Mode Transformation of Growing Stage I Cracks in Polycrystals

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ABSTRACT

The mode transformation associated with the variation of crack tip displacements during stage I growth was examined both numerically in a FEM model and experimentally by using fiducial grids attached to the crack tip in aluminum bicrystals. The mode of stage I cracks is generally mixed and contains variable mode I, II and III components during stage I growth. As a stage I crack grows along a slip band hindered at a grain boundary under constant cyclic stress, the shear mode represented in $CTSD_{II}$ and $CTSD_{III}$ decreases, but tensile mode corresponding to CTOD increases. Dramatic mode change occurs in the vicinity of grain boundary where the stage I crack branches and splits. Evidence is presented that the CTSD of stage I cracks is mainly determined by the coplanar slip which is local microstructure-sensitive, but the CTOD is principally macro-mechanics controlled.

INTRODUCTION

The high cycle fatigue lives of engineering alloys (1) are often dominated by the propagation of stage I cracks which are generally referred to microstructure small cracks (2). A stage I small crack grows along a coplanar slip band with a growth rate that is far in excess of those of large cracks subjected to the same nominal K_I(3) and is also sensitive to the microstructures (4).

The fast growth behaviour of stage I small cracks has been accounted for by lesser amount of crack closure (5), or sheilding (6) due to short crack wake. Even though the shielding effect of both large cracks and small cracks was excluded by considering K_{eff} only, the small cracks still grow faster than the large ones (6), which suggests that the so called "anomalous growth" of stage I small cracks essentially arises due to misuse of the global fracture mechanics parameter as "crack driving force".

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A foundamental factor relevant to the choice of "driving force" is the crack mode, the mechanical nature of a crack. The mode of small crack in polycrystals has been referred as shear mode (7) and mixed mode (8). Chan (9) pointed out that stage I crack in nickel alloy single crystals is of mixed mode with components I, II and III. However, a fundamental understanding about the effect of coplanar slip and grain boundary on the mode transformation is still lacking.

Crack tip opening displacement (CTOD) and crack tip sliding displacement ($CTSD_{II}$ and $CTSD_{III}$) are not only local, mesurable parameters, but also more directly mechanisms-related, respectively, to tensile mode cracking (10) and shear mode cracking (7). Li (11, 12) has developed a vector CTD parameter as vector summation of CTOD and CTSD, by which the branching angle and growth rate of mixed mode cracks in the near threshold range were successfully predicted.

The aim of this research forcused on the effect of the grain boundary and the coplanar slip on the mode transformation during stage I growth. Based on the CTD methodology, the CTOD and CTSD of growing stage I cracks in aluminum bicrystals were examined by using fiducial grids. The experimental data were also compared with the numerical results by a FEM model of stage I small crack in polycrystals.

EXPERIMENTAL PROCEDURE

Bicrystals, with designed orientation, were produced in 99.999 % pure aluminum. The bicrystals were tilt ones representing different grain-boundary misfit angles.

The orientation of the specimens is given in Fig. 1. An inclined notch was spark cut along the primary slip band. After careful mechanical polishing, the samples were electro-polished in the ethanol solution of 50 g $Mg(ClO_4)_2$. Following annealing at 300° C for 2 hr, the orientations of the bicrystals were determined in Laüe technique. The tensile axis is along Z axis parallel to grain boundary as shown in Fig. 1.

1 mm^2 gold square grids with 10 µm mesh size were deposited on the interesting places of the surface, such as crack tip and grain boundary on the crack path. The fiducial grid technique was explained in more detail in (13). The crack tip displacements were extrapolated from the measured values at the 3 couples of points 5 µm apart behind the crack tip.

FEM MODEL

As shown in Fig. 2, a FEM model of the stage I small crack in polycrystals was developed based on observed stage I growth behaviour and micromechanics of polycrystals deformation. The cut out in the right figure is shown enlarged in the left one. The width of the mesh, 14 mm, is about 200 times as long as the small crack.
A stage I small crack and a coplanar slip band lie in line ab which is 45 degrees inclined to the axial stress direction. All nodes on the line are double named. The width of each element along line ab is 2 µm. All nodes on the coplanar slip band between the crack tip and grain boundary are constrained to permit only sliding parallel to line ab during deformation. The constrain equation for each couple (i,j) of nodes on line ab is as follows:

$$V_i - V_j = tg\ \alpha\ (U_i - U_j) \tag{1}$$

where α is the angle between slip line and applied stress axis.

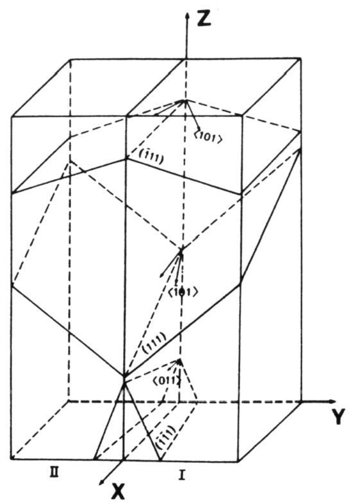

Fig. 1 - Orientation of the bicrystal specimen.

For the crack growing into the adjacent grain, the nodes on line cd are constrained by the same equations except for a different α value.

It was confirmed experimentally that the interruption of a small crack in polycrystals is in such a short ranges as a grain size (14). Kocks (15) has proposed that the action of all grains on the surrounded one is equivalent to the action of an isotropic continuum on the grain. Consequently, only one crystalline grain with anisotropic properties ahead of the stage I small crack tip is modefined as a hexagon in Fig. 2. With the hexagon it is convienent to model a grain with a different orientation and a deflected crack in a different angle.

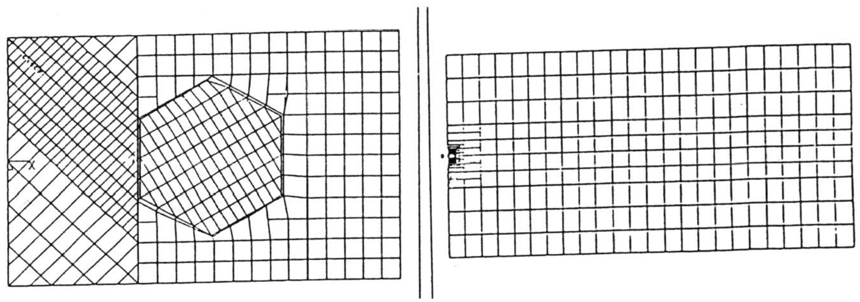

Fig. 2 - Finite element idealization of stage I small crack in crystal grains

RESULTS

It is observed that stage I cracks in aluminum bicrystals preferably grow along the primary slip band except the micro-branching along a bundle of slip bands and the macro-branching in the vicinity of grain boundary. The micro-branching results in a step-wise growth which makes the crack path deviate a small angle from the primary slip band, as shown in Fig. 3.

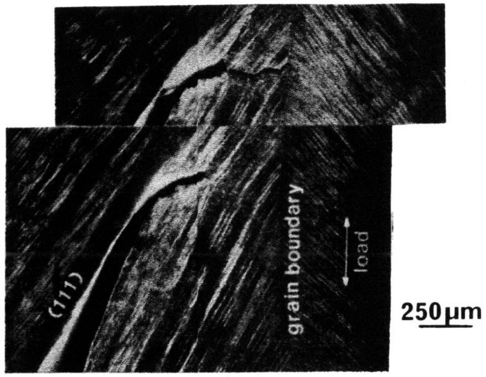

Fig. 3 - The stage I crack path and branching at the grain boundary

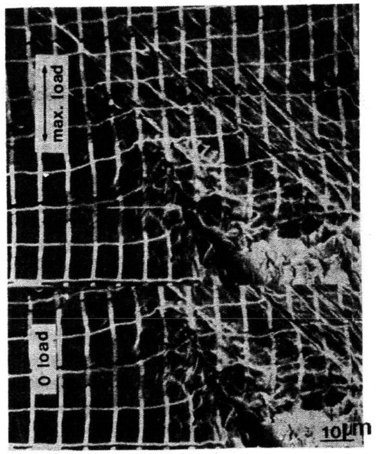

Fig. 4 - Stage I crack tip displacement during loading from $\sigma = 0$ to σ_{max} in situ in SEM.

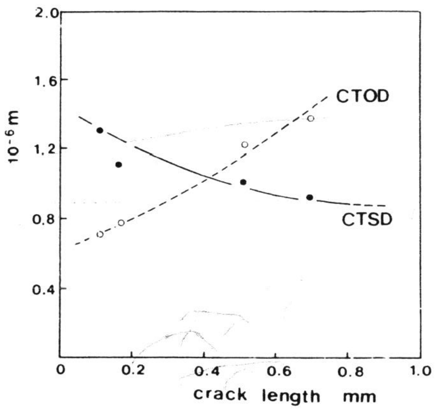

Fig. 5 - Crack tip displacements versus stage I crack length in the aluminum bicrystal.

The opening and sliding of a stage I crack in aluminum bicrystals during loading are obviously identified in the two pictures of Fig. 4, respectively, taken under the maximum cyclic stress and zero stress exerted in situ in SEM. Being different from the roughness induced closure, the crack closes under 0.9 maximum cyclic stress during the loading. Fig. 5 displays that CTOD continuously increases, but CTSD decreases when the stage I crack grows under constant applied stress before branching.

As the crack approaches a point 300 µm from the grain boundary, it branches as shown in Fig. 3. When the crack approaches the grain boundary, the crack front splits into several pieces which propagate either along the grain boundary, or along different orientations. Fig. 6 is the fractography in the vicinity of the grain boundary. There is a narrow band of about 200 µm width along the grain boundary, with striation which is known as the characteristic of mode I growth. With the split crack front, the cracks entering the adjacent crystal are decelerating under constant applied stress till a minimum value at about 200 µm from the boundary (16).

The numerical results in more detail about the variation of CTOD and CTSD versus the crack length at the constant maximum cyclic stress are displayed in Fig. 7. The CTSD decreases as the crack grows in the first grain with the shortening coplanar slip band. As the crack penetrates the grain boundary and grows along an activated slip band, the CTSD increases dramatically.

On the other hand, CTOD increases almost linearly with the crack length except minor drops at the grain boundary. The dashed line in Fig. 5 is the theoretical value predicted by (17)

$$\text{CTOD} = \frac{C\Delta K_I^2}{E\,\sigma_{ys}} \qquad (2)$$

where σ_{ys} is the cyclic yield stress of the material. It is remarkable to note the coincidence of numerical data with the theoretical value, which suggests that CTOD is principally macro-fracture-mechanics controlled even for the cracks in a heterogeneous material.

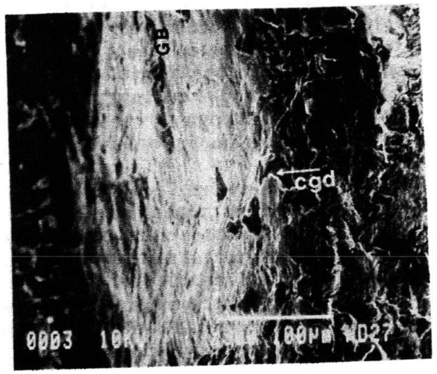

Fig. 6 - Fractography in the vicinity of bicrystal boundary.
GB : grain boundary; cgd : crack propagation direction.

The FEM has been proven to be a useful tool to study the closure behaviour of cracks (18).

In this study attention was paid to the closure created by the deflected crack at the grain boundary. The range of CTOD and CTSD are, respectively, defined as

$$\Delta CTOD = CTOD_{max} - CTOD_{min}$$
$$\Delta CTSD = CTSD_{max} - CTSD_{min} \qquad (3)$$

$CTOD_{min}$ for the stage I small crack is observed to be approximatelly zero. The variation of $CTSD_{min}$ and ΔCTSD under the cyclic stress, σ_{max} = 220 MPa and R = - 1, in the first two grains beneath the surface is shown in Fig. 8. It turns out that the shear closure or toughness-induced closure, occurs mainly for the crack penetrating grain boundary which hinders the reversed sliding.

DISCUSSION

Since mode I, II and III growth are, respectively, governed by CTOD, $CTSD_{II}$ and $CTSD_{III}$, both numerical and experimental results in Fig. 5 and Fig. 7 display the mode characteristics of growing stage I crack in the same tendency. As a stage I crack grows along the slip band hindered at a grain boundary under constant cyclic stress, tensile mode of the crack increases graduately at the expense of shear mode. The intrusion of 3 μm depth has been suggested to be an initiated stage I crack (19), for which CTOD is negligible. This means that only very small stage I crack can be treated as a pure shear mode crack. Generally speaking, the mode of stage I cracking is mixed and contains mode I, II and III components which vary during stage I growth.

Of an essential character during stage I growth is the branching which also occurs in 2024 aluminum alloy (8) and nickel alloy single crystals (9). As a stage I crack grows along a slip band under constant cyclic stress, CTOD and tensile stress at the crack tip are unable to be released by the coplanar and cross slip (20) unless branching or out-plane slip. Therefore, the micro-branching may be necessitated to keep growing along the primary slip band. The roughness-induced closure due to branching is well noted (21), however, sliding closure during loading also results from micro-branching as shown in Fig. 4, even though it is occasional. Both types of closure contribute to the transformation from shear mode to tensile mode.

The effect of grain boundary on the stage I growth is critical : it checks the crystallographic growth, as illustrated in Fig. 3 and Fig. 6. The incompatible tensile strain and shear strain components (8) across the grain boundary result in large residual stresses (22) which may be a main cause of macro-branching and splitting of the crack front. The minimum growth rate reached at the point 200 μm beyond, rather than exactly at, the grain boundary is obviously associated with the disordered growth of the split pieces of the crack front.

Of particular significance in this work is the identification that ΔCTOD component of stage I crack is macro-fracture-mechanics determined, but ΔCTSD component of the crack is local microstructure controlled.

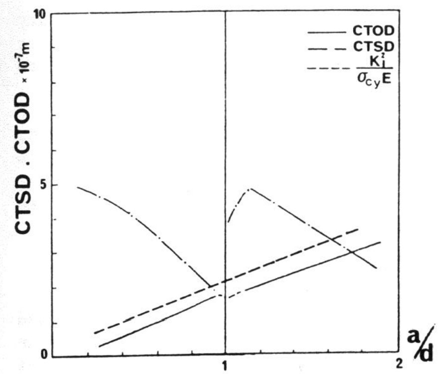

Fig.7- Crack tip displacements at maxmum cyclic stress vs relative crack length.

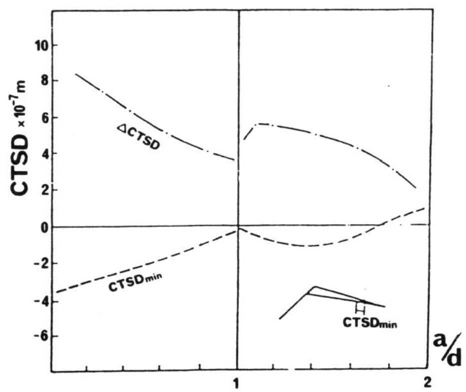

Fig.8- Variation of CTSD and ΔCTSD as the crack entered into the adjacent grain.

This results can also be expected by considering the plastic zone at the crack tip which fairly correlates with CTOD (17). The plastic zone of stage I crack due to secondary slip in single crystals has been given as (20)

$$r_p^s = \frac{K_I^2}{18\,(\sigma_y^2 - 3\,(\sigma_{xy}^{*2} + \sigma_{zy}^{*2})} \qquad (4)$$

where σ_y is the yielding stress. The values σ_{xy}^* and σ_{zy}^* are roughly fixed for cracks with coplanar slip band. Hence, plastic zone and CTOD are independent of the anisotropy of the crystals. As it is identified experimentally and numerically, the ΔCTSD of stage I cracks is partially produced by the local enhanced shear deformation in PSB. The concentration of shear deformation may become even more severe due to the material weakness in PSB in age hardening materials (22). On other hand, ΔCTSD may also be reduced by micro-branching to cross slip band and by macro-branching, splitting and closure at the grain boundary which compose the main mechanisms of crack sheilding at the boundary. Obviously, local microstructure and the interaction among the stage I crack, slip band and grain boundary determine the coplanar shear, and CTSD. The different dependence of CTOD and CTSD suggests that the components of local "driving force" of stage I crack are, respectively, related to macro-fracture-mechanics and microstructures. As a consequence, this finding may throw light on searching a suitable global approach to the stage I small crack growth.

CONCLUSION

1) Stage I cracks in aluminum bicrystals grow preferably along the primary slip band with frequent micro-branching. The grain boundary suppresses the crystallographic growth in short area nearby the boundary and decelerates the stage I growth to a minimum value or ceases the crack to propagate at a point little beyond the boundary by macro-branching and splitting the crack front.

2) Stage I cracks in polycrystals are of mixed mode which contains mode I, II and III components variable during it's growth. The tensile mode of growing stage I crack graduately increases at the expense of shear mode unless the crack branches or penetrates a grain boundary.

3) The tensile mode of stage I crack in polycrystals or CTOD, is mainly macro-fracture-mechanics controlled, but the shear mode of the crack, or $CTSD_{II}$ and $CTSD_{III}$, relates also to coplanar slip which is sensitive to microstructures, such as grain boundaries and inclusions.

4) The transformation from "pure shear mode" to pure tensile mode during stage I growth is graduately promoted by the reduction of coplanar slip band and micro-branching, but dramatically by macro-branching, splitting and closure at the grain boundary due to the strain incompatibility besides the boundary.

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