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A MODEL OF DUCTILE CRACK GROWTH

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1. INTRODUCTION: In ductile metals, stable crack growth, following tip blunting, and ending in unstable fracture, is observed with increase in resistance to fracture. The characterization of this phenomenon is not yet fully available. This study is to present a model reproducing the stable crack growth prior to instability and suggesting an answer to the transition problem from stable to unstable crack growth. The emphasis is put on the role of the residual strains to oppose crack advance. The influence of unloading phenomena in the trail of the tip is investigated.

2. CRACK GROWTH MODELS: In ductile materials, a plastic zone develops at the tip of the crack upon loading, and the tip blunts (fig. 1a). At some critical state, the crack starts a stable growth, and the plastic zone extends (fig. 1c). During this extension, a part of the former plastic zone is unloaded, and some reverse plastic deformation occurs close to the crack faces.

We introduce an analytical model to study the ductile growth of a semi-infinite crack in an infinite plane, under mode I loading and plane strain state.

The plastic zone is modeled by symmetric slip planes emanating from the crack tip, along which flow is allowed when τ equals the yield stress in shear, τ_y (fig. 1b).

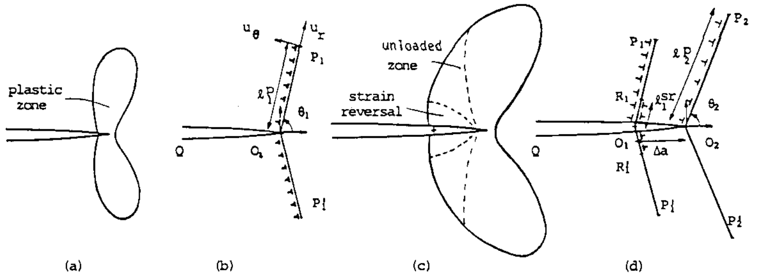

Fig.1 The plastic zone at the tip of a semi-infinite crack in plane strain mode I before (a) and after (c) the initiation of stable growth, and the associated models (b) and (d); the model (d) consist of a couple of tip planes O_2P_2 and O_2P_2', a couple of reversal planes O_1R_1, O_1R_1' and of passive, residual strains planes O_1P_1 and O_1P_1'. The step Δa is characteristic for the material.

We represent the stable advance of the crack by stepwise propagation of the tip. The crack extension is assumed to occur when the crack tip opening displacement (CTOD) reaches a critical value, equal for the first advance to δ_i (initiation), and reduced to a constant value δ_t (tip) during stable crack growth [1]; we consider the amount of crack advance as a material characteristic length. At the new crack tip, a new set of symmetric yield planes is formed (fig. 1d). The former planes of plastic flow act as residual strains.

We propose two versions of this model. The first one does not consider strain reversal during crack advance, thus restricting the active plastic zone to two symmetric planes at the tip. The boundary conditions on the tip planes are:

$$\sigma_y = \tau_{xy} = 0 \text{ on } O_iQ \ ; \ u_\theta^+ = u_\theta^- , \ \tau_{r\theta} = \tau_y \text{ on } O_iP_i \ ; \ K_{II} = 0 \text{ at } P_i$$

where O_i is the i-th crack tip

We then introduce the second model to examine and quantify the effects of strain reversal (fig. 1d): we add to the first model a reversal line co-linear to the previous tip line, representing an inverse slip on it. The supplementary boundary conditions are:

$$u_\theta^+ = u_\theta^- , \ \tau_{r\theta} = -\tau_y \text{ on } O_{i-1}R_{i-1} \ ; \ K_{II} = 0 \text{ at } R_{i-1}$$

Distributed dislocations method yields singular integral equations for the dislocation densities, which are solved numerically. The used loading parameter is called the applied K-value, K_{IA} [2], stress intensity factor evaluated under the applied loads if the material were perfectly elastic. The length of the yield lines, the dissipated energy, the J-integral, the CTOD and other parameters are computed for a given applied K-value.

3. RESULTS: Just before the stable advance, the CTOD reaches a critical value. During the crack extension the applied K-value is kept constant. After propagation, the CTOD at the new tip is less than the critical value because of the effect of the residual strains. This allows increase in the load, until a critical value of CTOD is reached again. The full growth process is then iterated, which permits scanning the load-crack growth path for the given material characteristics.

We present herein (fig.2) such computed growth curves, compared to experimental ones from the literature. The applied K-value is plotted against the crack advance. The results with and without strain reversal do not differ significantly. The J-integral is however much more affected (not shown). Curves compatible with usual tests are obtained for values of the crack advance step $\Delta a / \ell_1^p$ from 0.04 to 0.1 (ℓ_1^p is the length of the first plastic line at CTOD = δ_i). δ_t / δ_i is taken equal to 0.667.

As in [2], the energy E_i required for unstable growth is calculated at each step of the stable growth (fig.3). It represents a potential barrier imposed by the residual strains, preventing an unstable propagation at $K_{IA} > K_{IC}$. Given the ratio of K_i , K_{IA} at stable growth initiation, to K_{IC} the curves are used to determine the energy required for unstable growth during stable crack advance (fig.3, broken lines). This energy decreases during loading and stable advance, but for local phenomena at ratio 1.1 or more. At some state of the stable growth, the required energy will become less than a critical value function of the loading conditions, and instability will be materialized.

4. CONCLUSION: A model for stable crack growth is presented. It allows the prediction of stable growth curves and provides some understanding of the initiation of unstable crack growth through an energy criterion. Effect of strain reversal is shown to be limited.

5. REFERENCES:

1. Garwood S.J., "The Measurement of Critical Values of Crack Tip Opening Displacement (CTOD) and J on Parent Steels and Weldments for Use in Fracture Assessments", Elastic-Plastic Fract. Mech., Larsson ed., 1985
2. Horii, Hasegawa and Nishino, "Mechanics of Unstable Crack Initiation: Effect of Residual Strain", Str. Eng./Earthq. Eng. 3-2, 215s-223s, 1986

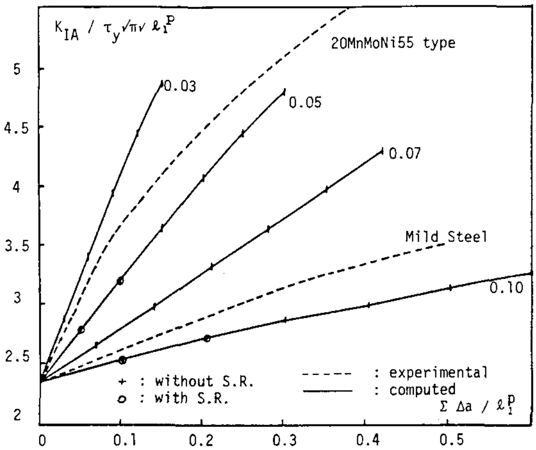

Fig. 2 The Applied K-value vs the Stable Crack Advance for some values of the step of crack advance, compared with experimental data; crack advance without stretch zone.

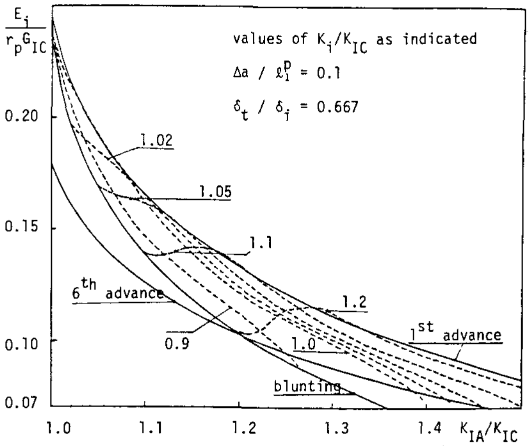

Fig. 3 The Energy Required for the Unstable Crack Extension vs the Applied K-value at various stages of the stable growth (solid lines) and during the growth process for various values of K_i/K_{IC} (broken lines).