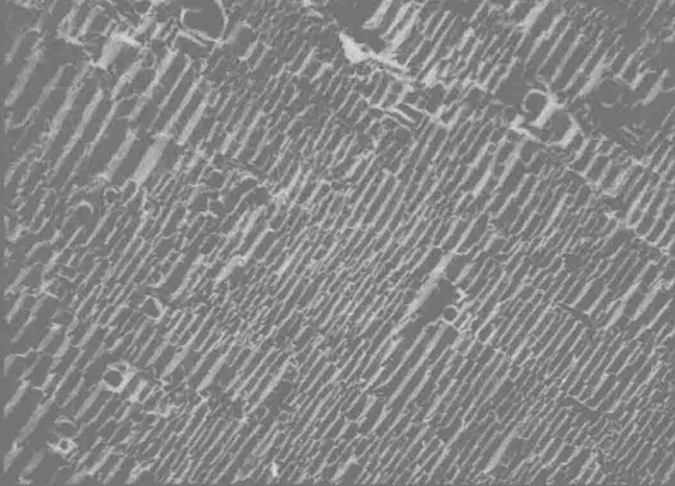

Fracture Mechanics

Eighteenth Symposium

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editors

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FRACTURE MECHANICS: EIGHTEENTH SYMPOSIUM

Eighteenth National Symposium
on Fracture Mechanics
sponsored by
ASTM Committee E-24
on Fracture Testing
Boulder, Colorado, 25–27 June 1985

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D. T. Read and R. P. Reed
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NOTE

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Contents

ELEVATED TEMPERATURE FATIGUE

POSTER SESSION—ANALYSIS

POSTER SESSION—ELASTIC PLASTIC FRACTURE MECHANICS I

APPLICATIONS

DUCTILE/BRITTLE TRANSITION

J-INTEGRAL TEST METHODS

ANALYSIS

Poster Session—Elastic Plastic Fracture Mechanics II

Poster Session—Fatigue

Subcritical Crack Growth

Fatigue I

Elastic-Plastic Fracture Mechanics II

Fatigue II

SUMMARY

Introduction

This volume is based on the Eighteenth National Symposium on Fracture Mechanics, held in Boulder, Colorado, 25–27 June 1985, sponsored by ASTM Committee E-24 on Fracture Testing. The conference was held at the University of Colorado; the support of the CU Office of Conference Services for the conference arrangements was excellent.

The National Symposium on Fracture Mechanics has served as an annual state of the art review of current fracture research since its beginnings in 1965. The Eighteenth Symposium carried on this tradition creating on open forum for fracture researchers from the whole world. There were over eighty papers presented by formal talks and posters. Six speakers were specifically invited, including one from England, one from Japan, two from U.S. universities, one from U.S. industry, and one from a U.S. national laboratory. The submitted papers were grouped into 16 sessions. The papers on elastic plastic fracture mechanics made up four sessions, with one session on each of the allied areas of ductile-to-brittle transition and J-integral test methods. Four sessions on fatigue emphasized elevated temperature studies, including frequency and hold-time dependence, and effects of short cracks. Two sessions were held on analysis, including linear elastic and elastic-plastic analyses, and the remaining four sessions covered applications, crack arrest, micromechanisms, and subcritical crack growth.

Continuing the standard practice for ASTM Symposium publications, each paper in this volume has been peer-reviewed by knowledgable researchers in relevant subject areas. The papers accepted for this volume have been revised and carefully edited to promote significance, technical accuracy, and relevance. It therefore truly represents a broad view of the current state of fracture mechanics research. It is recommended to stimulate and aid future research, to give design and failure analysis practitioners needed insight and new approaches, and to contribute to new and improved test standards through its record of advances in basic understanding and the latest test procedures and results.

R. P. Reed

National Bureau of Standards, Boulder, CO 80303; symposium chairman and coeditor.

Micromechanisms

William W. Gerberich[1]

Metallurgical Aspects of Crack-Tip Failure Processes

REFERENCE: Gerberich, W. W., "**Metallurgical Aspects of Crack-Tip Failure Processes,**" *Fracture Mechanics: Eighteenth Symposium, ASTM STP 945,* D. T. Read and R. P. Reed, Eds., American Society for Testing and Materials, Philadelphia, 1988, pp. 5-18.

ABSTRACT: Process zone models for fracture of fiber-reinforced concrete, metal-particle reinforced glass, and polymer crazes have good experimental verification. This is because the microfracture process zone is often macroscopic in size or easily identifiable or both. Similar models have been proposed for metals and ceramic microstructures. This paper addresses how the microfracture process zone develops in such microstructures. Specifically, the microcrack evolution process may be controlled by chemistry and microstructure as well as localized stress distributions. The importance of this is that the microcrack distribution and the energy dissipation process in the remaining ligaments behind the advancing crack front control the R-curve and final fracture instability. Examples of R-curve behavior in ductile fracture and semibrittle composites are shown, and a model for brittle fracture of steel is proposed. The latter shows that a semi-cohesive process zone of variable size and strength may represent an approach to brittle fracture where weakest-link models are not applicable. Predictions of fracture toughness for ferrite/pearlite steels as a function of test temperature and grain size are obtained with such an approach.

KEY WORDS: fracture toughness, process zones, R-curves, microstructure, ductile ligaments, composites, brittle fracture, cleavage

The process zone concept was introduced two decades ago by Krafft [*1*] as a fundamental microstructural length parameter. Since then, there have been numerous applications of characteristic length parameters to ductile fracture [*2*], metal-metal composites [*3*], cleavage in the lower shelf region [*4*], and subcritical growth phenomena [*5,6*]. Although such process zones recently have been reviewed [*7*], the microscopic and macroscopic character of such zones will be addressed. This will then be applied to the ductile-brittle transition region of steels and, specifically, to classes of steel which range from the lower shelf to toughness levels where mixed modes may be becoming dominant. This is believed to be important because weakest-link hypotheses, for example, cleavage initiating at the largest carbide, cannot be applied to ductile fracture. In all probability, they are also not applicable to the upper shelf region near the transition temperature where a mixture of microvoid coalescence and cleavage or quasi-cleavage is found. In fact, the weakest-link hypothesis often might not apply to the lower shelf regime when a fine crack is present, but may be restricted to fractures emanating from blunt cracks or notches. The evidence for and treatment of multiple fracture origins rather than a single weakest link follows.

First, consider the process zone as a microscopic region where microcracks develop. This may be a single fractured carbide near the nil-ductility transition temperature (NDTT) which, as a weakest link, triggers cleavage in the surrounding grains. On the other hand, it may be a group of second-phase particles such as sulfides or oxides which nucleate multiple regions of void

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growth. This zone, containing a distribution of microcracks, has been designated a semicohesive zone [6] and is depicted in Fig. 1. Here, the crack-tip opening angle is approximately equal to the crack-tip "final stretch," displacement divided by the process zone, or $\hat{\delta}/\Delta$ [8-10]. Such a zone would have to develop, at least in a two-dimensional sense, in ductile fracture where microvoids nucleate and grow at multiple origins along a growing crack front. Other types of zones are depicted in Fig. 2, as taken from Ref 7. Brittle or semibrittle zones are depicted as being filled with a series of microcracks of varying sizes or spacings within Δ. Such microstructural zones could include properly oriented cleavage microcracks or populations of the weakest intergranular facets or brittle regions between ductile ligaments in two-phase materials. Next, the theoretical concept will be illustrated and then it will be applied to microscopic and macroscopic composite data.

Theoretical Model

The theoretical concept was first presented [7] and described as a series of traction forces in two zones, one a microcracked, semicohesive zone, and a second, monolithic, cohesive zone. A depiction of equilibrium is schematically shown in Fig. 3 where the "fishhooks" are trying to pull the imaginary crack open while the "springs" in the two zones are holding it together. Note that because of the voids in the semicohesive zone, the density of springs, that is, the traction force, is less. This was first applied to organic solvent-induced slow crack growth in glassy polymers where the larger semi-cohesive region was used to predict "equilibrium" craze lengths [11]. The microfibrils of the craze represented internal traction forces and in order to produce additional crazing at the crack tip, after equilibrium, greater applied stress intensities would be required.

With such a model as depicted in Fig. 3, integrating the stress field within each zone gives

$$K_I\left(\frac{\pi}{c}\right)^{1/2} - 2(\sigma_c - \sigma_{sc})\cos^{-1}\left(\frac{b}{a}\right) - 2\sigma_{sc}\cos^{-1}\left(\frac{c}{a}\right) = 0 \quad (1)$$

Here, σ_{sc} is the strength of the semicohesive zone and σ_c is the strength of the cohesive zone. For a ductile material, σ_c is the flow stress, whereas for a truly brittle material it may approach the theoretical strength [7]. In a yielding situation for crack initiation in an elastic-perfectly plastic material, the parameters are

$$\begin{aligned} \sigma_c &= \sigma_{ys}; & b &= c + \Delta \\ \sigma_{sc} &= \sigma_{ys}(1 - f_v); & a &= c + \Delta + R_{p_{Io}} \end{aligned} \quad (2)$$

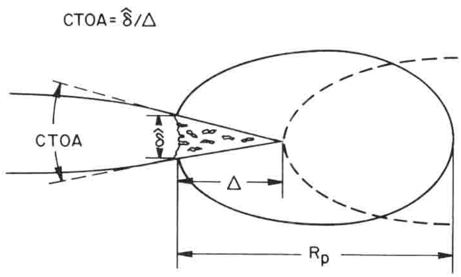

FIG. 1—*Process zone model (Refs* 8-10*) for a growing crack. The crack-tip opening angle (CTOA) may be represented by the "final stretch" displacement, δ, and the process zone, Δ.*

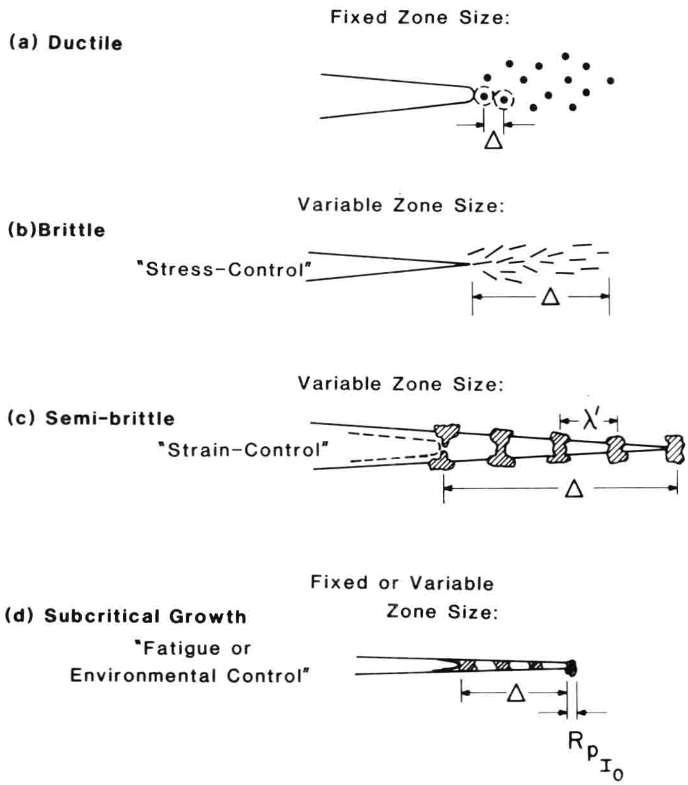

FIG. 2—*Process zone size variations, Δ, as a function of different controlling microstructural features. (Courtesy of Ref 7.)*

where

f_v = microvoid volume fraction,
Δ = process zone,
c = half-crack length, and
$R_{P_{\mathrm{Io}}}$ = plastic zone size for nucleating the process zone.

The assumption here is that a minimum strain or stress for failure, as related to the size of $R_{P_{\mathrm{Io}}}$, is required to initiate microvoids or microcracks in the absence of the process zone. Since in plane stress, $R_{P_{\mathrm{Io}}}$ is given by

$$R_{P_{\mathrm{Io}}} = \frac{\pi K_{\mathrm{Io}}^2}{8\sigma_{\mathrm{ys}}^2} \tag{3}$$

there are three unspecified parameters K_{Io}, Δ, and f_v. In principle, K_{Io} is the initiation value for the onset of crack growth and may be estimated by sensitive crack-tip opening angle (CTOA) nonlinearities or acoustic emission. Both Δ and f_v would be dictated by the microstructure and could be measured by either serial sectioning techniques or fractographic analysis or both. It is seen that once K_{Io}, Δ, and f_v are either measured or estimated, all parameters are known from Eqs 1, 2, and 3 for a material with a given yield strength, containing a crack of length c. Although it appears as though K_{I} for equilibrium with the first crack jump through Δ is strongly