A Model to Estimate the Ductile Crack Growth in Metallic Materials with Node Release Technique Using Potential †

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Abstract

A model in which the micro-void mechanics and macro-fracture mechanics are combined is proposed to estimate the ductile crack growth in metallic materials. A node release technique using a potential function is employed in the proposed finite element method. J-integral, far from the crack tip, is taken as a fracture parameter and the criterion of node releasing is described in terms of fracture strain and stress triaxiality near the crack tip. The ductile crack growth and the influential factors are investigated numerically for three-point bend specimens. The predicted curves of J-integral versus crack-extension show good agreements with the experimental measurements.

KEY WORDS: (Ductile Crack Growth) (J-Integral) (Finite Element Simulation)

1. Introduction

Researches on ductile crack growth simulations in recent years have been making remarkable progress due to the development of the micro-macro fracture mechanics and computing technology[1-5]. Numerical estimation of the ductile crack growth is a very important and complicated topic in nonlinear fracture mechanics. The procedure to simulate the ductile crack propagation consists of two stages, i.e., generation phase and application phase[6]. The so-called generation phase requires estimations of the fracture toughness parameters such as COD, CTOA, COA and J-integral based on the experimental data on the relation between the load-point displacement and the crack growth length. The application phase is a study of the load-point displacement and crack growth according to the fracture criteria at crack tip. Most researches are concentrated on the generation phase. One of the most difficult parts in numerical simulation is how to determine the fracture criterion during the ductile crack propagation in large scale yielding.

Numerical investigations applying the J-integral concept to stationary cracks in large scale yielding show that the ductile crack growth cannot be described adequately by the single parameter concept of J-controlled crack growth[7, 8]. It is shown that the crack growth in elastic-plastic materials changes the strength of the singularity in the stress and the strain fields at the actual crack tip. In case of ductile fracture, it has been observed experimentally that the crack tip opening displacement or J-integral at the initiation of ductile fracture is larger for specimens with low constraint than those with high constraint[9]. The J-integral along the contour far from the crack tip remains path-independent with crack growth and can be used to express the crack growth behavior, although the J-integral along the contour near the crack tip vanishes during stable crack growth. Therefore, the effects of stress triaxiality should be taken into account[10-12].

It is predicted from metallurgical researches that the nucleation and growth of voids play an important role in the fracture process of ductile metallic materials, which cannot be described by conventional continuum mechanics. In structural materials, the voids nucleate mainly at second phase particles and inclusions. Usually, the micro-voids can be divided into two families, i.e., 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 the surrounding matrix material and final failure occurs when the larger voids coalesce with each other or link up

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Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan.

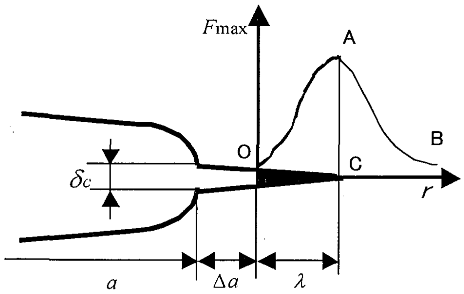

Fig.1 Crack growth model.

with a nearby crack tip via a void sheet consisting of voids nucleated from smaller particles[13-15]. Some of the recent approaches introduce new mechanical concepts for failure characterization of these kinds of materials[16,17].

Combining micro-void damage mechanics and macro-fracture mechanics, a model to estimate the ductile crack growth in ductile materials is proposed in this paper. A node release technique using a potential function is introduced into the finite element simulation. The ductile crack growth in the three point bend specimen is analyzed using the proposed method and the influence of various factors is investigated numerically.

2. Cohesive Zone and Node Release Technique

The ductile fracture of mild steels can be described as a progressive process consisting of the nucleation, growth and coalescence of voids or micro-cracks. In the vicinity of a pre-existing macro-crack, a large damage evolution occurs due to the high stress and strain concentrations. It has been shown from experiments that the damaged zone is confined to very near 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 shown in **Fig.1**. The black region ahead of a growing crack tip shown in Fig.1 is a narrow strip joining the two elastic-plastic bodies which interact with each other through a kind of separation law. In general, a one-dimensional separation relation is assumed to be acting on the ligament for cases under mode I loading conditions. Varieties of separation functions were proposed for different applications[1-5]. The traditional node release technique is to modify the boundary condition by releasing the node force. In this paper, a new kind of node release technique is proposed.

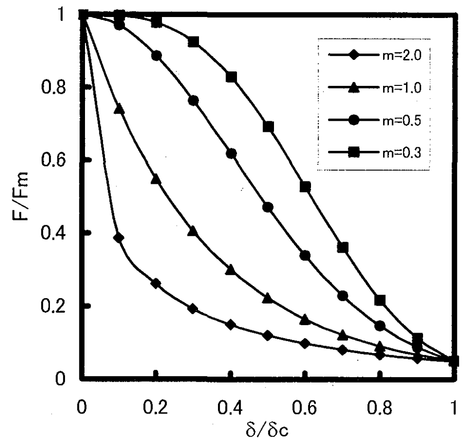

Fig.2 Effect of constant m on node force release scheme.

In this method the nodes are release gradually under the applied load according to the potential function. Since the potential function can be chosen rather arbitrarily, the power exponent function is used in this paper.

The distance of the node when 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.

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

where, $F_{\max}$ is the maximum force when the node is released, δ_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 to the fracture stress. In fact, traction in the cohesive zone is changing with applied load. So it is important to keep the traction in the cohesive zone the same as that predicted using the continuum mechanics.

There are two parameters in Eq.(1). The relationship of dimensionless $F/F_{\max}$ and δ/δ_c with material constant m is presented in **Fig.2**. It can be seen from Fig.2 that the larger the constant m is, the more difficult the separation of the node and the higher the fracture tearing toughness will be. The constant m can be used to describe the fracture property in some degree. It should have some relation with the necking property in standard tensile testing. The detail will be discussed in the later section.

3. Crack Driving Force

According to the theoretical Rice-Tracey model for void growth, which was derived for a fully plastic material of infinite extent with one spherical void, the void growth occurs under the combined effects of the applied plastic strain and stress triaxiality[18, 19]. The relationship between the void radius increment and applied plastic strain increment can be derived as follows.

$$\frac{dR}{R} = 0.322\exp\left(\frac{3}{2}F_\sigma\right)d\varepsilon_p \tag{2}$$

Where, R is the void radius, $d\varepsilon_p$ increment of applied plastic strain, $F_\sigma = \sigma_m / \bar{\sigma}$ the stress triaxiality which is the ratio of mean stress σ_m to Von Mises equivalent stress $\bar{\sigma}$.

Equation (2) can be integrated as:

$$\frac{R}{R_0} = \exp\left\{0.322\int\exp\left(\frac{3}{2}F_\sigma\right)d\varepsilon_p\right\} \tag{3}$$

where R_0 is the initial radius of isolated void.

From Eq.(3), it can be seen that the void growth can be described as a function of both the plastic strain and the stress triaxiality. From this point, the parameter U could be defined[15]:

$$U = \int\exp\left(\frac{3}{2}F_\sigma\right)d\varepsilon_p \tag{4}$$

This parameter expresses the driving force for void growth in ductile fracture. If the void grows to its critical value, the driving force will become the material constant. According to the theoretical and experimental research, the dR/R is not sensitive to stress triaxiality, and it can be assumed that the critical value U_c is independent of constraint. In other words, this means that the fracture strain is dependent on the stress triaxiality near the crack tip. The coalescence of voids can be thought of as some kind of necking. The stress triaxiality in tensile specimen is 0.866. On the basis of the ultimate strain ε_u obtained from the measured tensile stress-strain curve and calculated driving force value, the fracture strain in the crack tip can be obtained using the following formula.

$$\varepsilon_f = 1.6487\exp\left(-\frac{3}{2}F_\sigma\right)\varepsilon_u \tag{5}$$

From the tensile testing, the stress-strain curve of the material can be obtained, and the maximum of stress σ_u and corresponding strain ε_u can be determined. When the strain becomes larger than the ε_u, the real stress decreases with necking. By assuming that the stress-strain relation in the tensile test can be applied to the criteria for node releasing as shown in Eq.(1), then the constant, m, can be obtained according to the simulation line.

4. Materials and Experiment Procedure

The materials used for fracture toughness tests were a pipeline steel plate of API-X52 and its J507 weldment.

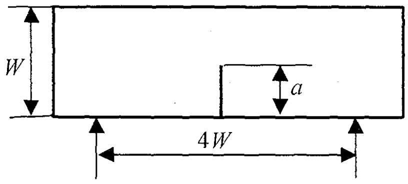

Fig.3 Three point bend specimen used in experiment and numerical analysis.

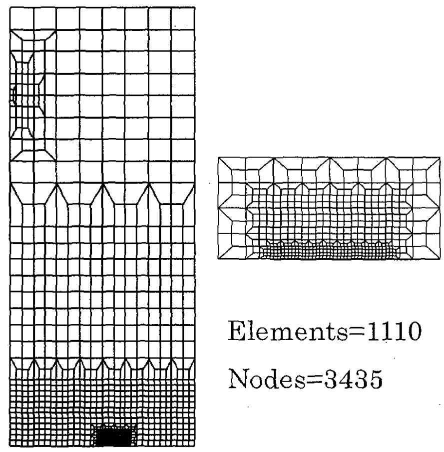

Fig.4 Finite element mesh for three point bend specimen.

The three point bend specimens of 8 x 16 x 80 mm were cut out and prepared as shown in **Fig.3**. The ratio of crack length to specimen width a/W is 0.5. The fatigue pre-crack was introduced using a high frequency testing machine with the stress intensity factor range Ki<750KJ/mm^2. The specimens were tested in three-point bend conditions under static loading on an INSTRON 1195 testing machine at room temperature. The multi-specimen method was used to determine the fracture toughness characteristics.

The stress-strain behavior in simple tension is described using the following equation,

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} \qquad \sigma \le \sigma_0 \tag{6}$$

$$\frac{\varepsilon}{\varepsilon_0} = \left\{\left(\frac{\sigma}{\sigma_0}\right)^n - 1\right\} \qquad \sigma > \sigma_0 \tag{7}$$

The yielding stresses of API-X52 and J507 weldment are 310MPa and 362MPa, respectively. Their strain hardening exponents are 7.99 and 7.10.

5. Numerical Procedure

The same three-point bend specimen was used both in the experiments and also in finite element simulations. The finite element mesh used in numerical analysis for three-point bend specimen is shown in **Fig.4**. The half specimen is meshed considering its symmetry. The meshes consisted of 1110 four-node isoparametric

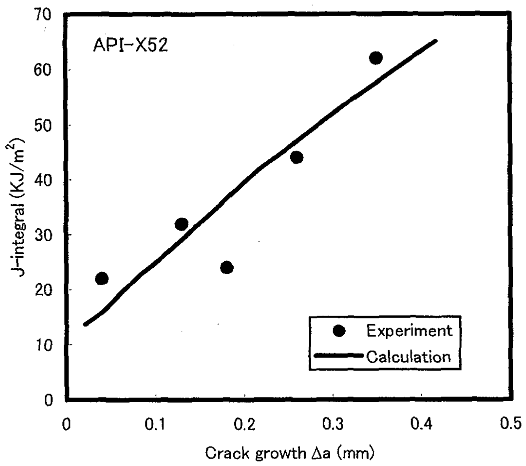

Fig.5 Comparison between experiment and estimation of J-integral vs. crack growth for API-X52 steel.

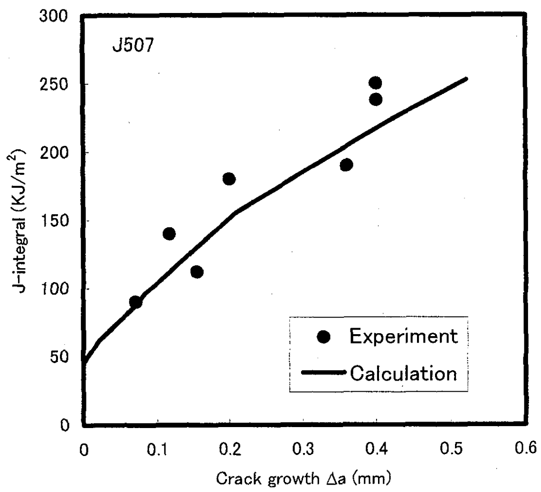

Fig.6 Comparison between experiment and estimation of J-integral vs. crack growth for J507 weldment.

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 through Gauss-point integration of the elements on the path with a standard weight function according to the reference[20]. The J-integral was estimated as the mean value for five different paths.

The procedure for the numerical simulations is simple. The crack driving force expressed by parameter U increases with the applied load. The cohesive zone is created and the corresponding node begin to be released when the calculated crack driving force U near the crack tip reaches 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 given by Eq.(1) which governs the node releasing process. If the external applied load increases further, the cohesive zone grows. The new crack increment forms when node displacement reaches its critical value, δ_c, or the node force reaches near zero. According to the crack increment and corresponding J-integral values, the evolution of J-integral with crack growth can be obtained.

6. Results and Discussions

The numerical results of J-resistance curves are compared with those obtained by experiments. **Figures 5** and **6** shows the results for J507 weldment and API-X52 pipeline steel, respectively. The solid lines show the numerical results and the solid points indicate the experimental results in these two figures. According to the fracture toughness testing and tensile testing, the parameters used in calculation of J-resistance curves by finite element methods are determined to be the following values. In case of the J507 weldment, yielding stress, strain-hardening exponent, the ultimate fracture strain, node release exponent m, the initial crack tip displacement are 362MPa, 7.99, 0.2, 0.4 and 0.03, respectively. For the API-X52 pipeline steel, the parameters used in calculation of J-resistance curve are the following: yielding stress is 310MPa, strain-hardening exponent is 7.1, the ultimate fracture strain is 0.1, node release exponent is 2.0, the initial crack tip displacement is 0.005 according to fracture toughness experiment. It can be seen from Figs.5 and 6 that there is a good agreement between numerical and experimental J-resistance curves. Although the parameters used to estimate the J-resistance curve are determined from experiments, the node release exponent and ultimate fracture strain are slightly modified considering the differences in stress state between tensile tests and crack problems.

In this model of simulating ductile crack growth, there are five parameters which may have an influence on the J-resistance curve, i.e., yield stress σ_0, strain hardening exponent n, fracture strain ε_u, critical crack tip displacement δ_c and node release exponent m. These parameters, except the critical crack tip displacement, can be determined from the tensile stress-strain curve. The critical crack tip displacement can be determined from void growth theory or from the fracture toughness experiment. For the application of the proposed method to practical problems, it is important to understand the influences of these parameters involved in the model on the J-resistance curve.

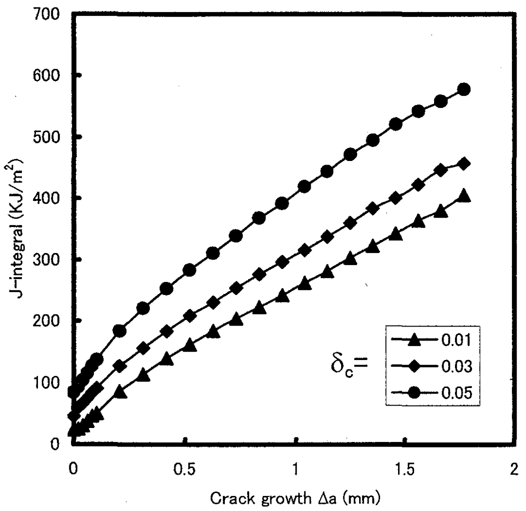

Fig.7 Effect of the critical crack tip displacement on J-resistance curve.

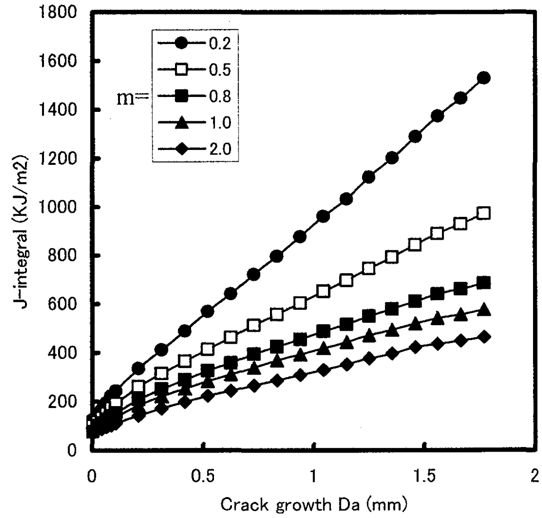

Fig.8 Effect of the node release exponent m on J-resistance curve.

The influence of critical crack tip displacement on the J-resistance curve is shown in **Fig.7**. The yield stress and strain hardening exponent of the ductile material used in these cases are 499MPa and 8.0, respectively, and the node release exponent is kept the same value as 1.0. The fracture strain for node releasing is 0.2. It is assumed that the critical crack tip displacement remains the same during crack growth. It is clearly shown in Fig.7 that the critical crack tip displacement influences 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 slope of the J-resistance curve becomes steeper as the critical crack tip displacement increases. For the given critical crack tip displacement, the slope of the J-resistance curve becomes smaller as the crack grows. The critical crack tip displacement has a significant influence on the initial J-integral.

Similarly, the effect of the node release exponent, m, on the J-resistance curve is investigated by keeping other material constants the same. The yielding stress, the strain-hardening exponent, the ultimate fracture strain, the critical crack tip displacement are assumed to be 490MPa, 8.0, 0.2 and 0.05mm. **Figure 8** shows the influence of the node release exponent, m, on the J-resistance curve. The initial J-integral becomes slightly greater, while the slope of the J-resistance curve becomes significantly steeper as the node release exponent decreases. It can be seen that the larger node release exponent results in the lower crack growth resistance. In the node release technique using potential, these two parameters, namely the critical crack tip displacement and the node release exponent, are the parameters which can reflect the initial J-integral and the J-resistance curve. These two parameters have some relations with the material properties, which can be determined from fracture toughness testing and tensile testing. From the aspect of 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. These need more detailed investigations.

The crack driving force U is taken as a crack growth criterion in this study. The critical values U_c is determined by the fracture strain and stress triaxiality near the crack tip as mentioned above. The stress triaxiality is dependent on the stress state of the cracked body. The fracture strain can be determined as the strain at the maximum stress point in the tensile stress-strain curve. The effect of the fracture strain on the J-resistance curve is examined by keeping the constants in the potential used for the node releasing. The critical crack tip displacement and the node release exponent are 0.05mm and 0.5, respectively. The yield stress and the strain-hardening exponent are 490MPa and 8.0. As is shown in **Fig.9**, the fracture strain also has influence on the J-resistance curve. The initial J-integral becomes slightly greater and the slope of J-resistance curve becomes steeper as the fracture strain increases.

The mechanical properties of ductile materials are defined by the yield stress and strain hardening exponent through Eqs.(6) and (7). The effect of the strain-hardening exponent and the yield stress has been examined. **Figure 10** shows the effect of the strain-hardening exponent. The yield stress of the material is 490MPa. The node release exponent, the critical crack

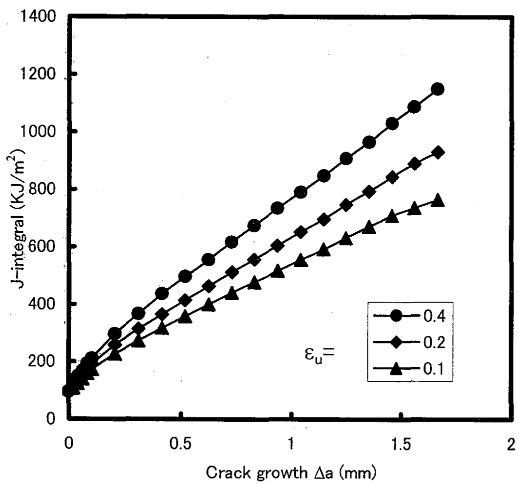

Fig.9 Effects of ultimate fracture strain on J-resistance curve.

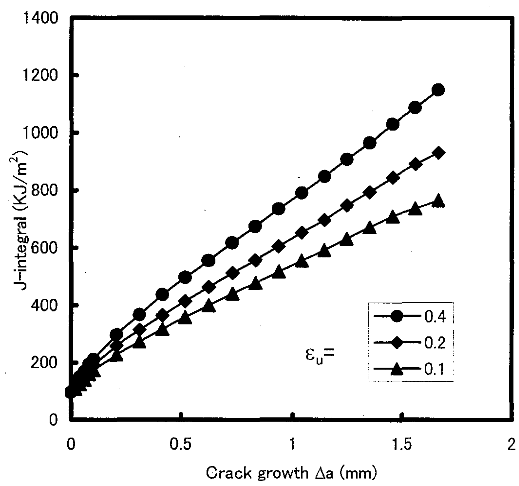

Fig.10 Effects of strain hardening exponent on J-resistance curve.

tip displacement and the ultimate fracture strain are kept the same and assumed to be 0.5, 0.05mm and 0.2 respectively. As shown in Fig.10, significant influence is observed in the slope of the J-resistance curve but its influence on the initial J-integral is small.

Similarly, the effect of yield stress on the J-resistance curve is investigated with keeping material constants except the yield stress are the same. The yield stresses are assumed to be 784MPa, 686MPa, 588MPa, 490MPa and 392MPa in each case. The strain-hardening exponent, the node release exponent, the ultimate fracture strain and the critical crack tip displacement are 6.0, 0.5, 0.2 and 0.05mm, respectively. It is clearly seen from **Fig.11** that the yield stress of ductile material influences not only the initial J-integral but also the J-resistance curve.

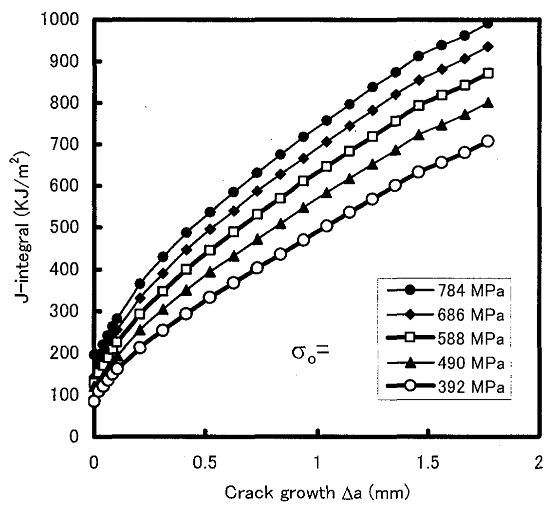

Fig.11 Influences of yielding stress of metallic materials on J-resistance curve.

7. Conclusions

Based on the combination of micro-void mechanics and macro-fracture mechanics, a model to estimate the ductile crack growth in metallic materials is proposed. A node release technique using the potential function is introduced into the finite element simulation. The ductile crack growth in three-point bend specimens is investigated numerically using the proposed finite element method. For the given material, there are five parameters which influence the J-resistance curve. The effects of parameters describing the node releasing criterion and the mechanical properties of the material are examined numerically. Through this study the following conclusions are drawn.

(1) The predicted curves of the J-integral versus crack-extension are compared with the experimental measurements.

(2) All the parameters in the model influence not only the initial J-integral but also the J-resistance curve.

(3) The node release exponent *m*, ultimate fracture strain and the strain-hardening exponent are the main factors which influence the slope of the J-resistance curve.

(4) The critical crack tip displacement and yielding stress are the main factors which influence the initial J-integral.

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