MECHANICS OF SUBCRITICAL CRACK GROWTH

G. C. Sih
Lehigh University
Bethlehem, Pennsylvania 18015 USA

INTRODUCTION

Subcritical crack growth is a commonly observed but still not well-understood phenomenon. It is generally identified with the process of slow crack growth in metals subjected to rising or cyclic load. The phenomenon, however, is not exclusively associated with ductile* fracture nor with plastic deformation. Cracks can spread slowly in an elastic stress environment as long as the crack driving force is kept below the critical state. More precisely, it is the combined interaction of loading, geometry and size of specimen, material and environment that determines the crack growth characteristics.

Despite the many attempts [1-5] made to analyze subcritical crack growth, the viewpoints on this subject remain diversified. There are different schools of thought that often appear to be a matter of personal appreciation. The education received, the traditions immersed in and the motive of research can highly affect the degree of this appreciation. The idea of quantifying the different failure modes of measuring the Charpy V-notch energy, the fracture toughness, crack opening displacement, etc., has led to an overwhelming number of parameters. However, it is not at all clear as to how they could be applied to situations other than those tested. While the material testing approach serves a useful purpose in cataloging material behavior under simulated laboratory conditions, it provides little or no useful purpose to a designer who needs to know the allowable load and net section size of structural components. Predictive capability is lacking in the material testing approach.

The initiation and termination of subcritical crack growth cannot be assessed quantitatively by a single parameter. Many of the current approaches involving the arbitrary selection of different and independent failure criteria for the same material damage process have not had success in that the results tend to be highly inconsistent. It should be recognized that global nonlinearity of load and displacement often observed during slow crack growth is fundamentally connected

---

*Ductility as defined by the uniaxial tensile test may not apply to other situations where the character of loading and specimen size are different.
with non-self similar\(^*\) profiles of the crack and permanent distortion of the neighboring material commonly known as plastic deformation. These two effects have to be treated simultaneously and are inherently load history dependent. Should plastic deformation occur along the prospective fracture path, then adjustments must also be made for the change of material resistance as the crack grows. To be remembered is that the determination of material resistance to fracture serves only as a pre-requisite for predicting the global behavior of a system containing flaws or imperfections. Hence, the validity of any fracture toughness parameters\(^**\) can only be tested by its predictive capability. The basic problem of subcritical crack growth lies in determining the available energy to drive the crack which is not always straightforward when energy dissipation due to plasticity is present.

The main objective of this communication is to illustrate how slow crack growth can be characterized in a consistent fashion. This involves the determination of crack initiation, slow growth and termination. The global response of an initially cracked specimen will be predicted from the uniaxial tensile data. Subcritical crack growth accompanied by irreversible plastic deformation is analyzed by assuming that the strain energy density function \((dW/dV)\)\(^*\) along the crack path attains various threshold values. When yielding prevails ahead of the crack, the energy lost \((dW/dV)_{p}\) due to plastic deformation is no longer available at the time of macrocrack growth. It must therefore be subtracted from \((dW/dV)_{c}\) which represents the total area under the nonlinear true stress and strain curve up to yield \((dW/dV)_{c}^{*}\). The crack tip energy density field is calculated for each load increment by employing the twelve-node isoparametric finite element procedure. On the basis of the general relation \(dW/dV = S/r\) where \(S\) is the strain energy density factor and \(r\) the distance from the crack tip, the condition \(dS/da = \text{const.}\) was found to yield a straight line relationship between \(S\) and half crack length \(a\). The slope of this line changes as the load increments are varied. This information is valuable for determining the influence of loading rate on crack growth.

**CRITERION ON CRACK INITIATION AND TERMINATION**

The selection of an appropriate crack growth criterion for characterizing ductile fracture has been problematic. There is always the temptation to prematurely fit data with analytical results. Agreements concocted by simple models are frequently found to be case-specific and shed no light on understanding the crack growth process. Consistency in reasoning and application of the mechanics discipline should be observed when choosing failure criteria. It is in this respect that the strain energy density criterion \([6,7]\) has been chosen in this work.

\(^*\) This feature has been frequently neglected in the analysis and can lead to gross error in predicting the allowable load on a flawed structural member.

\(^**\) The \(K_{lc}\) quantity should not be regarded as a material constant but material behavioral parameter that is identified with the phenomenon of the sudden exchange of stored energy with free surface energy. The result is the onset of rapid crack propagation. This is simply because surface creation behavior is governed by the combination of loading, specimen size and geometry even if the metallurgical properties of the material are the same.