THE CRACK LAYER APPROACH TO TOUGHNESS CHARACTERIZATION IN STEEL

M. Bessendorff and A. Chudnovsky

Department of Civil Engineering, Case Western Reserve University, Cleveland, OH, USA

ABSTRACT

The crack extension resistance parameter R_1 based on the morphological study of microdefects is introduced.

Experimental study of the history-dependent nature of fracture toughness G_c supports the representation of G_c as a product of specific enthalpy of damage (material constant) and R_1. The latter accounts for the history-dependence.

KEYWORDS

Fracture toughness; damage accumulation; history dependence.

INTRODUCTION

There are two alternative approaches to the study of laws of crack propagation and toughness characterization. The fracture mechanics approach is concerned with the stress intensity factor K or energy release rate J which are derived using the concepts of continuum mechanics. The material science approach concentrates on knowledge of the hierarchy of defects, their development, and interactions; that is, this approach emphasizes the micromechanisms of fracture processes. In the current work one of the possible ways of unifying these two approaches based on CL theory is discussed.

The studies of the critical energy release rate G_c show that this parameter is history dependent. In addition, observations of the kinetics of crack growth show nonmonotonic crack advance under monotonic changes of energy release rate J (or stress intensity factor K). This implies the existence of intrinsic properties of materials which are not reflected by the G_c or K_c and J or K parameters.

The recently proposed crack layer (CL) theory [Khandogin and Chudnovsky,1978, Chudnovsky,1980] considers the crack together with the surrounding defects as one system which has several degrees of freedom. Within CL an active zone, where the nucleation and development of defects occur, can be distinguished. The propagation of the active zone is decomposed into translation, rotation, and deformation. The generalized forces associated with the above mentioned elements of the active zone movement are derived within the framework of the thermodynamics of irreversible processes. These generalized forces are represented by linear functions of the path-independent integrals J_1, L, M [Knowles and Sternberg, 1972] and integral characteristics of damage within the active zone [Chudnovsky, 1984]. Consequently the CL theory defines the relationship between the parameters of fracture mechanics and the characteristics of microstructural changes which are the subject of material science.

The toughness characteristic is represented as the product of the specific enthalpy of damage γ^* and translational resistance moment R_1. The specific enthalpy of damage is a candidate for being a material constant. The latter (R_1) is loading history-dependent and is responsible for the widely observed changes of G_c.

DESCRIPTION OF EXPERIMENTAL PROCEDURES

The study of the relationship of material toughness and the macroscopic process of crack growth with microscopic changes is the objective of this paper.

Toughness Characterization Test

Data on fracture toughness parameters usually show large scatter [Curran and others,1977]. In order to obtain statistically representative data, an ensemble of identical samples was prepared. The geometry of the samples is 150mm in length and 20mm in width. The thickness was 0.2mm. A sixty degree notch was cut in the middle of a long side of each panel. The ensemble included eight groups of 10 samples each. In each group of samples, cracks were grown to a specified length using sinusoidal tension-tension testing conditions ($R = \sigma_{min}/\sigma_{max} = 1/3$, stress $\sigma_{max} = 1/4\ \sigma_{yield}$, frequency $\nu = 50$ Hz, $T = 20^{o}C$). All the samples were then subjected to the test for fracture toughness evaluation.

Microscopic studies consisted of direct observation of the CL propagation, analysis of dislocation density, and study of discontinuity surfaces. The damage zone surrounding the crack was observed through metallographic and SEM microscopes.

Dislocation density was obtained by a systematic mapping of the hardness measurements taken in the region of the crack tip according to [Foulds and Moteff,1982]. Discontinuities around the crack were measured as follows. A grid consisting of two orthogonal sets of parallel lines was superimposed on the picture taken at 500X magnification. Discontinuities had a prefered orientation. Therefore, the method of biased sampling was employed to obtain statistics of discontinuities [Cramer,1964].

EXPERIMENTAL RESULTS

Phenomenological Study of Toughness Characterization

We consider the simplest loading history: the constant amplitude sinusoidal tension-tension loading. For these loading conditions the maximum local stresses in the vicinity of the growing crack tip monotonically increase with the crack length. Therefore, the J integral alone is sufficient to characterize the particular loading history. We use the value of J at the end of the fatigue stage 'J_h' as the parameter to reflect the history of loading.

The statistical analysis of fracture toughness was conducted for stainless steel. Fig. 1 shows the results of 80 experiments on fracture toughness for that material.

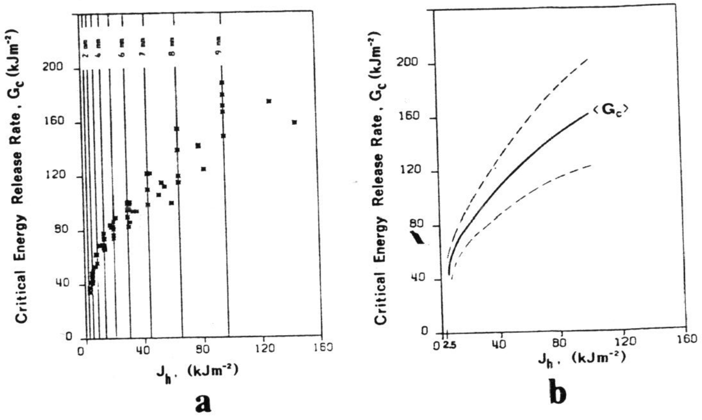

Fig. 1 a – Data on fracture toughness of eight groups of ten samples each. Each group was chosen on the basis of the crack length interval. Corresponding crack lengths are indicated on the vertical lines.

b – This plot is the result of the statistical evaluation of the data in a. Dashed lines indicate the 63% confidence zone.

Morphology of Crack Layer

If the damage is viewed on a progressively finer scale a hierarchy of defects can be visualized. At low magnification nonhomogeneous deformation of continuous media is observed; no discrete defects could be identified (Figure 2a,2b). In Fig. 2c the traces of discontinuous surfaces, which correspond to slip band extrusions and intrusions, are clearly observed. In this paper two types of defects were considered and the energy dissipation associated with these were estimated.

The first type of defect is the dislocations around the crack tip since dislocations are commonly associated with the plastic deformation. In Fig. (3) the map of dislocation density ρ_{disl} around the fatigue crack based on the measurements of microhardness is shown. In order to plot this map the relationship between the microhardness and dislocation density proposed in [Kuhlman-Wilsdorf,1975, Foulds and Moteff,1982] was used.

The discontinuity surfaces represent the second type of defects under consideration.

The discontinuity surface density ρ_{disc} is calculated following [Saltykov,

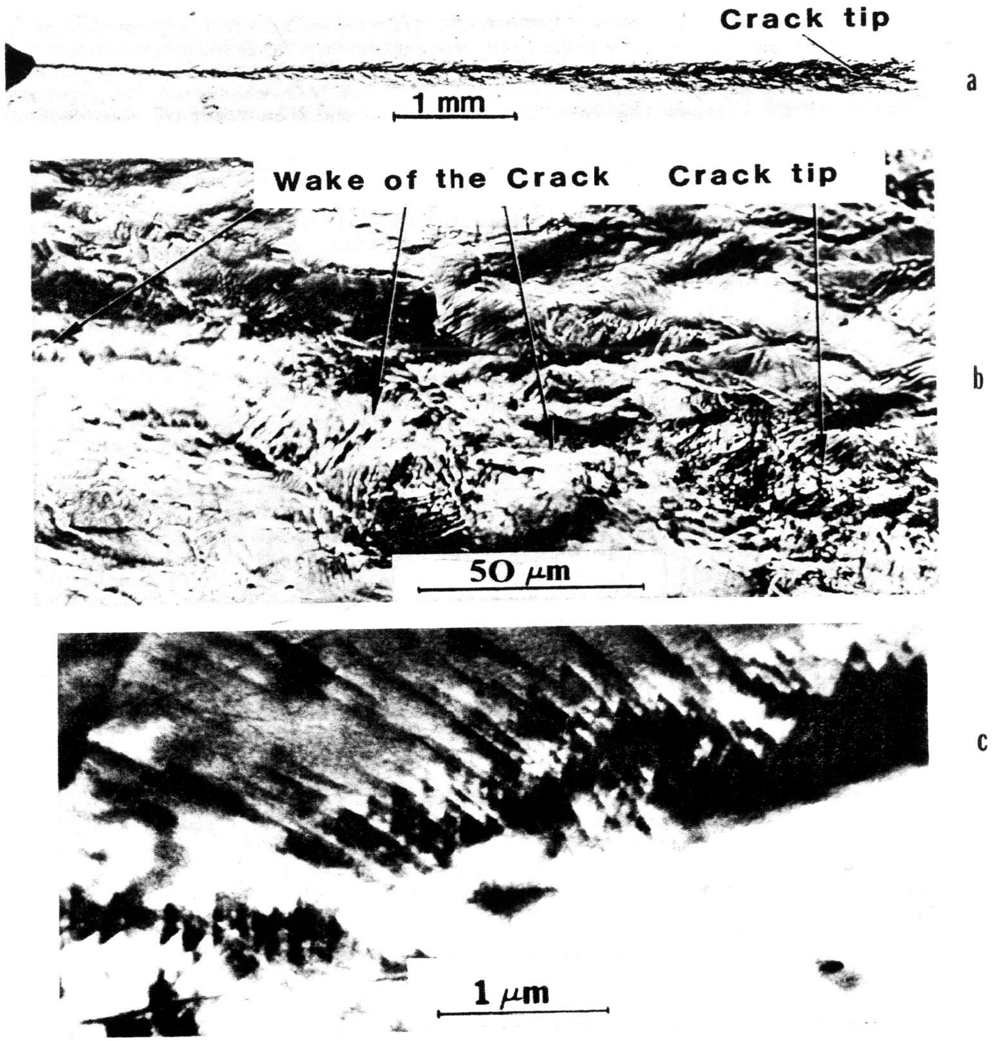

Fig. 2 Morphology of the crack layer on different magnifications.

a - General view of the fatigue crack layer at low magnification.

b - The crack tip region. Extensive damage is seen around and in front of the crack tip.

c - SEM picture of an element of damage from the area in b taken at 20,000x magnification.

1958]

$$\rho_{disc} = 2P_L \frac{mm^2}{mm^3} \tag{1}$$

where P_L is the number of intersections of the traces of discontinuity (see the micrographs Fig. 2b, c) with a test line [Chudnovsky, Bessendorf,1983].

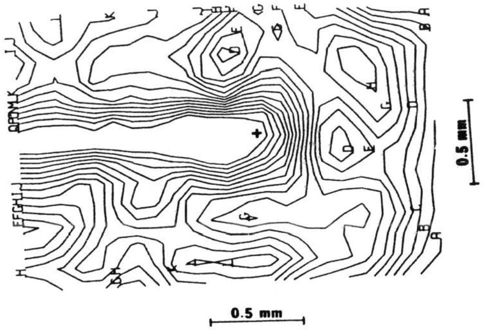

Fig. 3 Contours of equal levels of dislocation density around the crack tip in 304 AISI stainless steel. Contour A corresponds to the dislocation density 10^7 cm^{-2}. B=A+d, C=A+2d, D=A+3d, Q=A+19d, where d=5.10^7 cm^{-2}. Symbol "+" indicates the crack tip.

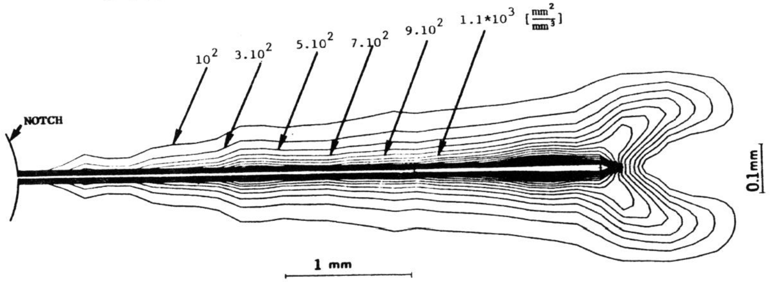

Fig. 4 The contours ofequal levels of distcontinuity density [mm^2/mm^3] around the fatigue crack in 304 AISI stainless steel. Symbol "+" indicates the crack tip.

DISCUSSION

Our results show that the critical energy release rate G_c depends on the methods employed in the preparation of the specimen for the fracture toughness test.

The nonmonotonic crack growth as well as the dependence of G_c and its variance on the history of the process call for an explanation in terms of the morphologic changes accompanying the crack propagation. An explanation is suggested by the CL theory.

Concept of Crack Layer (CL)

CL is represented schematically in Figure 5. The zone surrounding the crack where $\rho > \rho_o$ (where ρ_o is the reference level of damage) is called crack layer. The active and wake zones are distinct in the following. The active zone where the damage growth takes place ($\rho>\rho_o$, $\dot{\rho}>\rho_o$ where $\dot{\rho}$ is a rate of damage growth) is bound by the leading and trailing edges $\Gamma^{(\ell)}$ and $\Gamma^{(t)}$. The wake zone can be described as the trace of the active zone movement and characterized by ($\rho>\rho_o$, $\dot{\rho} = 0$). We are considering only two elementary movements of the active zone: translation as a rigid body and isotropic expansion (the spread of damage),

$$v_k(x) = v_k(x^o) + \dot{e}(x_k - x_k^o) \tag{2}$$

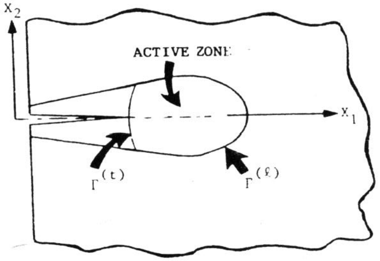

Fig. 5

where v_k is a rate of the translation of the center of the active zone x^o, $x-x^o$ is a radius vector of the arbitrary point of the active zone, $\dot{e}$ is a rate of isotropic expansion.

For rectilinear CL growth $v_1 = \dot{\ell}$ - rate of crack length growth, $v_2 = 0$.

Then according to the CL theory [Chudnovsky, 1984] the rates of extension (γ) and expansion ($\dot{e}$) are given correspondingly

$$\dot{\ell} = \frac{\beta_1 \dot{D}}{\gamma^* R_1 - J_1(\ell)} \tag{3}$$

$$\dot{e} = \frac{\beta_2 \dot{D}}{\gamma^* R_o - M} \tag{4}$$

Here $\beta_1 \dot{D}$ and $\beta_2 \dot{D}$ represent the fraction of the total dissipated energy spent on CL translation, and expansion, respectively, γ^* is the specific enthalpy of damage, J_1 and M are the energy release rates while R_1 and R_o represent the CL resistance moments associated with translation and expansion respectively:

$$R_1 = \int_{\Gamma^{(t)}} \rho \cdot n_1 \, d\Gamma \tag{5}$$

$$R_o = \int_A \rho \, dA \tag{6}$$

The rate of crack growth becomes uncontrolled ($\dot{\ell}\to\infty$) when J_1 approaches $\gamma^* R_1$ in unstable configuration (see Chudnovsky, 1974). Thus, conventional G_c could be identified with R_1:

$$\gamma^* R_1 = G_c. \tag{7}$$

Therefore, history dependency of G_c corresponds to the evolution of R_1, where R_1 is the variable part of the resistance moment.

The critical value of G_c can be resolved into two parts: G_c associated with the core of damage R_1^* and $\tilde{G}_c$ associated with the damage dissemination around the crack,

$$G_c = G_c^* + \tilde{G}_c \tag{8}$$

The value of G_c is measured in the conventional fracture toughness test. On the other hand, according to the CL theory, G_c can be evaluated in terms of R_1 obtained from damage analysis and specific enthalpy of damage γ^*. The evaluation of the values of G_c based on particular defect consideration reveals the contribution of the species of defects for the fracture process.

Evaluation of Energy Stored in the Dislocation Network

Energy E_{disl} of one dislocation could be estimated as 10–20 nJ/m [Hirth and Lothe]. When the dislocation network is generated the energy associated with dislocations per unit crack increment is

$$E = E_{disl} R_1 \tag{9}$$

Resistance moment R_1 evaluated from the map (Fig. 3) is $R_1 = 10^{10}$ m^{-1}. Then the energy stored in the dislocation network

$$E = 10^{-8} \text{ J/m} * 10^{10} \text{ m}^{-1} = 10^2 \text{ J/m}^2$$

constitutes 0.1% from the experimentally measured critical energy release rate G_c = 120 kJ/m^2.

If we consider the case when the maximum dislocation density is everywhere in the CL, the full energy of dislocation network will not be higher than 1% of the G_c value. Therefore, the generation of dislocations can explain neither value of G_c nor of evolution of G_c with crack advance. We conclude that such a simplistic dislocation approach cannot account for actual values of critical energy release rate G_c.

Evaluation of Energy Associated With the Discontinuity Surfaces

The resistance moment R_1 for 304 AISI steel was experimentally obtained according to the methodology and formula (Eq. 5) given above. Using the method of least squares the functional relationship between R_1 and J_h is found and plotted in Fig. 6 as a solid line, stars represent experimental data. The experimental data on fracture toughness (Fig. 1) are plotted in Fig. 7 as G_c vs. R_1.

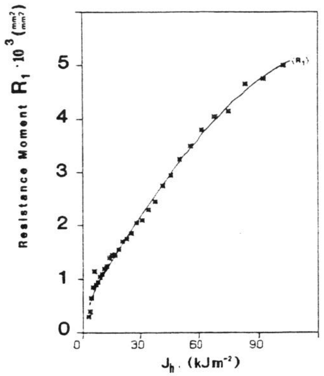

Fig. 6

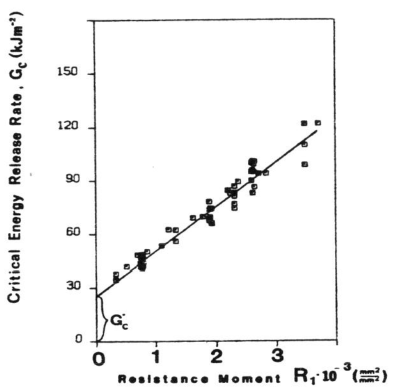

Fig. 7

Following the idea of Born and Furth the processes of fracture can be associated with melting and/or disassociation of material. Hence, the value of the specific enthalpy of damage γ can be taken in the range between the heat of fusion and vapor [Smithells,1967]. In this case the thickness of the layer of the material affected by the discontinuity surfaces is estimated to be $50 \div 500 A^{o}$. This figure appears to be high, suggesting there are other fracture mechanisms which where not taken into consideration.

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