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Large deformation FEM analysis of ductile fracture

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Summary

Several methods are in vogue to understand the process of crack initiation and propagation in ductile materials. In an attempt to achieve a unified understanding of these methods, a large deformation finite element analysis has been carried out. An attempt has been made to understand ductile fracture by numerically determining the ductile fracture toughness by three different methods viz. 1) Load-displacement method 2) Path-integral method 3) Stretch zone width method (SZW). In addition, an attempt has to be made to explore the possibility of using 'characteristic distance' (l_c) approach for establishing fracture toughness. The present study attempts at achieving an insight into defining the procedure for numerical determination of SZW. This method of determination also explains the mechanism behind the creation of featureless zone, defined as SZW, which was missing in its earlier method of determination by 45 degree lines. The investigation essentially comprises of number of FEM simulation to study & correlate crack tip blunting with experimental fracture toughness. It is concluded that large deformation FEM analysis can reasonably represent the process of fracture in the crack tip area and can fairly accurately predict the material's toughness, SZW and its critical value using tensile test data.

Introduction

When a material with a crack is loaded in tension, the deformation energy builds up around the crack tip and it is understood that at a certain critical condition voids are formed ahead of the crack tip. The crack extension occurs by coalescence of voids with the crack tip. A fracture criterion that could accurately predict failure would be a useful engineering tool both for the evaluation of structural integrity and the selection of materials. Complex structures may experience stress in some regions that exceed the elastic limit necessitating a fracture criterion that also includes elastic-plastic behaviour. Several attempts had been made to understand the process of crack initiation and propagation in ductile materials. Landes and Begley [1] had presented an experimental means to predict the fracture toughness, which is popularly referred to as load-displacement method. Paranjpe and Banerjee [2], Mills [3] and Kobayashi [4] demonstrated experimentally the procedure to evaluate the fracture toughness using SZW measurement. Tai [5] employed FEM route to study the damage ahead of the crack tip. Wang and Hwang [6] used crack tip

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opening angle and J-integral to understand the experimental test data of CT specimen. Knott [7, 8] related the characteristic distance to microstructural parameters such as grain size, inter-particle distance etc. Srinivas et al. [9, 10] established $l_c$experimentally in Armco iron, relatively a ‘clean material’, in order to assess its dependency on grain size or particle spacing.

The present investigation essentially comprises a number of FEM simulation to study & correlate crack tip blunting with experimental fracture toughness. An attempt has been made to understand ductile fracture by numerically determining the ductile fracture toughness by three different methods viz. 1) Load-displacement method 2) Path-integral method 3) Stretch zone width method with SZW defined using 45 degree lines. In addition, the characteristic distance (l_c) approach that links the fracture toughness to the microscopic mechanism considered responsible for ductile fracture, was also studied. Although, all the four methods mentioned above can calculate fracture toughness for different level of deformation, but calculation of critical fracture toughness using the critical values of flow curves was still remains to be understood. For the first time in the present investigation a procedure is explained to determine SZW numerically and also its critical value. This method of determination also explains the mechanism behind the creation of featureless zone, defined as SZW, which was missing in its earlier method of determination. The experimentally [9, 10] obtained properties of Armco iron for different grain sizes are used as the effective properties of the homogeneous continuum in the present study. The study essentially pertains to ductile crack initiation and is not concerned with crack growth related aspects.

Numerical analysis

The investigation was limited to compact tension (CT) specimen subjected to mode-I type of loading. The 2D mesh was constructed with a set of bi-linear four-noded quadrilateral elements. For modeling details of the fracture specimen, refer to Ramkrishnan et al. [8]. The material undergoes large strain and rotation at the crack tip necessitating a constitutive framework based on finite deformation for the numerical simulation. Accordingly the present investigation used a finite deformation algorithm [11] based on total-elastic-incremental-plastic strain incorporated in an in-house program. The flow behavior of the material is assumed to follow power-law as given below:

$$\sigma_f = K\varepsilon^n \tag{1}$$

where $\sigma_f$is true flow stress, K is strength coefficient,g ε is elasto-plastic strain and n is the strain hardening exponent. The material property of Armco iron for different grain sizes are given in Ref. [9, 10].

FEM Simulation

In load-displacement method, the study is carried out as a numerical experiment, that is, a complete CT specimen is subjected to loading as done in a real experiment and the determination of J is done akin to the experimental procedure. In the second method, the fracture toughness is calculated using the path-integral method, which is well known. In the third method, usually SZW is assumed as half of the crack tip opening displacement that is calculated using the 45 degrees lines. SZW measured this way has been used to characterize the fracture toughness. FEM simulations are carried out considering plane stress and plane strain conditions separately. The average of these two conditions results are then compared with experimental fracture toughness. The details of the work can be referred in Ref. 12. In addition, an attempt has to be made to explore the possibility of using 'characteristic distance' (l_c) approach for establishing fracture toughness, where the significant void is found to form at the critical distance from the crack tip. In this investigation plastic strain, strain energy density and instability parameters are studied. The detail of the work can be referred in Ref. 8. The present investigation essentially comprises a number of FEM simulation to study & correlate crack tip blunting, stress and strain contours with experimental results.

The present study also attempts at achieving an insight into defining a procedure for numerical determination of SZW and its critical value using a large deformation FEM analysis. The stretch zone width is the indicative of the extent of plastic blunting at the crack tip, which can be measured experimentally from the fractographs, obtained using scanning electron microscaope (SEM). In the crack tip blunting process, the virtual crack extension represents the SZW and crack tip opening displacement roughly corresponds to twice the stretch zone depth. Using the tensile test data, FEM analyses have been carried out to study the deformed crack tip behaviour with the increase in load-line displacement. The region of high deformation called the 'featureless zone' at the crack tip is delineated based on the nucleation and fracture strains obtained in the tensile specimen test. SZW is defined as the region near the crack tip exceeding the nucleation strain value. ABAQUS software is used in the study of determination of numerical procedure to define SZW and SZWc. Well refined optimum meshes are used in the analysis. Experimental results of critical SZW are compared with numerical results of SZW determined by using conventional procedure of calculation of SZW (using 45 degree lines) and by using proposed method of measuring SZW and its critical value.

Results and Conclusions

The study essentially demonstrates FEM predictability of J by three different methods with a reasonable accuracy with an input of material tensile stress-strain variation obtained experimentally. The comparison of experimental and numerical results is shown in Fig.1.

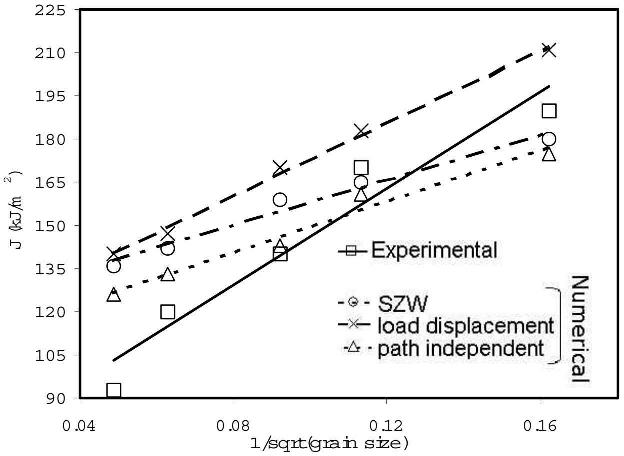

Figure 1: Comparison of experimental [9,10] and numerical results.

The fracture toughness results at three different scales compare well, not only with each other, but also with the experimental results. Fracture toughness values determined through different methods exhibit almost the same type of variation but with a dispersion of about 10%. The investigation also examines the possibility of predicting 'characteristic distance' (l_c) using FEM analysis. It emerges that l_c is not just an adjustable length-parameter but it can be regarded as the size of the region of intense plastic zone. The zone of intense plastic deformation compares well with the experimental measure of l_c of different grains of Armco iron [9,10]. The details of l_c correlation with fracture toughness can be seen in Ref. [8].

Using the large deformation FEM analysis and the input of material tensile test data, a procedure is established, for the first time, to determined SZW and its critical value and is compared with experimental SZWc values. Critical SZW is obtained when the maximum crack tip strain reaches material fracture strain value. Figure 2 shows the SZWc prediction procedure and results for 252-micron grain sized of Armco iron. The numerically predicted SZWc values are quite comparable with that of experimental results. The experimental SZWc results showed decrease in SZWc values with increase in grain size of Armco iron whereas usual procedure of SZW determination showed an increase trend. The proposed method of SZW determination accurately predicts the trend as well as the magnitude of SZWc.

Once the critical stretch zone width is predicted numerically accurately, the fracture toughness can easily be calculated by relation such as given in Ref. [13]:

$$J_{1C} = m\ \sigma^{*}\ (2\,SZW_c) \tag{2}$$

From the comparison of simulation with experiment, it is confirmed that large deformation FEM analysis can reasonably represent the process of fracture in the

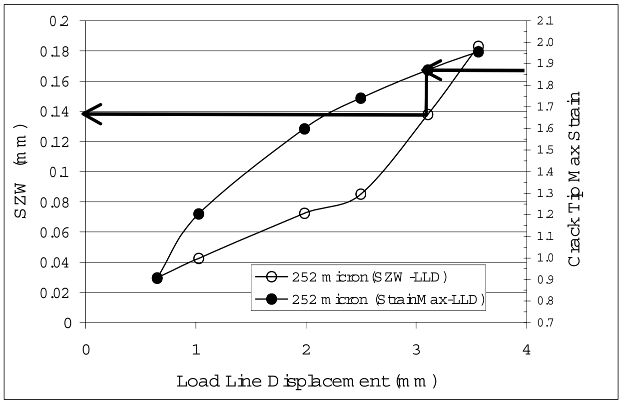

Figure 2: Determination of critical SZW using tensile test data

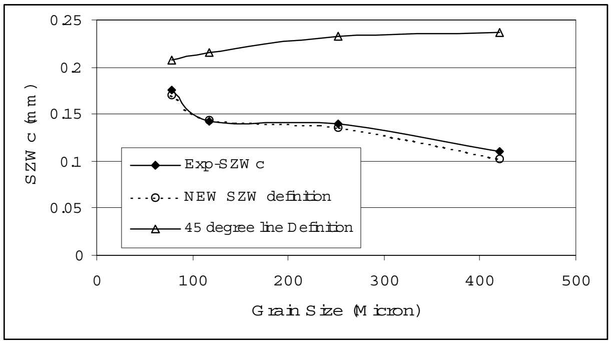

Figure 3: Comparison of Numerical SZW$_c$ with experimental results.

crack tip area and can predict the material's toughness and critical SZW using tensile test data. Using large deformation FEM analysis a procedure to determine SZW is also established by utilizing the tensile test data.

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