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A Potential Node Release Technique for Estimating Ductile Crack Growth in Metallic Materials

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ABSTRACT

In order to estimate the ductile crack growth in metallic materials, a potential node release technique is proposed in finite element simulation by introducing a potential node release law in traditional node release technique. J-integral far from crack tip is taken as a fracture parameter and the criterion of node releasing is a crack driving force relating with ultimate fracture strain and stress triaxiality near crack tip. The ductile crack growth and affecting factors are investigated numerically for three-point bend specimen.

KEY WORDS: Damage Mechanics, Fracture Modeling, FEM

INTRODUCTION

It is a very important and complicated topic to estimate numerically the ductile crack growth in nonlinear fracture mechanics. There exist two kinds of methods to simulating the ductile crack propagation, i.e., generation phase and application phase [1]. The so-called generation phase is to study numerically the fracture mechanics parameters such as COD, CTOA, COA and J-integral based on the experiment relationship between load-point displacement and crack growth length. The application phase is to study the load-point displacement and crack growth according to the fracture criteria at crack tip. Most researches are concentrated in the generation phase. One of the most difficulties in numerical simulation is how to determine the fracture criterion for ductile fracture in large scale yielding as the crack propagation.

It is predicted from metallurgical researches that the nucleation and growth of voids play an important role for the fracture process of ductile metallic materials, which cannot be described by conventional continuum mechanics. In structural materials, voids nucleate mainly at second phase particles and inclusions. Usually, micro-voids can be divided into two families, larger voids and smaller voids. The larger voids nucleate from inclusions at relatively low strains and smaller voids nucleate from carbides or precipitates at considerably larger strains. Consequently, void growth takes place due to the plastic deformation of surrounding matrix material and final failure occurs when the larger voids coalesce with each other or link up with a nearby crack tip via a void sheet consisting of voids nucleated from smaller particles [2-3].

Combining the micro-void damage mechanics and macro-fracture mechanics, a model to estimate the ductile crack growth in ductile materials is proposed in this paper. Potential node release technique is developed in finite element simulation by introducing a potential node releasing law in traditional node release technique. The ductile crack growth and affecting factors are investigated numerically for three-point bend specimen.

COHENSIVE ZONE AND PNRT

The ductile fracture of mild steels can be described as a progressive process with the nucleation, growth and coalescence of voids or micro-cracks. At the vicinity of a pre-existing macro-crack, a large damage evolution occurs due to the high stress and strain concentrations. It has shown from experiments that the damaged zone is confined very near to the macro-crack tip. The fracture toughness, the crack resistance and tearing modulus of ductile materials may be considerably affected by the presence of such localized damages near the crack tip. The so-called cohesive zone model is proposed to incorporate more details of the separation process than the modeling with conventional continuum mechanics as. The region ahead of a growing crack tip is a narrow strip joining the two elastic-plastic bodies which interact with each other with a kind of separation law. In general, one-dimensional separation relation is assumed acting on the ligament for cases under mode I loading conditions.

The traditional node release technique is to modify the boundary condition by releasing simultaneously the node force. In this paper, a new kind of node release technique is proposed by introducing potential node release law letting the node force release gradually. The potential node release law can be arbitrary in some degree as well as it reflects some characteristics of failure. As shown in Fig.1, the distance of the node as releasing is denoted by δ. The mechanical characteristics of the node releasing are defined through a power exponent function F as shown in the following.

$$F = F_{\max} \exp\{-3(\frac{\delta}{\delta_c})^{\frac{1}{m}}\} \tag{1}$$

where, F_{max} is the maximum force when the node is released, $\delta_c$the critical displacement when the new crack increment forms, and m the material constant.

In the model of cohesive zone, it is assumed that the maximum traction is given and related with the fracture stress. In fact, traction in the cohesive zone is changing with applied load. So it is important to keep that the traction in the cohesive zone is the same as predicted using the continuum mechanics. There are two parameters in Equ.1. It can be seen from Equ.1 that the larger the constant m is, the more difficult the separation of node and the higher the fracture tearing toughness will be. The constant *m* can be used to describing the fracture property in some degree.

NUMERICAL PROCEDURE

The three-point bend specimen was used in finite element simulation. The half specimen is meshed according to its symmetry. The meshes consisted of 1110 four-node isoparametric elements with 3435 nodes. In the large strain gradient zone the mesh was refined. The minimum mesh size near crack tip is about 1/400 of ligament length. The numerical evaluation of the J-integral was conducted incrementally throng Gauss-point integration of the elements on the path with standard weight function according to the reference [4]. The J-integral was calculated as the mean value for five different paths.

The procedure in the numerical simulations is simply as follows. Initially, the crack driving force expressed by parameter *U* increases with the increase of applied load[5]. The cohesive zone creates and the corresponding node begin to release when the calculated crack driving force *U* near the crack tip reaches to its critical value *U*c, which is the function of ultimate fracture strain ε_u and stress triaxiality near crack tip. In general, the traction at the nodes inside the cohesive zone has to follow the potential node release law as shown Equ.1. If the external applied load increases further, the cohesive zone grows. The new crack increment forms when node displacement gets to its critical value or the node force reaches near zero. According to the crack increment and corresponding J-integral values, the development of J-integral as crack growth can be obtained.

RESULTS AND DISCUSSION

In this model of simulating ductile crack growth, there are five parameters to affect the J-resistance curve, i.e., yielding stress, strain hardening exponent, ultimate fracture strain, critical crack tip displacement and node release exponent. The yielding stress, strain hardening exponent and ultimate strain can be determined from tensile stress strain curve. And the critical crack tip displacement can be determined from void growth theory or from fracture toughness experiment. In order to check the potential node release technique in simulating the crack growth, it is important to understand the influences of the parameters in Equ.1.

The influence of critical crack tip displacement on J-resistance curve is illustrated in Fig.2. The yielding stress and strain hardening exponent of the ductile material used in calculation are 499MPa and 8.0 respectively. And the node force release exponent is kept the same value as 1.0. The ultimate fracture strain for node releasing is 0.2. It is well shown in figure 2 that the critical crack tip displacement affects not only the initial J-integral but also the J-resistance curve. It seems that the effect of the critical crack tip displacement on J-resistance curve is not linear. The larger the critical crack tip displacement is, the larger the initial J-integral and the slope of J-resistance line. As the assumption in the model, the critical crack tip displacement keeps the same as the crack growth. It is clear from the figure that the tendency of J-resistance curve becomes steeper as the critical crack tip displacement increasing. For the given critical crack tip displacement, the tendency of J-resistance curve becomes smaller as the crack growth. The critical crack tip displacement is a main factor influencing the initial J-integral.

The material constants are kept the same in the calculations in order to investigate the effect of node release exponent on the J-resistance curve. The yielding stress is taken as 490MPa. The strain-hardening exponent is 8.0. The ultimate fracture strain keeps 0.2. The critical crack tip displacement is 0.05mm. It is displayed in Fig.2 that the node release exponent m affects strongly on the J-resistance curve. The initial J-integral gets greater and the slope of J-resistance curve becomes steeper as the node release exponent decreasing. It can be obtained that the larger node release exponent expresses the lower crack growth resistance. In the potential node release technique, there are two parameters which can expresses the changes of the initial J-integral and J-resistance. These two parameters have some relations with the material properties, which can be determined from fracture toughness testing and tensile testing. From the micro-mechanics of ductile fracture, the critical crack tip displacement and node releasing exponent in the model should have some relation with void properties. Those need more detailed investigations.

The crack driving force U is taken as a crack growth criterion in this study. The critical values Uc is determined by the ultimate fracture strain and stress triaxiality near crack tip as mentioned above. The stress triaxiality is dependent on the state of crack body. The ultimate fracture strain can be determined from the maximum point in the tensile stress-strain line. The constants in potential node release law are kept the same in the calculations in order to investigate the effect of ultimate fracture strain on the J-resistance curve. The yielding stress is taken as 490MPa. The strain-hardening exponent is 8.0. The node release exponent is 0.5. The critical crack tip displacement is 0.05mm. It is displayed in figure 4 that the ultimate fracture strain affects significantly on the J-resistance curve. The initial J-integral gets greater and the slope of J-resistance curve becomes steeper as the ultimate fracture strain increasing.

CONCLUSION

Based on the combination of micro-void mechanics and macro-fracture mechanics, a model to estimate the ductile crack growth in ductile materials is proposed. A potential node release technique is developed in finite element simulation by introducing a potential node releasing law in traditional node release technique. The ductile crack growth of three-point bend specimen is investigated numerically making use of self-developed finite element method. Conclusion shows that all the parameters in the model affect not only the initial J-integral but also J-resistance curve, that the node release exponent m, ultimate fracture strain and the strain hardening exponent are the main factors which influence the J-resistance slope, that the critical crack tip displacement, and yielding stress are the main factors affecting the initial J-integral.

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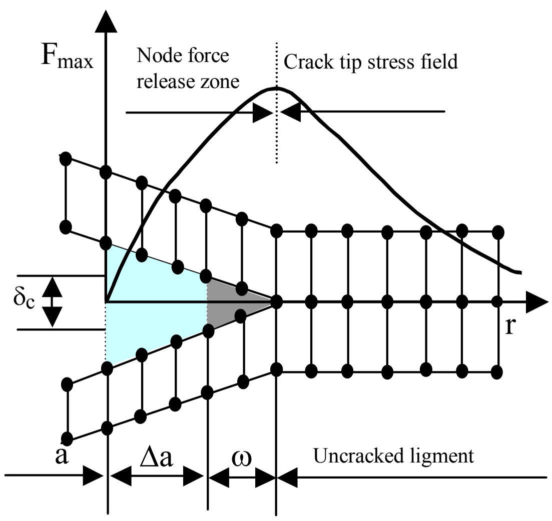

Fig.1 The simulating model for potential node release technique

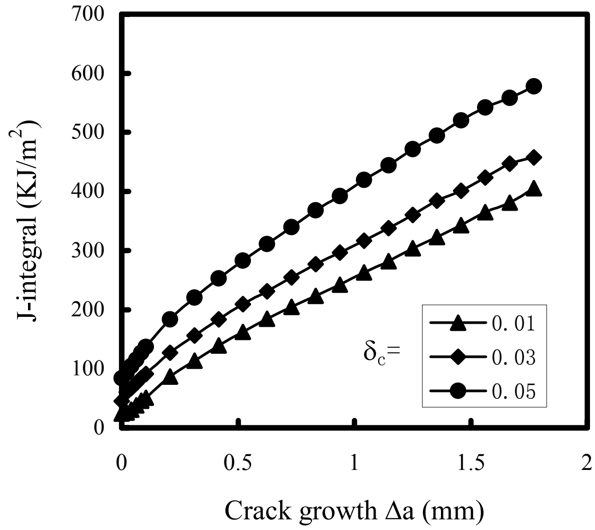

Fig.2 Effect of the critical crack tip displacement on J-resistance curve

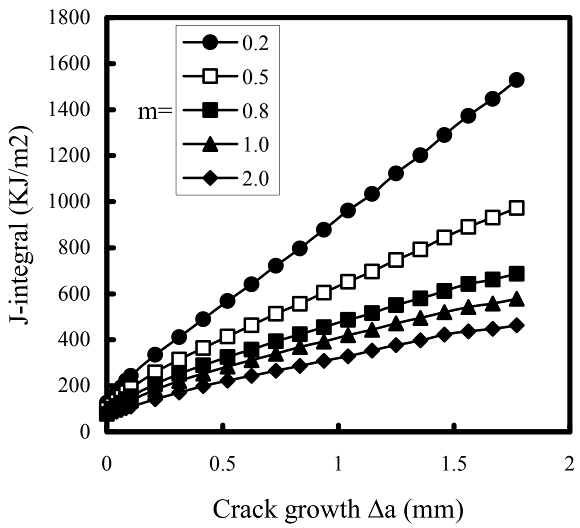

Fig.3 Effect of the node release exponent m on J-resistance curve

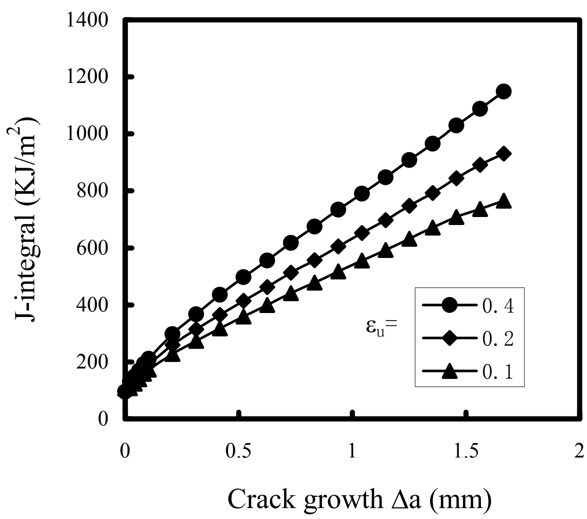

Fig.4 The effects of ultimate fracture strain on J-resistance curve.