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Authors
Yao, D.
Chu, D.
Morris, J.W.

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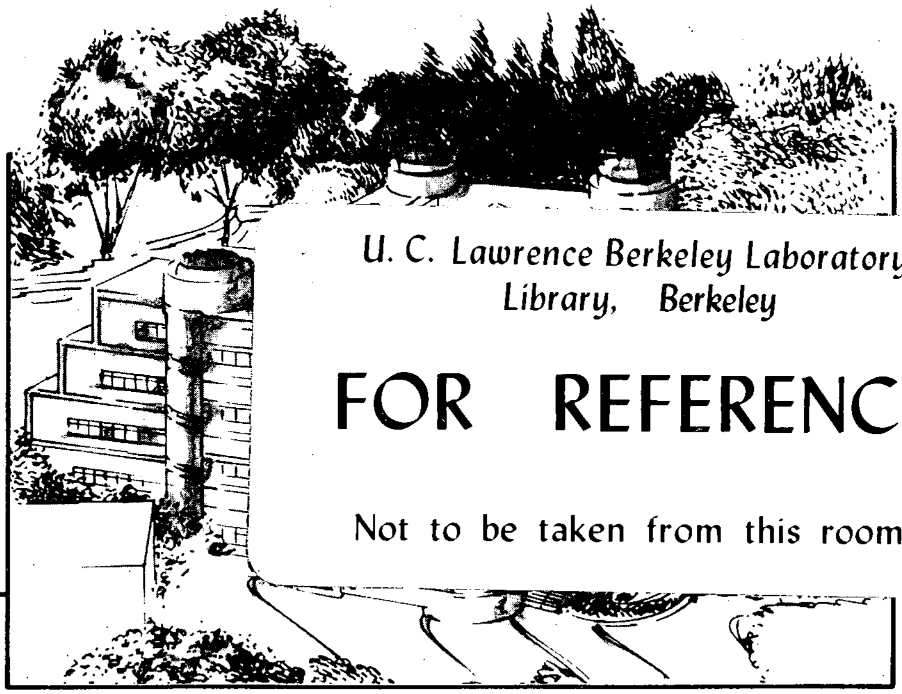

Materials and Chemical Sciences Division

Lawrence Berkeley Laboratory • University of California

ONE CYCLOTRON ROAD, BERKELEY, CA 94720 • (415) 486-4755

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Daping Yao, David Chu and J.W. Morris, Jr.

Center for Advanced Materials
Materials and Chemical Sciences Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

and

Department of Materials Science and Mineral Engineering
University of California

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Lawrence Berkeley Laboratory
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The deformation behavior of a 12.7 mm (0.5 in.) 2090-T8E41 (Vintage I) plate material in tension is studied at 298 and 77K. An increase in the roughness of slip relief patterns is observed on polished surfaces of deformed tensile specimens tested at 77K. The increased roughness at the lower temperature is believed to be induced by a microstructural factor that resists the transmission of slip from grain to grain and results in reduced slip continuity across grain boundaries. The reduced slip continuity is believed to encourage greater deformation homogeneity at the lower test temperature and, subsequently, results in an improved work hardening capacity. A microstructural relation between the increased slip discontinuity and the improvement in the work hardening characteristic and subsequent mechanical properties at low temperatures is proposed.

Introduction

Interest in aluminum-lithium alloys has increased in the past decade due to its potential as a structural material with lower density, higher stiffness and strength relative to current high strength aluminum alloys.[1,2] Design studies have shown that reductions in weight density provide the most efficient means of increasing both weight savings and aircraft performance.[3-5] In addition, early studies on the Al-Cu-Li-Zr alloy 2090 have revealed a dramatic increase in the strength-toughness combination with decreasing temperature.[6-11] Subsequently, 2090 and other aluminum-lithium alloys have become candidate materials for aerospace applications.[7,12]

A significant body of research on 2090 has concentrated on understanding the source of the excellent properties at cryogenic temperatures in hopes of duplicating such effects in other alloys. It has been well established that the improvement in the work hardening capacity with decreasing temperature plays a major role in the concurrent increase in fracture toughness.[9,12] However, the source of this increased work hardening capacity is unclear.

A number of studies on aluminum alloys including 2090 have spotlighted an increase in the homogeneity of slip with decreasing temperature.[13-15] It is suggested that slip homogeneity is associated with a higher work hardening rate, especially in aluminum-lithium alloys where planar slip is associated with work softening.[12] Cross slip plays an important role in determining the dislocation structure on the microscopic level. Because it is a thermally activated process, it is sensitive to temperature and to solute atoms that interact with dislocations. When cross slip is difficult, as it is at cryogenic temperatures, work hardening is expected to increase due to the decreased ability of a dislocation to bypass an impenetrable obstacle. Following this line of reasoning, the improved work hardening observed in 2090 and other aluminum-lithium alloys may be regarded as a temperature-induced phenomenon.[6,9,12,14,15]

More recent work by Chu and Morris[16,17] on Vintage III 2090-T81 suggests that the improved work hardening capacity may also be a function of the microstructure. Vintage III 2090-T81 is a laminate of two distinctly different microstructures with relatively thin unrecrystallized grains at mid-thickness bounded by a coarser pre-recrystallized grain structure. Mechanical tests conducted on tensile specimens isolating the different regions reveal a dramatic difference in the work hardening characteristic at the *same* test temperature.[17] However, the mechanism by which the different microstructures are creating different work hardening responses is unclear.

The present work addresses this issue through an optical study of the slip relief pattern obtained from 2090-T8E41 tensile specimens. Evidence of a microstructurally induced mechanism activated at the lower test temperature is found. It is believed that the mechanism is associated with an increase in the degree of out-of-plane rotation of grains.

Experimental Procedure

The material investigated in this study was a Vintage I 2090-T8E41 plate provided by Alcoa in the form of a 12.7 mm (0.5 in.) plate. This temper includes a solution heat treatment and quench followed by a 6 to 8% stretch and a final peak-age at 163°C for approximately 24 hours. This thermomechanical processing results in a material containing thin, elongated, unrecrystallized grains. Chemical analysis obtained a composition of Al-2.86Cu-2.05Li-0.12Zr.

Flat tensile specimens of 3.2 mm (0.125 in.) thickness were taken from the plate, parallel to the rolling direction, and at a distance of 3.2 mm (0.125 in.) from the surface of the plate. Tensile tests were conducted at room temperature (~298K) and within a liquid nitrogen bath (77K) at a strain rate of approximately $8\times10^{-4}\ s^{-1}$. The elongation was monitored over a 25.4 mm (1.0 in.) gage length by a strain gauge. A number of tests were interrupted at predetermined engineering strains in order to observe the slip morphologies at different stages of deformation. Engineering stress and strain data were collected via computer and then converted to true stress (σ) and strain (ε) values. Following the methods of Chu and Morris[16,17], the instantaneous strain hardening rate, $\partial\sigma/\partial\varepsilon$, was calculated by means of a sliding five-point fit to the parabolic relation $\sigma = A\varepsilon^n$, where A is the stress at unit strain and n is the strain hardening exponent that varies with the amount of deformation.

Tensile specimens were mechanically polished to 0.05 μm and lightly etched prior to testing to improve visibility of grain boundary traces. The deformation morphology was examined optically using Nomarski interference contrast.

Results & Discussion

The measured tensile properties of 2090-T8E41 are listed in Table I. The most notable trend is the increase in all mechanical properties between 298 and 77K. The concurrent increases in strength, elongation, and the work hardening exponent has been observed in other studies of 2090-T8E41.[6-12,14-17] Note also that the improvement in total elongation is directly linked to an increase in the uniform elongation; the strain to failure after geometric instability ($\varepsilon_{total} - \varepsilon_{uniform}$) increases only 0.6% from 298 to 77K. Hence, the improved ductility is associated with an improvement in the stability of plastic deformation prior to necking.

Temperature (K)	Yield Strength (MPa)	Ultimate Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)	Strain Hardening Exponent
298	448	494	5.1	6.5	0.06
77	481	564	12.3	14.3	0.10

Table I: Tensile Properties for 2090-T8E41 at 298 and 77K.

Figure 1 plots the strain hardening rate ($\partial\sigma/\partial\varepsilon$) and true stress ($\sigma$) as a function of true strain (ε). At both temperatures failure is occurring slightly beyond the point of geometric instability. A comparison of the work hardening curves shows an increase of the work hardening rate with decreasing temperature. Consequently, the onset of geometric instability is retarded which results in improved elongation values at 77K.

Figure 2 depicts the slip relief pattern observed on the polished surfaces of tensile specimens tested at 298 and 77K and pulled to two strains, 1.5% and 4.5%. Figure 1 shows that at 1.5% strain, the work hardening rates at both temperatures are equivalent, thus suggesting that on the macroscopic level the development of slip between the two temperatures is similar. Figures 2a and 2b, however, indicate that a relatively finer slip distribution is exhibited at 77K. It is apparent that despite equivalent work hardening rates, the development of the deformation structure has already begun to differ. At this small strain the greater slip homogeneity is most likely temperature-induced. Despite the greater slip homogeneity, the transmission of slip from grain to grain is relatively unhindered at both temperatures.

A difference is also seen at 4.5% strain. Figures 2c and 2d show that the surface of the specimen deformed at the lower temperature appears rougher. Similar observations of increased roughness upon large deformation and low test temperatures were reported by Glazer.[12] In that study the roughest regions were found to correspond to areas where subgrains or fine grains at grain boundaries had deformed independently. Glazer also observed that slip was much finer in the regions of greatest roughness.

Figure 3 compares specimens pulled to equivalent instability points at the two test temperatures (5% at 298K and 12% at 77K). It is apparent that the increased roughness continues to be a dominant feature at 77K. The granular level at which this roughness occurs is also evident. It is speculated that the strain induced out-of-plane rotation of grains at 77K is a direct consequence of the greater difficulty for the transmission of slip from grain to grain.

Combined with the results obtained by Chu and Morris[16,17], the observations made in this study suggest that the microstructure plays an important role on the resulting work hardening characteristic. The details of this relationship is the topic of future research.

Summary and Conclusion

An optical analysis of the slip relief pattern was conducted for the Al-Cu-Li-Zr alloy 2090-T8E41. An increase in the degree of slip relief at the granular level is observed for specimens tested at 77K. The out-of-plane rotation of grains is believed to promote greater slip homogeneity thereby increasing the work hardening capacity. This observation is potentially important, as it may provide a microstructural means to obtain the excellent work hardening properties observed at cryogenic temperatures.

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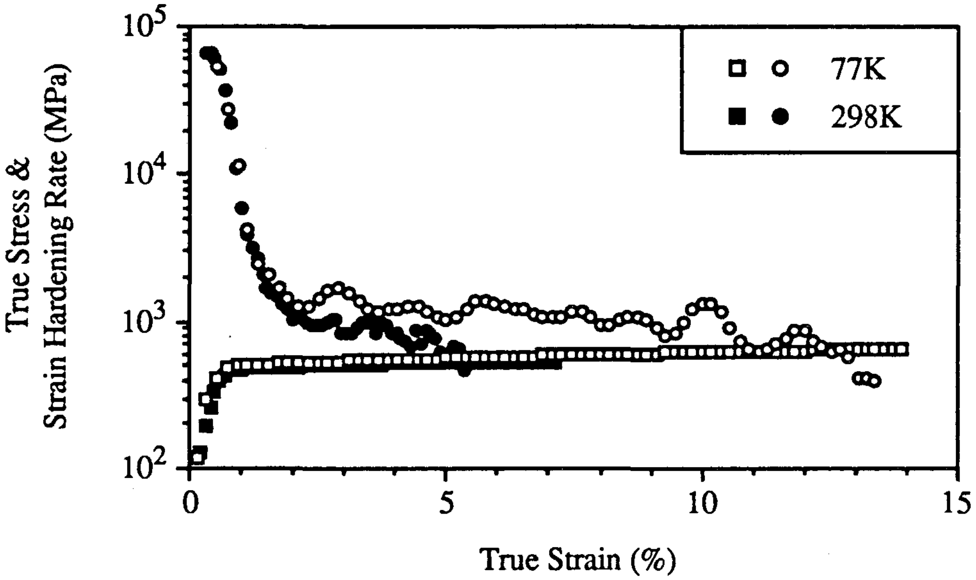

Figure 1: Comparison of the true stress and strain hardening rate as a function of true strain for 2090-T8E41 (Vintage I) longitudinal tensile specimens tested at 77 and 298K.

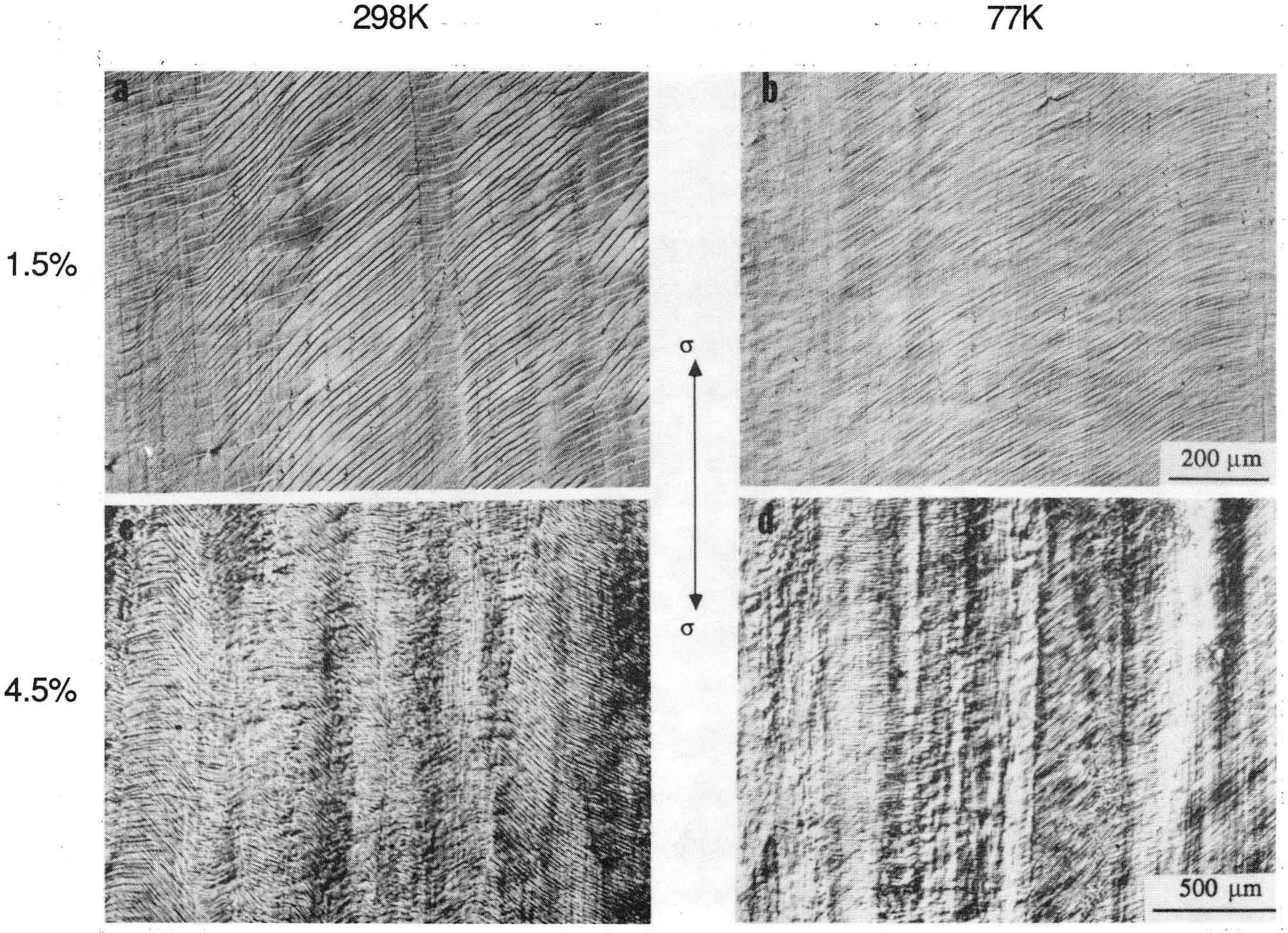

Figure 2: Optical micrograph of slip traces on pre-polished tensile specimens pulled to 1.5% (a,b) and 4.5% (c,d) strain. (XBB 905-4318)

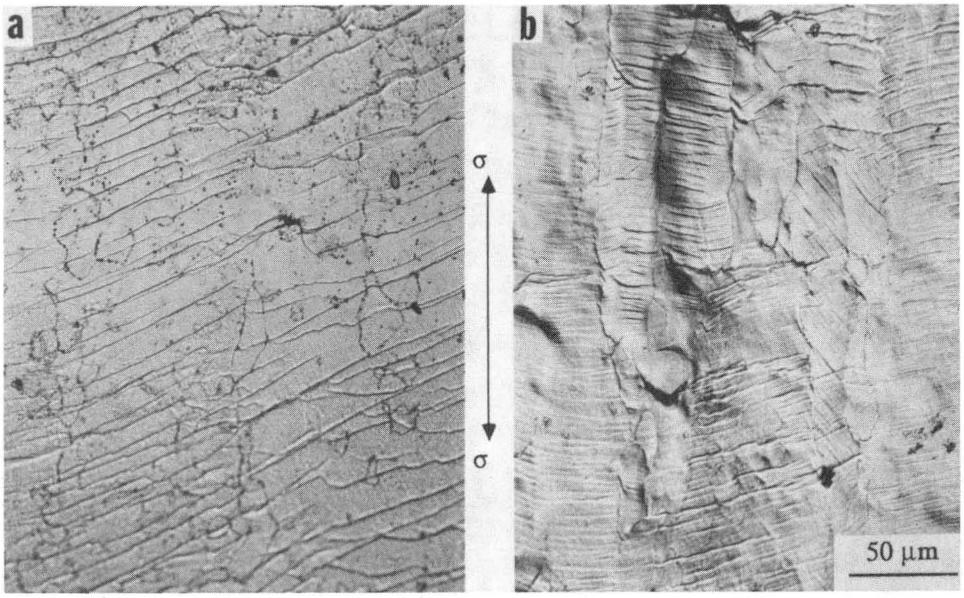

Figure 3: Optical micrograph of slip traces on pre-polished tensile specimens pulled to equivalent instability points: a) 5% at 298K and b) 12% at 77K. Note the appearance of deformation at the granular level at 77K. (XBB 906-4642)

LAWRENCE BERKELEY LABORATORY
CENTER FOR ADVANCED MATERIALS
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720