Crack Tip Plasticity and Fracture Initiation Criteria

James R. Rice, Brown University, Providence, R. I., U. S. A.

Introduction

This paper is concerned with fracture initiation from the tips of macroscopic pre-cracks in structural metals, under plane-strain-like conditions at the crack front. At the microstructural level such fractures are frequently due to the large ductile growth and final coalescence of cavities which originate by the decohesion or cracking of second phase particles. Alternatively, brittle stress-dominated mechanisms such as cleavage microcracking may sometimes be responsible and sometimes it is more the initiation of cavities by particle fractures, rather than their subsequent ductile growth, which is to be regarded as the critical mechanism.

The elastic-plastic continuum mechanics analysis of crack tip stress and deformation fields is now fairly complete for a stationary crack under plane strain conditions. This paper will follow upon the work of Rice and Johnson [1] in utilizing such results, in combination with models for fracture micromechanisms, as background for the interpretation of experimental results and hence for the development of fracture initiation criteria.

Plane-strain elastic-plastic crack tip stress fields

The works of Cherepanov, Hutchinson, Rice, and Rice and Rosengren, summarized in [1,2], have established the structure of the near tip field for non-hardening and for power-law strain hardening materials. Further, while these works considered the dominant singular term only, they allowed the development of effective methods for computational finite-element analysis in the works of Hilton and Hutchinson, of Levy, Marcal, Ostergren and Rice, and of Rice and Tracey.

From these the following features may be cited:

With contained plane strain yielding there are enormous triaxial stress elevations ahead of the crack but, at least when the large geometry changes of progressive crack tip blunting are neglected, there are only very small plastic strains, of elastic order, directly ahead of the tip. In contrast, regions of intense shearing form above and below the tip. For example, the stress state of the Prandtl slip line field constitutes the state immediately at the crack tip for a non-hardening material, and 1/r strain singularities form in the centered fan sectors above and below the tip. The maximum stress is 3 times the tensile flow stress; this diminishes rapidly with distance from the tip. Also, the effect of strain hardening (at least of the power law type) is to cause yet greater stresses very near the tip. Quantitative results on these stress distributions may be taken from figs. 1 & 4 of [1]. When hardening is neglected the crack tip opening displacement and the maximum radius of the plastic zone (occurring at approx. ±70°) are

$$\delta_t \approx 0.5\, K^2/E\sigma_o \quad , \qquad r_p \approx 0.15\, K^2/\sigma_o^2 \quad ,$$

for small scale yielding under a stress intensity factor K , where E is Young's modulus and σ_o the yield stress. Also, when the shear stress-strain relation takes the form $\tau \propto \gamma^N$, numerical results of Tracey [3] verify the prediction from the writer's Mode III studies that an effective definition of δ_t may be made by identifying σ_o as the tensile flow stress corresponding to the equivalent shear strain $\gamma = N/(1 + N)$.

McClintock and Rice and Johnson have noted, however, that the large but highly localized geometry changes of crack tip blunting drastically alter the near tip field over a size scale comparable to δ_t . Indeed, large plastic strains of order unity result directly ahead of the tip over this size scale (see fig. 7 of [1]), although the greatest straining seems to occur at angles with the crack plane. Also, the very large concentrated stresses are due primarily to triaxial stress elevations and these cannot be maintained at the blunted tip. The result is that the stress is limited to a maximum achievable value, attained at a distance of approximately $2\delta_t$ ahead of the tip. Fig. 10 of [1] provides an estimate of this local modification.

Cleavage microcracking

The simplest model for cleavage initiation is the attainment of a critical tensile stress. Recently Griffiths and Owen [4] were able to infer, from a precise finite element stress analysis, that cleavage initiation in Si-Iron specimens with round-ended notches occurred at an essentially constant maximum stress in the specimen, over the slip-nucleated cleavage range from -150°C to +50°C . On the other hand, elastic-plastic solutions for sharp cracks suggest that their critical stress would be exceeded near the tip over this same temperature range even at very small applied loads. Hence it seems necessary to supplement this criterion with the requirement that it be met over at least some microstructurally significant size scale ahead of the tip [1].

Indeed, the writer and Knott and Ritchie of Cambridge have had some success in interpreting data from the latter on the temperature dependence of K_{IC} for a high-N mild steel of 60μ grain size on this basis. Results were consistent with attaining a critical stress of approximately 900 NM/mm^2 at a distance of 2 to 3 grain diameters; K_{IC} values were inferred from measured flow properties at the different temperatures and from the dimensionless stress distributions of [1]. Of course, if the maximum achievable stress is insufficient to equal the critical value, fracture cannot initiate as cleavage according to the model, and this corresponds to a fracture mode transition to ductile rupture. The magnitude of the maximum achievable stress and, indeed, the stress levels at points near the tip for a given applied load are very much dependent on the yield stress and hardening properties. Such considerations may similarly allow a prediction of the effects of high loading rate, prestrain, radiation damage, etc. on cleavage initiation from known effects on the yield and hardening properties.

Ductile void growth and coalescence

In the simplest case of ductile rupture, there is a single population of void nucleating particles which crack or decohere in the precursor stress field which envelops material points prior to their exposure to the large strains involved in progressive crack tip blunting. Since δ_t sets the size scale over which strains of order unity occur, it is then reasonable to expect fracture initiation to correspond to a value of δ_t which is of the same order as the particle spacing, the precise ratio of δ_t to spacing depending on factors such as volume fraction, anisotropy of particle shape or distribution, and degree of hardening of the matrix material. This was remarked by Rice and Johnson [1] who presented supporting data from Pellissier and coworkers on a series of high strength steels with MnS particles ranging from 3.7 to 6.1μ mean surface spacing and corresponding δ_t values, as computed above, from 3.3 to 7.4μ . Further support comes from the work of Smith and Knott [5] on a fully plastic fracture of a low strength steel, also containing MnS particles, but now with a 42 and 53μ surface spacing, depending on

orientation, and corresponding δ_t values of 37 and 120μ , the latter possibly being influenced by delamination.

These are, however, the most ideal cases; even for them the precise role of volume fraction and hardening remains unclear. Also, there is no complete model of the coalescence stage, which may involve the formation of zig-zag shear bands as McClintock proposed. More generally, there may be several types of particles, each of which tends to initiate voids at different stages of the deformation history. Aluminum alloys are an example. A recent report by Low et al. [6] seems to be among the few cases for which an attempt is made to identify all participating particles and also when each type nucleates voids. The study includes 5 aluminum alloys (2000 & 7000 series). Spacings of the first particles to nucleate voids seem to bear ratios in the expected range to inferred δ_t values. Nevertheless, even the smaller precipitate particles ultimately come loose on the final fracture. They very likely determine the limiting strains which can be attained in coalescence between the larger voids before final instability, but their complete role in the fracture remains unclear.

References

1) J. R. Rice & M. A. Johnson, In Inelastic Behavior of Solids (ed. Kanninen et al.), McGraw-Hill, 1970, p. 641.

2) J. R. Rice, In Fracture (Vol. II) (ed. Liebowitz), Academic Press, 1968, p. 191.

3) D. M. Tracey, Ph.D. Thesis in preparation, Brown University, 1972.

4) J.R. Griffiths & D.R.J. Owen, J. Mech. Phys. Solids, 19, 419, 1971.

5) R. F. Smith & J. F. Knott, In Practical Application of Fracture Mechanics to Pressure Vessel Technology, Instn. Mech. Engrs. 1971, p. 65.

6) J. R. Low, R. H. VanStone & R. H. Merchant, Carnegie-Mellon Univ., Tech. Rpt. NGR 39-087-003/2 to NASA, 1972.