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The effect of subcritical ductile crack growth on cleavage fracture probability in the transition regime using continuum damage mechanics simulation

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ABSTRACT

There are compelling experimental evidences that demonstrate a significant effect of specimen size, a/W ratio and ductile tearing on cleavage fracture toughness values (K_{Jc}) measured in the ductile-to-brittle transition region of materials such as ferritic steels. In this work, the influence of ductile tearing and constraint loss on Weibull stress and failure probability in ductile to brittle transition (DBT) region is investigated. The study was carried out using a modeling approach that combines the modified Beremin model (MBM) for cleavage fracture and the Bonora damage model (BDM) for ductile tearing. Here, CT and SEB, with deep and shallow crack, specimen geometries, which are characterized by different crack tip constraint, have been analyzed. Results show that the occurrence of ductile crack growth in the mid-to-upper transition region affects the nature of the stress field in the region surrounding the crack tip in terms of maximum principal stress peak, its spatial gradient – which has a direct consequence on the calculated Weibull stress – and stress triaxiality, which affects the constraint loss. This combination of effects leads to much lower fracture toughness values that those predicted by not considering ductile crack growth.

1. Introduction

In materials exhibiting a ductile-to-brittle toughness transition with temperature, rupture is determined by the competition of cleavage and ductile tearing. Increasing the temperature, some amount of stable ductile crack growth can occur followed by brittle fracture [1]. This behavior becomes more marked over the mid-to-upper end of the ductile-to-brittle transition (DBT) region [2].

Numerical investigations [3,4] indicated that stress and deformation fields ahead of a growing crack differs significantly from those ahead of a stationary crack. The occurrence of crack growth causes an increase of stress triaxiality as a consequence of the re-sharpening of the blunted stationary crack tip and by increasing the crack depth [5,6]. In metals and alloys, stress triaxiality has the major effect to reduce material ductility. In the upper shelf, where the crack growth is controlled by plastic deformation, a higher stress triaxiality implies a more rapid crack advance for given load. In the lower shelf, fracture controlled by cleavage, can be assumed to occur when the maximum principal stress over a stressed volume of material surrounding the crack tip, containing potential cleavage initiation sites, exceeds a limit value [7–9].

In this case, the occurrence of even a small amount of subcritical crack growth influences the stressed volume in two ways: (1) a higher stress triaxiality occurs in the stressed volume (defined by the principal stress contour) by increasing the absolute distance from the tip; (2) new volumes of material are subjected to high principal stress, as the tip moves forward, see Fig. 1 [10]. In other words, a growing crack increases the stressed volume of material ahead of the tip, thereby increasing the probability of sampling the critical trigger point for cleavage fracture initiation. Consequently, the stress field ahead of a growing crack would be more severe, in term of fracture resistance, than that of a stationary crack loaded at the same nominal J-value.

Fracture behavior in the DBT region of materials such as ferritic steels, has been investigated by means of micromechanical modeling by several authors. Wallin [11], for four large data sets corresponding to four different kinds of pressure vessel steels, found that the Beremin approach [12] still gives good results if appropriate correction to account for subcritical crack growth is made. A possible way of accounting for ductile growth on cleavage fracture

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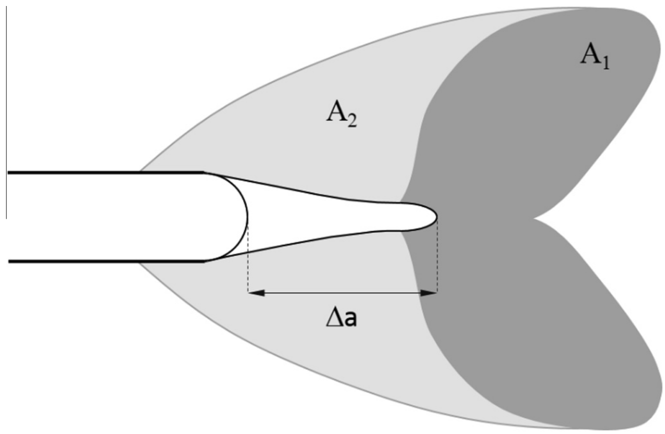

Fig. 1. Illustration of principal stress contours (s1) for a steady and growing crack. Here, A_1 is the current area (volume) where the principal stress is exceeded, A_2 is the material volume where the stress has reached σ_1 during the load history [10].

calculation is combining continuum damage mechanics (CDM) models with the weakest link modeling. This approach was firstly proposed by Xia and Shih [13]. They used a computational cell model to simulate the effect of ductile crack growth on the evaluation of the cleavage fracture probability. The computational cell models for ductile crack growth simulated the void nucleation, growth, and coalescence process. In that case, they found that ductile tearing process increased the Weibull stress due to additional material volume experiencing high stresses as the crack grows and due to the influence of growing voids near the crack front on the local stress fields.

Ruggieri and Dodds [14] analyzed the effect of ductile tearing and constraint on cleavage fracture stress. Gao et al. [15], based on the experimental fracture data provided by Petti and Dodds [2], investigated the effect of ductile tearing on cleavage fracture by means of discrete modeling of microvoids. Others, including Xia and Cheng [16] and Neto and Ruggieri [17], followed the same approach coupling the Weibull stress concept (and similar formulations) with computational cell type models. Sobotka and Dodds [18] examined numerically the effects of ductile crack growth on cleavage fracture by using 3D small-scale yielding simulations. Their results showed that at small load levels, plane-strain models remain realistic. They also investigated the effect of steady ductile tearing and side groove on the calculated Weibull stress values.

In this study, the effect of specimen geometry constraint and stable ductile tearing on the corresponding cleavage fracture have been investigated numerically. Here, the modified Beremin model (MBM) [19] for cleavage fracture and the Bonora damage model (BDM) [20] for ductile rupture have been combined and used for this purpose. In the following, the combined model, which was previously used to predict specimen geometry effect on the master curve reference temperature T_0 [21], is briefly reviewed. Successively, results of a detailed computational analysis of compact tension (CT) and single edge notch in bending (SEB) specimen geometry, with different crack depth ratios, in the upper shelf region (T_0 + 50 °C) – where stable crack growth prior to cleavage fracture becomes relevant-are presented and discussed.

2. Micro-mechanical modeling in the transition regime

2.1. Cleavage fracture modeling

The micromechanics-based, Weibull stress models, originally proposed by the Beremin group [13], continue to have widespread use in the assessment and understanding of cleavage fracture. The model defines a stochastic, scalar measure of the local stress field ahead of the crack front, (i.e., the Weibull stress σ_w), that reflects a weakest link mechanism for the fracture initiation of micro cracks at cleavage nucleation sites (carbides, grain boundaries, etc.). The model assumes a random distribution for these initiators to predict the observed scatter in experimental values of fracture toughness. The model employs a prescribed, power-law form for the random distribution of micro cracks present in small, statistically independent volumes of material comprising the crack-front region. Each small volume experiences loading from the macroscopic (continuum) stress field described, for example, by a local value of maximum (tensile) principal stress. Integration of the local stress fields over all material volumes ahead of a crack front leads to a relatively simple expression for macroscopic failure probability based on a scalar measure of the crack-front conditions — the Weibull stress, σ_W.

An alternative approach to predict cleavage fracture is to use a local approach that adopts a stress based Weibull distribution and the assumptions of the weakest link theory. The best known and most widely used of the local approach methods is that proposed by Beremin et al. [12]. In the Beremin model, it is assumed that cleavage nucleation sites (assumed as micro-cracks) becomes active at the onset of plastic deformation. Unstable fracture is assumed to occur when the maximum principal stress reaches a critical level in accordance to Griffith fracture criterion. Here, plastic deformation is referred to as a primary event before the condition to failure is reached. Global failure is predicted by invoking the weakest link theory, which assumes that a body of material can be subdivided into several elementary reference volumes, V_o, all connected like links in a chain, and that global failure is determined by the rupture of the weakest volume element. The expression of the probability of failure provided in the original Beremin formulation is a two-parameters Weibull distribution which suffers of the fact that it predicts a non zero failure probability for stress going to zero. In order to avoid such limitation, Bakker and Koers [22] introduced a threshold stress, σ_{th}, in the derivation of the failure probability given by the following expression,

$$P_f = 1 - \exp\left[-\left(\frac{\sigma_W - \sigma_{th}}{\sigma_u - \sigma_{th}}\right)^m\right] \tag{1}$$

where σ_W is the Weibull stress defined as:

$$\sigma_W = \left(\frac{1}{V_0}\int_V \sigma_1^m dV\right)^{1/m} \tag{2}$$

being σ_u the reference stress, which correspond to a failure probability of 63.2% for a volume V, and m the Weibull exponent. The calculation of the Weibull stress requires the definition of a process zone where cleavage fracture can potentially occurs. Beremin initially proposed to consider the material volume where the equivalent stress is exceeded. Later Xia and Shih [13] defined the process zone as the region surrounding the crack tip where the maximum principal stress is λ-times the yield stress, being λ an arbitrary number between 1 and 3, often assumed 2.5. Recently Esposito et al. [23] suggested to limit the process zone as the region where the equivalent plastic strain is larger than σ_y/E, at the given temperature, and the stress triaxiality, defined as the ratio between the mean stress and the equivalent Mises stress, is positive. In the present work, a criterion that combines the Xia and Shih and Esposito et al criteria was used,

$$[\sigma_1 \geqslant 2.5\sigma_y]\&[\varepsilon_{eq}^p \geqslant \sigma_y(T)/E(T)]\&[\sigma_m/\sigma_{eq} \geqslant 0] \tag{3}$$

This choice provides a general definition that can be used independently for notches and cracks preventing to consider, in the Weibull stress calculation, material volumes that do not contribute to cleavage fracture process. For cracks, the proposed criterion