STUDIES OF CRACK TIPS IN STEEL AND ALUMINUM ALLOYS

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INTRODUCTION

This paper presents results of two studies: the nature and mechanism of formation of the stretched zone in steel and aluminum, and COD behaviour in aluminum as a function of specimen size and geometry. Some comparisons of COD and fractographically measured crack tip displacements were made in the second project.

Considerable interest has been shown in dimensional changes at crack tips for the past several years. Some of this interest has been in the area of fracture testing where investigators have attempted to relate fracture toughness in tough materials to crack tip dimensional changes in terms of Crack Opening Displacements (COD). Wells [1] postulated that a finite opening at the tip of a crack, δ, was developed as a consequence of the formation of the plastic zone at the crack tip. This should be on the order of:

$$\delta = \frac{4G}{\sigma_y} = \mathrm{COD} \qquad (1)$$

where σ_y = yield stress, G = strain energy release rate. A critical δ_c similar to G_c and K_c was expected because of the relationship between G_c and δ_c.

COD has been observed to predict well nonplane-strain fracture in steels. (Reference [2] provides references in this area.) COD and crack tip strains measured at the onset of ductile tearing were observed to be material constants. Fractographic studies [3] of crack tips and finite element models [4, 5] of crack tips have provided a physical basis for Well's concept of a critical COD for fracture.

Fractographic studies of crack tips were initiated after the COD concept was established. A feature called the stretched zone was discovered at crack tips in fracture specimens. The size of this feature was observed to be proportional to the fracture toughness of the specimen. Reference [3] provides a review of stretch zone studies and efforts to explain its formation.

PROCEDURE

A 302D steel was tested in the form of standard ASTM 50.8 mm thick compact tension specimens at different temperatures [3]. Aluminum specimens of conventional and high toughness 7075-T651 alloy were tested at room temperature with compact tension and three-point bend specimens. Three point bend specimens had a B/W (thickness to width) ratio of 0.25 for specimens

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cut from 12.7 mm thick plate and a B/W ratio of 0.5 for specimens cut from 25.4 mm thick plate. All specimens were machined in the T-L orientation (crack propagation direction parallel to the rolling direction).

COD measurements were made on the aluminum specimens with crack mouth compliance gages using a technique described in Reference [6]. COD measurements were made at the first indication of crack instability or growth as determined from electric potential observations during testing.

All fractographic observations of the crack tip were performed using scanning electron microscopes (SEM's). Stereo pairs of matching fracture surfaces were used extensively in morphological studies of the actual crack tip blunting. Fractographic measurements of the amount of blunting or Crack Tip Opening Displacement (CTOD) were made using a technique in Reference [7]. This technique permitted crack tips to be measured *in situ* relative to the overall specimen geometry. Matching surfaces at the crack tip were measured to accurately determine CTOD as shown in Figure 1. (CTOD will refer to fractographically determined crack tip dimensions while COD will refer to mechanically derived crack tip dimensions).

RESULTS

Figures 2 and 3 are typical results for the steel specimens which fractured in a brittle fashion but displayed plasticity in terms of nonlinear load vs. deflection curves. An SEM picture of the steel crack tip is shown in Figure 2 with a cross section for orientation. The ripple marks at the crack tip are considered to be caused by alternating slip.

The metallographic cross section shown in Figure 3 shows the severity and localized nature of the crack tip deformation in the steel specimens. Fractographic examination of this specimen did not reveal evidence of ductile fracture before mounting for sectioning and polishing.

Blunted crack tips were observed only in steel specimens that displayed nonlinearity in load vs. deflection curves produced during the fracture test. Specimens which did not display nonlinearity in the load vs. deflection curves exhibited only localized crack tip deformation.

The aluminum specimens also exhibited crack tip blunting but in a fashion generally similar to the sharp crack tips predicted by Pelloux [8]. A complete crack tip similar to that predicted by Pelloux is preserved on one surface of a fracture specimen as shown in Figure 4. The included angle at the crack tip in this picture is approximately 70°. This feature was observed in several aluminum fracture specimens studied. Other variations on this morphology were observed in individual grains depending on the crystallographic orientation of the grain to the principal stress axis.

Several aluminum fracture specimens were tested to determine COD and CTOD. Results of the COD tests given in Figure 5 indicate that COD in 7075-T651 is affected by specimen geometry and the type of specimen used. Crack tips were fractographically measured in two aluminum specimens and CTOD results were observed to be approximately an order of magnitude smaller than COD results for the same specimen.

DISCUSSION

The fractographic study of the crack tips in steel and aluminum fracture specimens revealed that the stretch zone was the result of crack tip deformation. This crack tip deformation produced blunted crack tips in the steel and aluminum specimens and provides a physical basis for the COD approach to fracture.

Careful study of the blunt crack tips provides several clues to the nature of crack tip deformation:

a) Severe crack tip deformation in the steel specimens produced elongated grains at the crack tip (Figure 3).
b) Equiaxed cleavage facets were observed right up to the crack tip in the steel specimen.
c) The very sharp crack tip in the aluminum specimens which did not produce fracture suggests that linear elastic fracture mechanics cannot be used to describe the stress state at the crack tip.

These clues show that simple plastic slip line analyses can be applied to describe crack tip behaviour in tough materials. The ideal plastic slip line solution for a single edge notched tension specimen [8], or the solution for an edge notched specimen in bending [9] predicts finite constant stresses ahead of the crack tip. These solutions predict that plastic deformation can only occur on two mathematical shear planes emanating from the crack tip. This leaves the region ahead of the crack tip distortion free in agreement with the microstructures observed in the steel specimens.

The elongated grain structure at the crack tip in the steel specimens in combination with equiaxed cleavage facets fit the slip line description of the crack tip. In fact the highly deformed grains at the crack tip can be qualitatively reproduced by simulating Pelloux's proposed simultaneous slip on both shear planes (taking into account strain hardening). Finally, the sharp crack tips occasionally found remaining on the aluminum specimens support the concept of constant, finite stresses ahead of the crack tip.

The difference in COD measured in the two types of aluminum specimens probably reflects basic differences in the two specimen types. Compact tension specimens with both tension and moment forces present probably have different rotational factors whereas one factor was used for both specimen types in these tests to calculate COD. Other unpublished work at Boeing suggests that crack mouth displacements from compact tension specimens also contain a displacement component due to bending of the two loading arms (cantilever beams).

The disagreement between CTOD and COD measurements is not surprising when the empirical nature of the method of Elliott, Walker, and May [6] is considered. They assumed the specimen to rotate about a hinge point in the remaining ligament in a fashion predicted by the slip line solution for an edge notched bend specimen. The experimental determination of the location of the hinge point is essential to this analysis. Neither this approach or Well's analytical approach address whether crack tips actually deform.

This work reveals that crack tips do deform or blunt and single slip line plastic analysis can describe the blunting mechanism. This crack tip blunting process in fracture is also the mechanism by which cracks grow in fatigue. If CTOD critical for fracture can be analytically predicted, a method is available to determine fracture toughness in low strength, high toughness materials. A fatigue crack growth analysis would be available if CTOD per cycle could be predicted as a function of previous load history.

CONCLUSIONS

1. Blunted crack tips were observed in steel and aluminum alloys.
2. The occurrence and behaviour of the blunted crack tips are explained with simple plastic slip line fields.
3. COD was a function of the specimen type and geometry.
4. CTOD measurements made with scanning electron microscope techniques were about an order of magnitude smaller than corresponding COD measurements.

ACKNOWLEDGEMENTS

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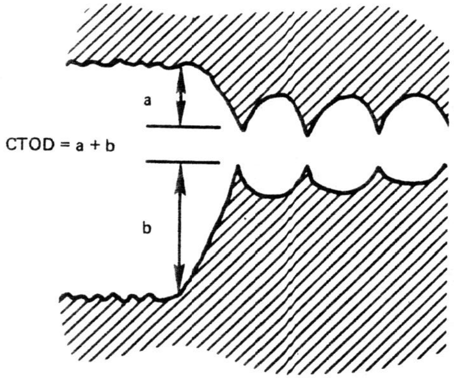

Figure 1 Fractographic Measurements of CTOD were made from Matching Fracture Surfaces

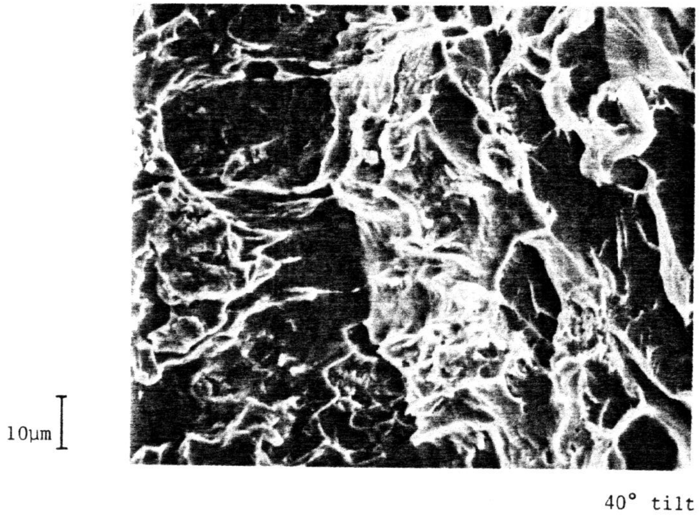

Figure 2A An SEM Picture of a Blunted Crack Tip (Stretch Zone) in a Steel Specimen

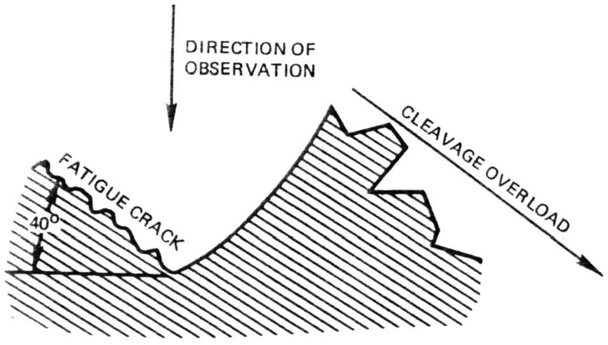

Figure 2B A Schematic Sketch of the Cross Section is Shown in this Figure to Provide Specimen Orientation in Figure 2A

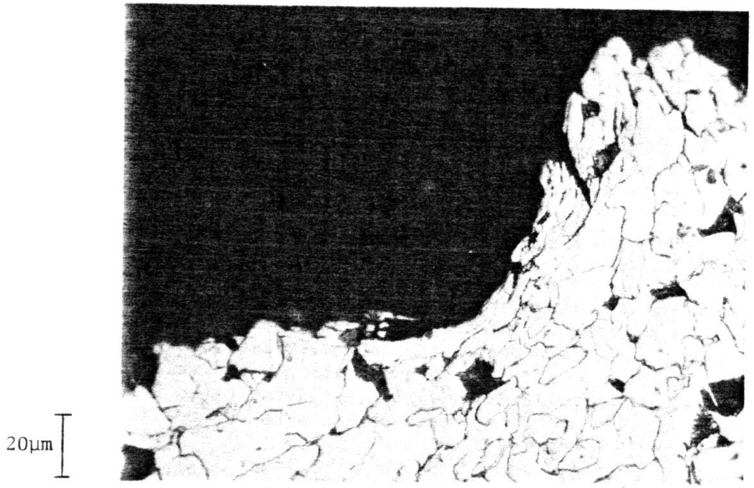

Figure 3 Metallographic Cross Sections of Steel Specimens Revealed Elongated Grains at the Crack Tip

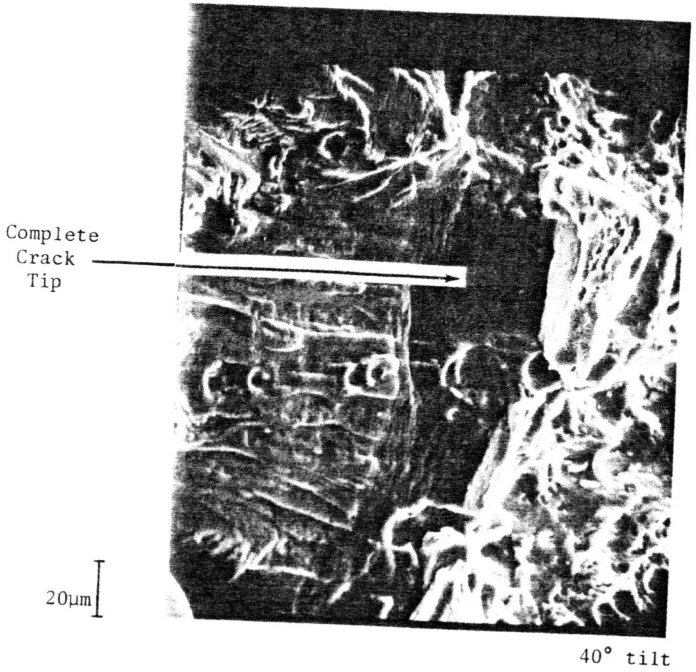

Figure 4 Sharp Crack Tips were Occasionally Found Intact on Aluminum Specimens

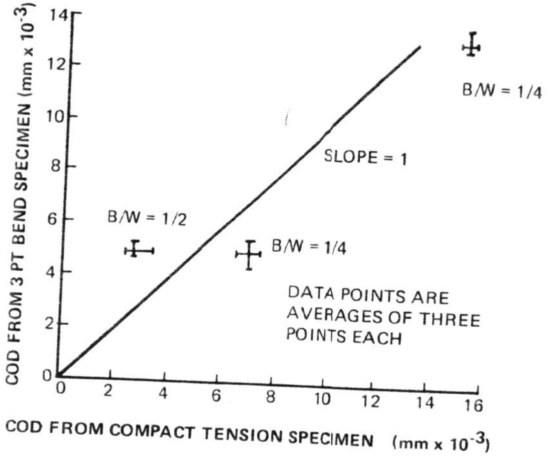

Figure 5 COD was Dependent on Specimen Type and Specimen Geometry for 7075-T651 Aluminum