Unusual Fracture Mode in the Fatigue of an Al–Li Alloy

G. R. YODER, P. S. PAO, M. A. IMAM and L. A. COOLEY

Materials Science and Technology Division, Naval Research Laboratory, Washington, DC 20375–5000, USA

ABSTRACT

The aluminum-lithium alloy 2090-T8E41, which exhibits uncommonly good resistance to the growth of fatigue cracks over a broad spectrum of stress-intensity range (ΔK), also exhibits a fatigue fracture surface morphology and crack closure levels that are quite different than observed with conventional aluminum alloys such as 7075-T651. For fatigue crack growth at a stress ratio of R = 0.10 in ambient air, the fracture surface of the Al-Li alloy exhibits an extraordinary tortuosity, with considerable oxide debris attributable to fretting --- giving rise to a macroscopically blackish appearance. Associated with this tortuosity, the fracture surface exhibits asperities of unusual height, as comprised of adjacent pairs of slip-band facets. This height is a consequence of two synergetic factors, viz. an extraordinary textural intensity and an uncommon propensity for a planar slip mode in Al-Li alloys. Thus individual, well defined slip-band facets are formed which can traverse multiple grains at a time to give asperities of unusual height --- which give rise to high closure levels at stress-intensity ranges much above near-threshold values. Moreover, it is shown that the characteristic included angle between an adjacent pair of slip-band facets which comprise an individual asperity is a consequence of the texture. Thus, important progress has been made to elucidate the vastly superior resistance of the 2090 alloy and its micromechanistic basis.

KEYWORDS

Al-Li alloy, fatigue crack growth, fracture, texture, crack closure

INTRODUCTION

Aluminum-lithium alloys are attracting a great deal of interest as candidate materials for next-generation aerospace applications, owing primarily to their superior specific weight and elastic modulus as compared to conventional aluminum alloys. Additionally, they have been reported to exhibit uncommonly good resistance to the growth of fatigue cracks [1-7], with an order-of-magnitude reduction in crack growth rates displayed over a broad spectrum of stress-intensity range (ΔK) --- when compared to conventional 2000 or 7000-series aluminum alloys. Though it has been suggested that this superior resistance is a consequence of enhanced crack closure levels, there is little understanding of the microstructural origins of the fatigue crack growth process in these alloys, which involves the development of an unusual fracture mode with an extraordinary surface roughness. The purpose of this paper is to offer some elucidation of these origins --- at least in preliminary form, which indicates that crystallographic texture plays an important role. This work illustrates not only that slip-band facet and asperity angles in the fatigue crack growth profile can be predicted from the texture, but suggests that the unusual height of asperities in the fatigue fracture surface develops as a consequence of extraordinary intensity of the texture, so that an individual shear facet can readily traverse several grains in concert.

MATERIAL AND PROCEDURE

The material studied was 2090-T8E41 alloy from Alcoa, in the form of 12.7-mm plate. Detailed documentation of the microstructure and mechanical properties is available elsewhere [7,8]; suffice it to say that the yield strength was 520 MPa in both the L (longitudinal or rolling direction) and T (long transverse) orientation, and that the microstructure contained pancake-shaped grains, the order of millimeters in length (L-direction) and 25-μm thick (S, or short transverse direction) --- with Fe/Cu-rich constituent particles lining the grain boundaries. Fatigue crack growth specimens of the WOL compact type [9] --- with half height-to-width ratio of 0.486 and with cracks in the LT orientation, were examined for fatigue crack growth resistance in accord with ASTM-E647 [10]. These 12.7 mm-thick specimens were cyclically loaded in air with a stress ratio of R = 0.10, a haversine waveform and a frequency of 5 Hz. The fractographic observations and textural characteristics were determined for the midthickness region. Inasmuch as an extraordinary tortuosity of the fatigue fracture surface was apparent to the naked eye, an individual specimen half was sectioned to examine metallographically the details of the crack path --- in both the as-polished and polished-and-etched (Keller's reagent) conditions.

RESULTS AND DISCUSSION

The propensity of the 2090 alloy for out-of-plane cracking is so great that even with sidegrooved specimens, crack paths typically deviated from the intended Mode I plane at large angles --- sometimes in excess of 35 degrees. Thus reliable determinations of fatigue crack growth rates (da/dN) were not feasible in most cases, as ASTM E647 limits such deviations to 5 degrees. However, on occasion (about 1 out of 10 specimens), the crack path did trace the Mode I plane to permit valid determinations of da/dN, as presented in Fig. 1. These data indicate that over a broad spectrum of stress-intensity range (ΔK), da/dN levels are roughly an order-of-magnitude smaller than counterpart growth rates for conventional aluminum alloy, 7075-T651. Associated with the much smaller da/dN levels of the Al-Li alloy, one clearly observes a much greater surface roughness in the fatigue fracture surface, as illustrated in Fig. 2 where comparison is made with the 7075-T651 alloy at $\Delta K \approx 11$ MPa $\sqrt{m}$. Extraordinary crack closure levels were also observed in the case of the Al-Li alloy --- e.g. 70 pct. of maximum load for $\Delta K \approx 11$ MPa $\sqrt{m}$, in contrast to 25 pct. observed

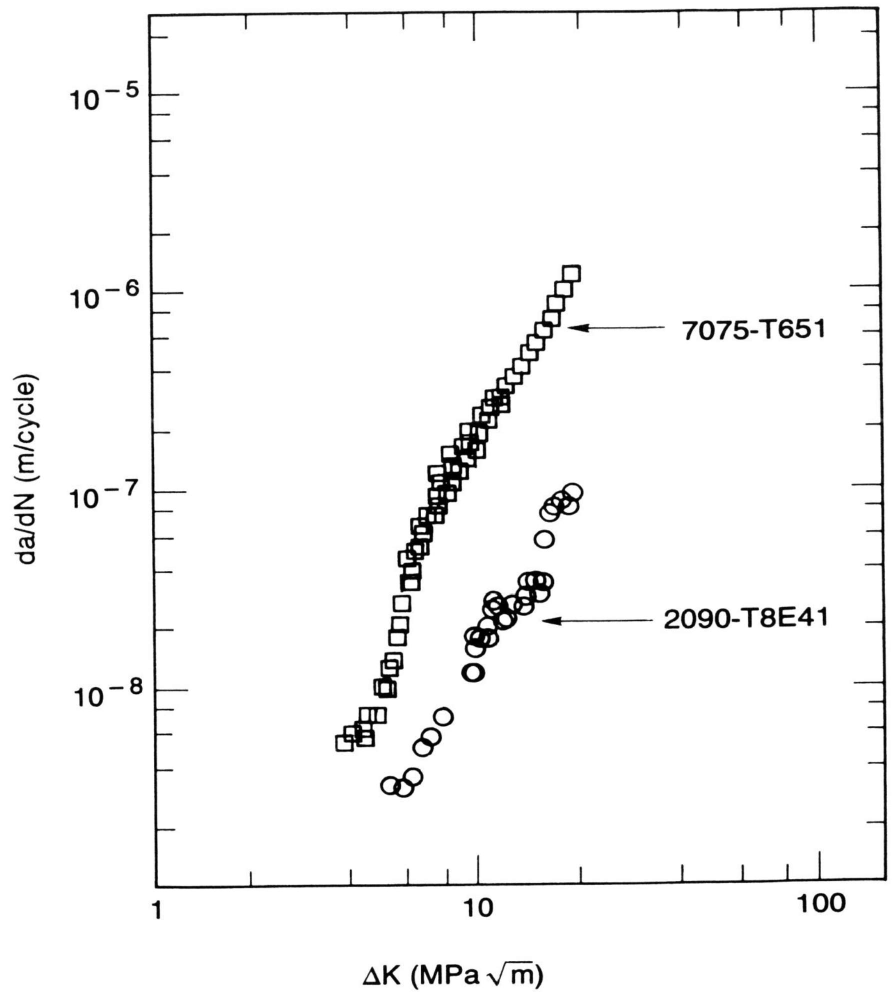

Fig. 1. Comparison of the kinetics of fatigue-crack growth in 2090-T8E41 and 7075-T651 in air.

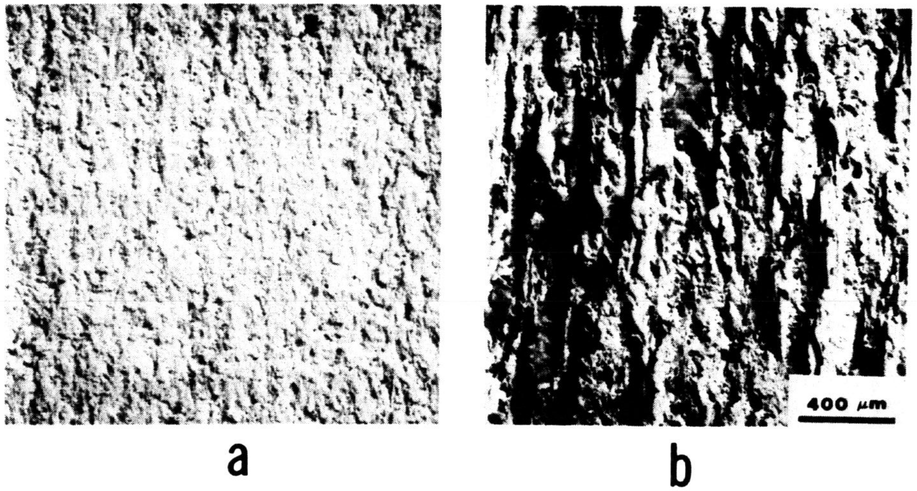

Fig. 2. Scanning electron micrographs showing difference in fracture surface roughness for fatigue-crack growth at $\Delta K \approx 11$ MPa $\sqrt{m}$: (a) 7075-T651, (b) 2090-T8E41. (Note: Crack growth direction is from bottom to top of micrographs.)

in the case of the 7075 alloy. Further details of the extraordinary tortuosity in the case of the 2090-T8E41 alloy can be observed in the micrographs of Fig. 3, which give evidence of mechanical rubbing marks (a) and consequent fretted oxide debris at higher magnification (b).

In order to understand the origins of the extraordinary tortuosity and associated crack closure levels, it is necessary to begin with consideration of texture in the Al-Li alloy. As observed at the midthickness position of the plate material, the texture was found to be comprised of three components — two of them strong, viz. {110} <112> or "brass" type and {123} <634> or "S" type, and the third weak, viz. {112} <111> or "Cu" type. Inasmuch as the detailed documentation of this texture has been reported elsewhere [7,8,11], it will not be repeated here — except as relevant to analysis of the shear-band facet angles developed in the fatigue crack growth process. An example of these facets is given in Fig. 4, which displays the as-polished crack path section in the T-plane — corresponding to $\Delta K = 11$ MPa$\sqrt{m}$. The nature of the asperities shown in the figure is not unique to this particular level of ΔK, but rather is characteristic over a broad spectrum of ΔK. Individual asperities, which are notably steep, are typically comprised of a pair of shear-band facets that meet in highly symmetric fashion with approximately a 50 degree included angle,* as outlined in the figure. The development of

*The included angle has on occasion been observed to deviate from 50 degrees by as much as plus or minus 10 degrees, which is consistent with the spectrum of pole concentrations about points A and B (cf. Fig. 5).

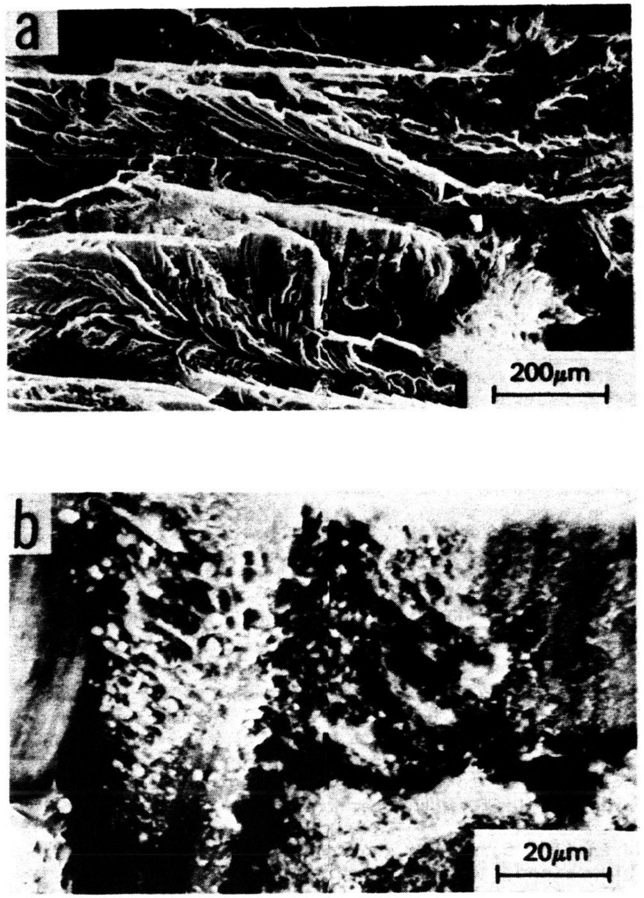

Fig. 3. Scanning electron micrographs of 2090-T8E41 alloy at $\Delta K = 11$ MPa $\sqrt{m}$, showing evidence of (a) mechanical rubbing marks, and (b) fretted oxide debris.

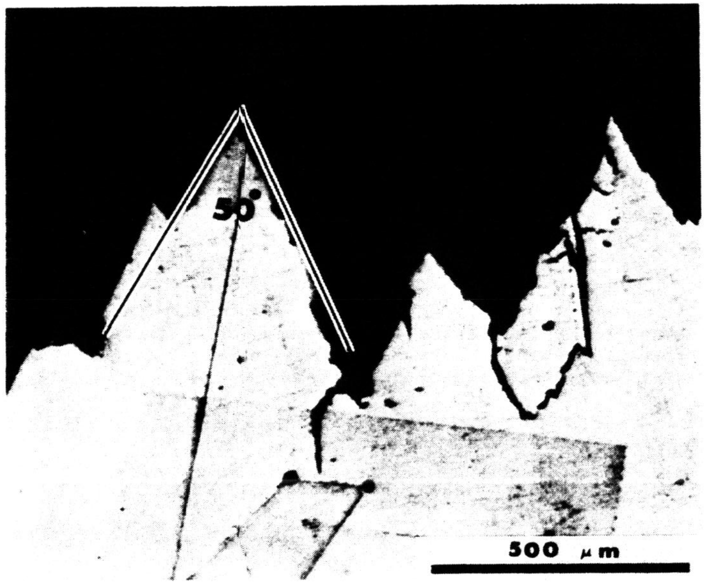

Fig. 4. Trace of crack path in specimen thickness direction, as revealed by sectioning normal to fracture surface; ΔK = 11 MPa $\sqrt{m}$, T-plane, as polished.

facets is facilitated by the increased propensity for a planar slip mode as lithium is added to aluminum. Slip bands in the fatigue of an Al-Li-Cu alloy are, of course, anticipated to be of the (111) type, as has been previously reported [12]. Thus, it is appropriate to examine the nature of the (111) pole figure to determine if the observed angles of the shear facets are predictable from the texture.

This is done in Fig. 5, which shows an isometric schematic of the fatigue crack growth specimen, as sectioned in the T-plane to analyze crack-path contour in direct relation to the texture. As the (111) pole figure is highly symmetric about the L-axis, only one half is mounted in the S-plane with the origin of the stereographic projection "0" placed in the Mode I crack plane at the point of the crack path section. Now significant concentrations of (111) poles lie (approximately) along the L-axis, with foci designated as points "A" and "B". These foci, in turn, exhibit symmetry about the T-axis, in that points A and B are each 25 degrees from point 0. In other words, A0' forms an angle of 25 degrees with 00' --- as illustrated, and so does B0'. Inasmuch as these normals to the planes lie in the T-plane, then the traces of the plane associated with each pole also lie in this same plane. Now the trace of the plane associated with A0' lies normal to it, illustrated as X0'X', which is 25 degrees from the L-axis; similarly, B0' lies normal to the trace of its plane --- shown as

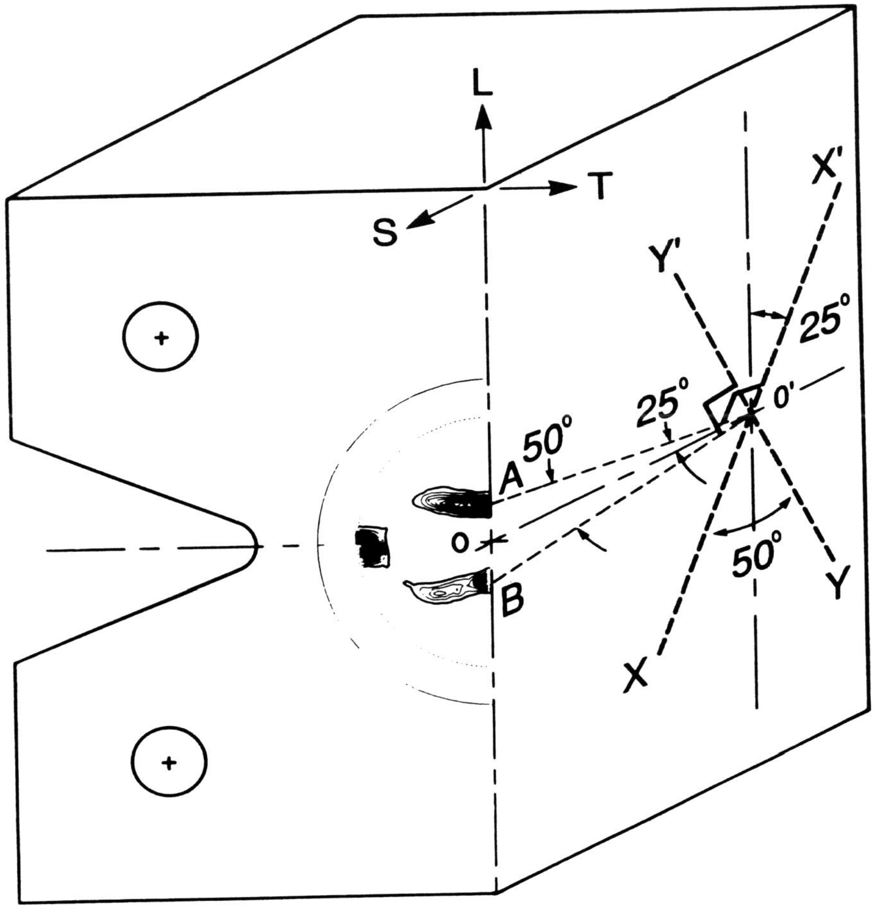

Fig. 5. Isometric schematic of fatigue crack growth specimen, with trace of slip band facet angles in T-plane predicted from foci in (111) pole figure.

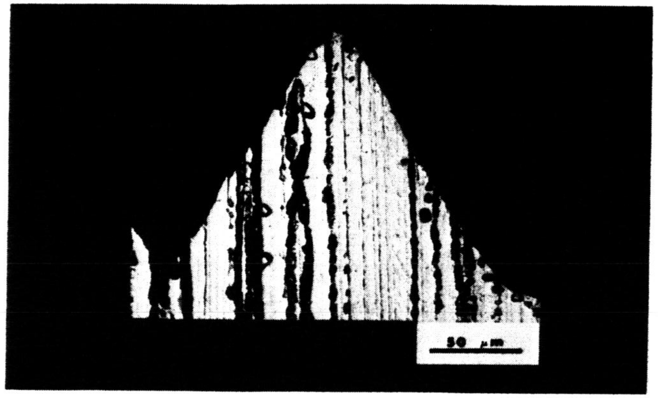

Fig. 6. Polished and etched crack path section in T-plane, with slip band facets of asperity traversing several grain boundaries, as decorated by constituent particles.

YO'Y', and tilted 25 degrees to the other side of the L-axis. Consequently, the angle between traces XO'X' and YO'Y' is 50 degrees. Thus, 50 degrees is the included angle predicted between the focal pair of (111) shear bands (or facets) which would comprise the trace facet angle from the texture is clearly in agreement with the observations of actual fatigue crack growth displayed in Fig. 4.

It is also appropriate to note that the intensity of the (111) pole figure examined herein was much greater than anticipated levels (with peak of 30.96 times the contour interval of 1.00). In view of such high degree of preferred orientation, it is not surprising to find that the slip-band facets --- such as displayed in Fig. 4, each traverse several of the thin pancake shaped grains in concert --- to give unusually great height to asperities developed in this alloy. This is clearly shown by Fig. 6, where one of the individual asperities in the T-plane crack path section (same orientation as Figs. 4 and 5) is displayed in the etched condition --- which reveals the multiplicity of "pancake" boundaries (associated with each facet), as decorated by the dark-etching constituent particles. In this figure, some secondary cracking is also apparent in the form of rolling-plane delamination.

CONCLUSIONS

1. Extraordinary surface roughness and crack closure levels are associated with the fatigue fracture of the Al-Li alloy 2090-T8E41, which exhibits order-of-magnitude lower levels of da/dN than the conventional 7075-T651 alloy.

2. This unusual fatigue crack growth behavior appears to be the consequence of (i) the propensity for a planar slip mode, and (ii) the alloy's crystallographic texture, which is of unusual intensity.

3. The included angle between an adjacent pair of slip-band facets which comprise an individual asperity, as observed in the fatigue fracture surface, can be predicted from symmetry of the (111) pole figure.

4. Observations of facet and asperity angles in the fatigue crack profile confirm these predictions, with an individual shear facet traversing several pancake shaped grains to give unusual height to individual asperities --- and thus the extraordinary surface roughness and crack closure levels.

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REFERENCES

Rao, K. T. Vankateswara, W. Yu and R. O. Ritchie (1988). Metall. Trans. A 19A, 549.
Harris, S. J., B. Noble and K. Dinsdale (1984). Fatigue '84, Vol.1, p. 361. EMAS Ltd., West Midlands, U.K.
Jata, K. V. and E. A. Starke (1986). Metall. Trans. A 17A, 1011.
Vasudevan, A. K., P. E. Bretz, A. C. Miller and S. Suresh (1984). Mater. Sci. Eng. 64, 113.
Coyne, E. J., T. H. Sanders and E. A. Starke (1981). Aluminum-Lithium Alloys, p. 393. TMS-AIME, Warrendale.
Pao, P. S., K. K. Sankaran and J. E. O'Neal (1981). Aluminum-Lithium Alloys, p. 307. TMS-AIME, Warrendale.
Yoder, G. R., P. S. Pao, M. A. Imam and L. A. Cooley (1987). Competitive Advances in Metals and Processes, Vol.1, p. 25. SAMPE, Covina, CA.
Imam, M. A., P. S. Pao and G. R. Yoder (1987). TMS Fall Meeting, Cincinnati, OH.
Saxena, A. and S. J. Hudak, Jr. (1978). Inter. Journ. Fracture 14, 453.
ASTM E647-86, Annual Book of ASTM Standards (1986) Vol.03.01, Sec. 3, p. 714. ASTM, Philadelphia, PA.
Imam, M. A., P. S. Pao and G. R. Yoder. To be published.
Chang, S. C. and S. H. Chen (1986). TMS Fall Meeting, Orlando, FL.