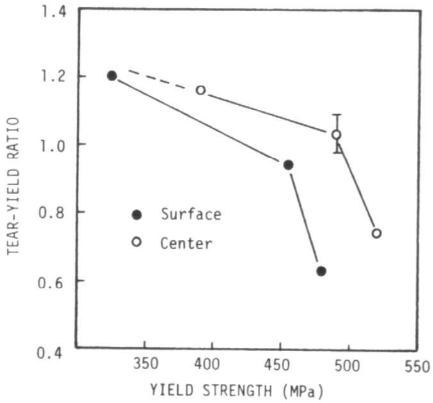

Fig. 6. Near-surface and center toughness of 2090 sheet as measured by Kahn tear strength.

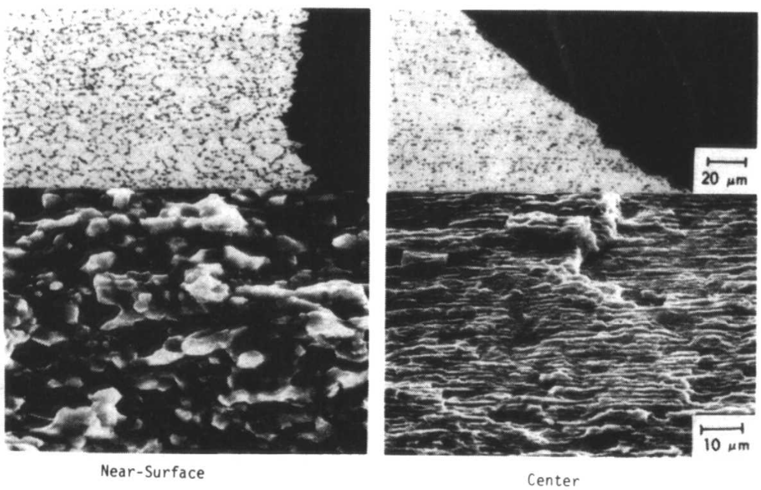

Fig. 7. Fracture cross sections and fractographs from near-surface and center regions of peak-aged 2090 sheet.