FRACTURE:

Interactions of Microstructure, Mechanisms, Mechanics

Edited by

J. M. Wells and J. D. Landes

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Interactions of Microstructure, Mechanisms and Mechanics

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Foreword

The phenomenon of fracture in structural metals has been the subject of many conferences and proceedings over the past few decades, Considerable progress has been made to understand the various fracture processes both from the metallurgical and the fracture mechanics disciplines separately. However, a truly integrated approach to fracture, which can adequately explain and predict apriori the fracture behavior of engineering alloys has yet to evolve. Such an integrated perspective must incorporate the considerations of continuum mechanics, macro- and micro-structural features, as well as the detailed mechanisms of crack initiation, propagation and final fracture. Today, a growing appreciation and interaction between the methods of fracture mechanics and the enlightened metallurgical concepts is occurring. Efforts in this direction are both desirable and essential to effectively minimize the enormous cost of metal fracture.

This volume contains 26 of the 31 technical papers which were presented during a symposium entitled *Synergism of Microstructure, Mechanisms and Mechanics in Fracture* held at the 113th AIME Annual Meeting on February 27-29, 1984, in Los Angeles, California. The focus of this six session symposium was on defining the current status and future directions of the synergistic interactions between fracture mechanics, metallurgical microstructure and fracture mechanisms. It was not intended to be a comprehensive review of all aspects of fracture, which is an impossible task for any single symposium or proceeding.

The articles collected herein represent all submitted manuscripts from the symposium presentations. The invited papers are broader in scope and present a good overview of their respective subject areas of the interactions between microstructure, mechanisms and mechanics considerations. The contributed papers are generally more specific examples of current interactions. While the editors realize that much further progress remains to be acheived in this area, we feel that this focussed volume is of current pragmatic usefulness and hope that it will serve as a stimulus to promote continued interactive efforts in this area.

Our sincere appreciation is extended to all the authors, session chairmen, sponsoring technical committees and the TMS staff for their contributions and assistance in making this volume possible.

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THE ROLE OF FRACTURE MECHANICS IN

THE STUDY OF FRACTURE MECHANISMS

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Abstract

Fracture mechanics has been important in providing a rationale for the study of fracture mechanisms. Fracture mechanics identifies what type of behavior is important and provides the parameters necessary to make a meaningful study of mechanisms. Nevertheless, the two areas have largely been separate, studied by different groups of people and reported at separate technical meetings. New advances in fracture mechanics have provided an increasing number of tools to incorporate in mechanistic studies and with these, the interaction between the two fields has increased. However, increasing efforts to unite the two fields of study must come from individuals who have a good understanding of both.

Introduction

Fracture mechanics, over the past 20 years, has developed into an engineering tool which can be used to evaluate the reliability and life expectancy of structures. It provides a quantitative method which can be used to account for the effect of crack-like defects on the load bearing capacity of a structural component. Although fracture mechanics has been used primarily to evaluate fracture of component structures it can be used in the evaluation of fracture mechanisms. The evaluation of structural integrity in large components is important for insuring safety and meeting life requirements. The evaluation of fracture mechanisms can be important for giving guidelines to improve the material structure which controls the properties needed to meet structural integrity requirements.

This paper covers the role of fracture mechanics in relating fracture mechanisms to structural integrity. It begins with a simple scheme which shows how fracture mechanics provides the link between fracture mechanisms and the behavior of structural components. This is followed by a review of fracture mechanics with an emphasis on the new developments which provide additional tools for studying fracture mechanisms. Finally examples are given to show how fracture mechanics principles can be applied to this study.

Fracture Mechanics and Fracture Mechanisms

A first step in exploring the relationship between fracture mechanics and fracture mechanisms is to consider the answers to some basic questions involving both. To understand why fracture mechanics is useful in the study of fracture mechanisms we could first ask: Why study fracture mechanics? and Why study fracture mechanisms?

The answer to the first lies in the consideration of the effect of defects on structural components. Large structural components may contain defects that develop during fabrication or that initiate during service life. These defects may cause premature failure of the component. Fracture mechanics provides a quantitative tool for predicting the behavior of structures containing defects and as such provides a link between the material behavior and the behavior of the structural component as illustrated in Figure 1.

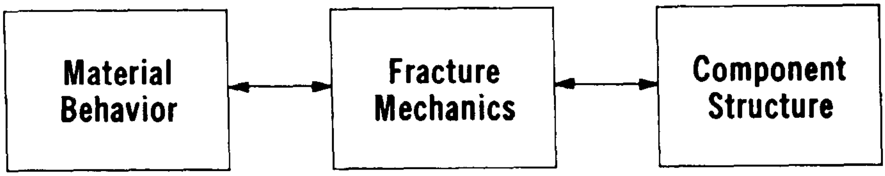


Figure 1 - Fracture mechanics connection

The question of why study fracture mechanisms was posed to various experts in the field. Answers ranged from "this provides a tool for telling how the materials fail" and "a rationale for interpolating and extrapolating data" to "this study provides a method for obtaining funding". Whereas fracture mechanics deals with the when and what of fracture, fracture mechanisms deal with the how and why of fracture. A schematic similar to the one in Figure 1 can be developed to show how the study of fracture mechanisms relate the material structure to material properties, Figure 2.

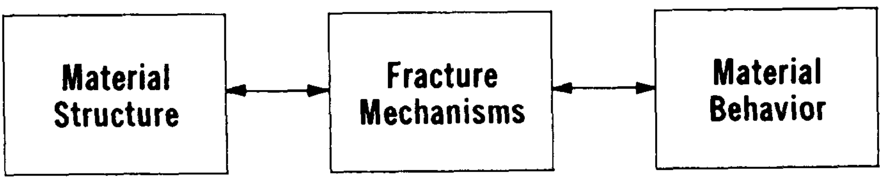


Figure 2 - Fracture mechanism connection

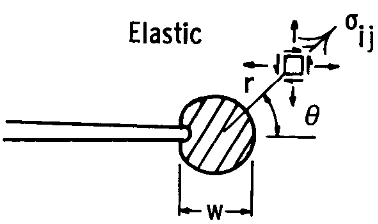
The relationships in Figures 1 and 2 can be combined to illustrate the link between fracture mechanics and fracture mechanisms, Figure 3. This relationship is labeled the "structural connection" because the behavior of the component structure is linked to the material structure. This relationship further illustrates how fracture mechanics is needed to give meaning to a study of fracture mechanisms. If a study of mechanisms is to improve the properties of the material, the pertinent properties which are to be improved must be identified, these can only be identified as they relate to improvements in the behavior of the structural component. Fracture mechanics identifies which properties must be improved and the parameters which are important. Fracture mechanics also helps to focus attention on mechanistic studies at the most important place for studying behavior; the crack tip.

Figure 3 - Structural connection

Fracture Mechanics

Background

Fracture mechanics provides an engineering tool which can be used to quantitatively assess the effect of a defect in a structure on its load bearing capacity. The first application of fracture mechanics used the priniciple of a unique linear elastic crack tip field (1), Figure 4. This field, which has a unique stress and strain distribution, is characterized by a single parameter, K, the crack tip stress intensity factor which determines magnitude of the field. The



$$\sigma_{ij} = \frac{K}{\sqrt{r}} \Sigma_{ij} (\theta)$$

$$\varepsilon_{ij} = \frac{K}{\sqrt{r}} K_{ij} (\theta)$$

if $w < r <<$ Planar Dimensions

$$w = \frac{1}{6\pi} \frac{K^2}{\sigma_o^2}$$

then : K is the Intensity of the Elastic Field Surrounding the Crack Tip

Figure 4 - Linear elastic crack tip field, K is characterizing

uniqueness provides a method for directly correlating the laboratory test results which measure fracture properties with the fracture behavior of the structural component. The application of fracture mechanics analysis is shown schematically in Figure 5. (2) Three areas are combined to make a fracture evaluation: stress analysis, defect characterization and material property data. These are all related through the K analysis. The types of material behavior of most concern are fracture, measured as K_{Ic} fracture toughness (3) and subcritical crack growth due to cyclic loading, da/dN vs. ΔK (4), due to environmental influences (5) and due to combinations of the two.

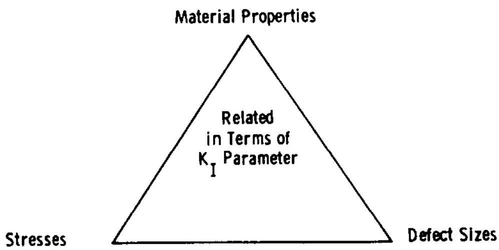
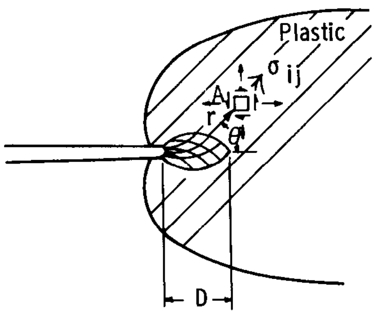


Figure 5 - Areas of information required in the utilization of fracture mechanics technology

By fracture mechanics principles these properties can be measured on a laboratory specimen and applied directly to the component structure. The most important consideration in the application of the K analysis is that both test specimen and component structure be essentially linear elastic. If large scale plastic stresses and strains are encountered, the K parameter is no longer a good characterization of the crack tip field. This limitation restricts the use of fracture mechanics for fracture toughness characterization to higher strength and lower toughness materials (6,7). Although these materials have some application, a large number of engineering structures use lower strength and higher toughness materials. For these the limitations of linear elastic fracture mechanics are exceeded and a method for extending the linear elastic fracture mechanics principles to include large scale plasticity is needed. The direction for this extension came from the work of Hutchinson (8), and Rice and Rosengren (9) who developed a plastic crack tip field stress- strain analysis which also had a showed a unique stress and strain distribution with a single characterizing parameter, J, to describe the magnitude of these stresses and strains, Figure 6 (10). The parameter J came from the path independent J integral developed by Rice (11), it could be used to characterize fracture toughness and subcritical crack grow for cases of large scale plasticity in a way that is analogous to the use of K for linear elastic cases.



$$\sigma_{ij} = \sigma_0 \left(\frac{J}{r \sigma_0 \varepsilon_0} \right)^{\frac{N}{1+N}} \bar{\Sigma}_{ij}(r, \theta, N)$$

$$\varepsilon_{ij} = \varepsilon_0 \left(\frac{J}{r \sigma_0 \varepsilon_0} \right)^{\frac{1}{1+N}} \bar{E}_{ij}(r, \theta, N)$$

if $D < r \ll$ Planar Dimensions

then: J is the Intensity of the Plastic Field Surrounding the Crack Tip

For Power Law Hardening Material

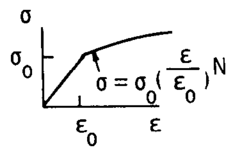


Figure 6 - Plastic crack tip field, J is characterizing

New Developments in Fracture Mechanics

The development of the crack tip field equations for large scale plasticity effectively extended the capability of fracture mechanics from the linear elastic regime into the elastic plastic regime where J now replaced K as the parameter to characaterize fracture type behavior. This made fracture mechanics more applicable to materials commonly used in engineering structures. The first use of these new principles was in describing the fracture toughness behavior of ductile materials. In an analogy to the linear elastic toughness K_{Ic}, the elastic-plastic fracture toughness was labeled J_{Ic}(12,13). This assumed that toughness could be specified as occurring at a single point. A more complete description of the ductile fracture process includes four steps as illustrated in Figure 7; one of these steps, the initiation of the tearing crack from the blunted crack tip, was taken as the point to specify J_{Ic}(14).

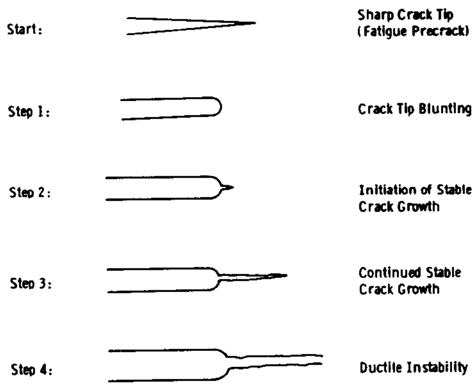


Figure 7 - Four steps in ductile fracture process

The entire process of ductile cracking is better described by the crack growth resistance curve, R curve, where a driving force is plotted as a function of crack extension. For the ductile fracture case J can be plotted versus physical crack extension, Figure 8 (15). The R curve could then be used to describe the initiation of the ductile cracking, J_{Ic}, and the process of stable crack advance. The method for testing to determine J_{Ic} has been standardized by ASTM (16,17) and the method for determining the ductile crack advance part of the R curve is in the process of being standardized.(18)

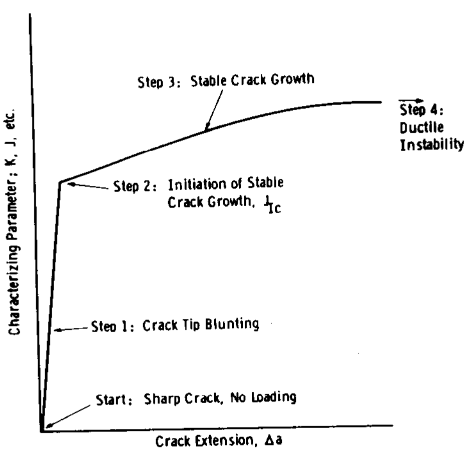


Figure 8 - Four steps of ductile fracture process on an R-curve

The stable crack growth part of the R curve described a useful part of the fracture life. The important question in using this is how to evaluate stability. Paris, et al. (19) developed the tearing stability concept to answer this question. They introduced a non-dimensional parameter labeled tearing modulus, T, where

$$T = [dJ/da][E/\sigma_o^2] \tag{1}$$

E is the elastic modulus and σ_o the flow stress. The tearing modulus for the toughness behavior was labeled T_{mat} and the rate of change of T for a virtual crack extension was labeled T_{appl}

$$T_{appl} > T_{mat} \tag{2}$$

gave the condition for unstable crack extension.

It was realized that the condition in Eq. 2 was not usually sufficient to specify instability because T was not usually constant on the R curve and an additional requirement on J must be met. To better describe the instability condition the J-T plot shown schematically in Fig. 9 was developed where instability could be determined by the intersection of a material line and an applied line. (20)

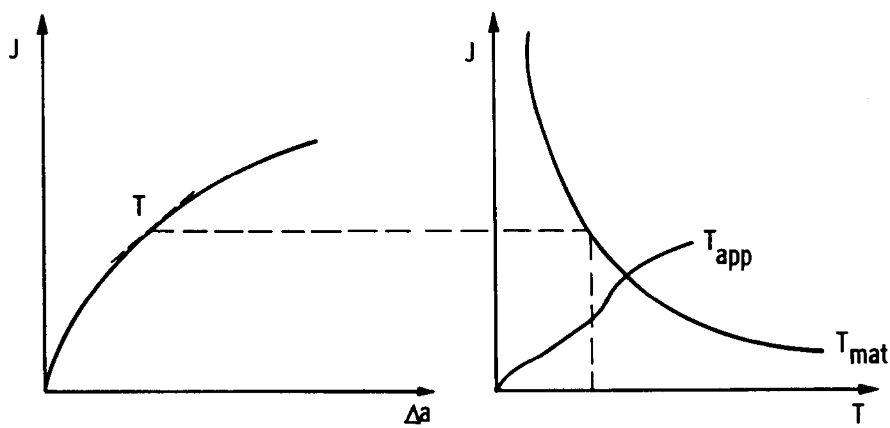


Figure 9 - J vs. T plot for instability prediction

Although the EPFM methodology extended the capability of fracture mechanics well beyond the linear elastic regime, there were also limitations to consider. The concept of a unique stress and strain field in the plastic zone requires that the field not be disturbed by structural or specimen boundaries. A requirement that specimen dimensions be greater than M J/σ_o, where σ_o is flow stress and M is a constant, was developed to satisfy this requirement. (16,21)

The concept of a J field was originally developed for deformation plasticity and as such was subject to many limitations. In particular the analysis was limited to the stationary crack case. A growing crack is necessary to develop an R curve so these conditions were overly restrictive. Hutchinson and Paris (22) showed that the concept of a J field is valid for the growing crack if certain conditions can be maintained. These were later quantified by Shih and labeled conditions for J controlled crack growth. (23) They include M = 25 and

$$\omega = (b/J)(dJ/da) > 5 \tag{3}$$

$$\Delta a/b < 0.1 \tag{4}$$

where b is remaining uncracked ligament length.

In developing an R curve for stability analysis it was found that very often an extensive amount of crack growth was needed to establish an instability point (i.e., extend the J-T material curve in Fig. 9 until it intersects the applied curve). The restriction in Equation 4 limits the amount of crack extension so that many times this intersection cannot be reached. Specimen sizes are often limited by material availability and there may be a need to exceed these limits. However, R curves tend to be geometry dependent when crack growth exceed the limits. A significant step in developing a geometry independent R curve for greater amounts of crack growth came from the work of Ernst (24) in which he suggested a modified J parameter, J_m, which could be used to characterize the R curve behavior. Experimental results showed that geometry independence was maintained in the R curve behavior for crack growth well in excess of the limits of Equation 4, Figures 10 and 11. (24,25)

As a result of these new developments, there is a much extensive list of parameters available to characterize fracture toughness. Consequently, the role of fracture mechanics in the study of fracture mechanisms can be significantly improved. A list of fracture mechanics parameters is given in Figure 12.

Curve 729695-A

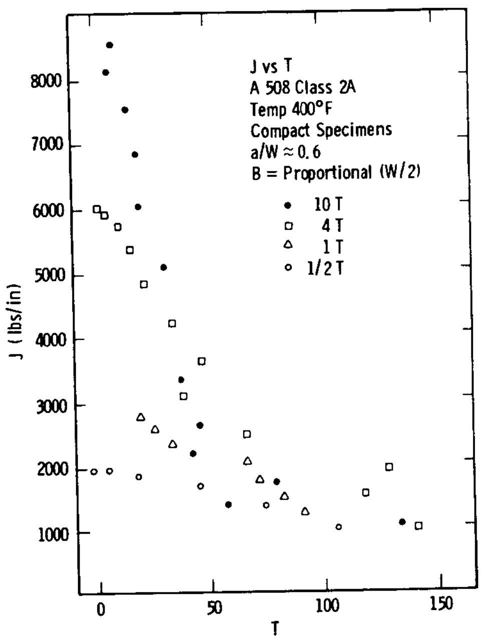


Figure 10 - J vs. T plot using deformation J for sizes ranging from 1/2T to10T showing size effects

Curve 729694-A

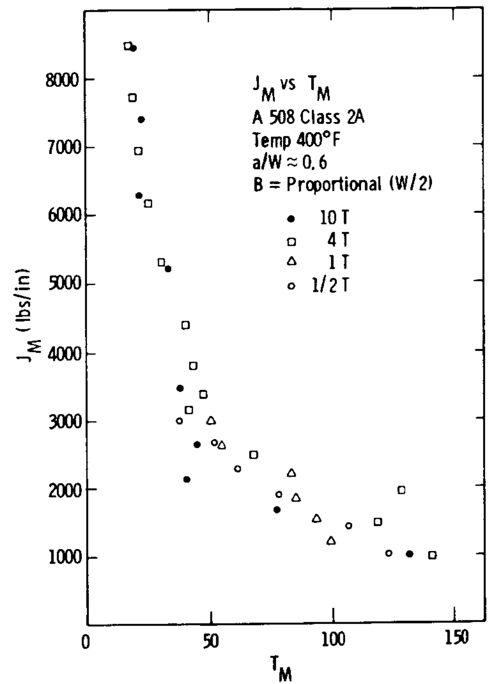


Figure 11 - J vs. T using showing the elimination of size effects resulting from using modified J