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Effect Analysis of Gurson Model Parameters on Crack Extension of Pipeline

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ABSTRACT

Leakage-before-break technique is widely used in high energy pipeline of nuclear plant, for which crack stability of pipeline under complex loading condition is a key issue, and crack growth resistance curve of pipeline material is the important foundation for crack stability analysis. In this paper, ferritic steel A533B is studied, Gurson damage model is used to simulate crack process of contact tension specimen under uni-tension, and effect of Gurson model parameter on simulation result is discussed. The following results are found during simulation: initial porosity factor f_0 is the main parameter, when it increases gradually, unstable crack extension will be observed; however, only initial J toughness is affected by critical porosity factor f_N; the minor parameter is load step control α, when it increases, stable and convergent result is obtained. All results in this paper can be used to determine parameters in Gurson mode, which will be foundation for crack extension analysis of pipeline.

Keywords: Leakage-Before-Break; Crack Growth Resistance Curve; Gurson Damage Model; Crack Extension

1. Introduction

In present, leakage-before-break (LBB) technique is widely used for collant pipeline in most operating and abuilding nuclear plants. In LBB technique, leakage can be detected in pipeline before unstable crack extension occurring in pipeline, and protective hardware and whip restraints can be removed for convenience of inspection operability, from which economic efficiency can be guaranteed. Since austenitic steel with high toughness is used for nuclear pipeline, elastic-plastic fracture is the main failure mode. Elastic-plastic fracture is a complex process, and fracture toughness J_{IC} cannot be adapted directly to fracture analysis in complex structure [1]. Combination of fracture test and material model is proposed by some researchers since fracture mechanism is required by fracture process simulation [2], material model parameters can be deduced from combination result [3], which can be used to simulate fracture process in any complex structure.

Gurson model is proved to simulate fracture process well for metallic material from a lot of tests and theoretic studies [4]. Contact tension specimen made of ferritic steel A533B is studied in this paper, Gurson model is combined to describe micro fracture process in A533B material, and effect of Gurson model parameter on simulation results is analyzed by finite element method.

2. Gurson Model

Metallic material is divided into two parts in Gurson model: basement material and porosity. Initial porosity is assumed as f_0, when material is loaded, bigger porosity is formed by connection of smaller porosity, and new crack surface is obtained at the same time. Material failure can be judged by the following equation:

$$g = \left(\frac{\sigma_e}{\bar{\sigma}}\right)^2 + 2q_1 f \cosh\left(\frac{3q_2\sigma_m}{2\bar{\sigma}}\right) - \left(1 + q_3 f^2\right) = 0 \quad (1)$$

In Equation (1), σ_e is regarded as equivalent stress of the whole material, σ_m is hydrostatic pressure, $\bar{\sigma}$ is equivalent stress of basement material, f is real-time porosity rate of the whole material. When f is larger than f_N, which is defined as the critic porosity, crack extension will be found. In above equation, q_1, q_2, q_3, is aspect ratio of porosity, which can be deduced by stress-strain curve of uni-tension test [5].

3. Simulation Analysis

3.1. Material Property

The stress-strain curve of ferritic steel A533B can be described as the following relationship:

$$\varepsilon = \frac{\sigma_0}{E}\left(\frac{\sigma}{\sigma_0}\right)^{1/N} \qquad (2)$$

In Equation (2), σ_0 is initial yielding stress of material, N is strain hardening index, E is young's modulus, and for material of A533B, parameters defined in Equation (2) are fixed as $\sigma_0 = 400 MPa, E = 2 \times 10^5 MPa, N = 0.1$.

3.2. Finite Element Model

According to ASME fracture toughness test standard E1820 [6], the geometric character of contact tension specimen can be plotted as **Figure 1**: w is 50.8 mm as width of specimen, B is 127 mm as depth of specimen, and size of the remanent part can be deduced by the proportion in **Figure 1**. Geometric size in **Figure 1** is used to build the finite element model.

Software Warp3d is used here for model creation and element C3D8 is selected. Since plastic deformation is included in simulation, crack tip singularity is not considered in this paper. Plot in **Figure 2** is the half model of contact tension specimen, one-layer element with Gurson model property is assigned to the crack face, and the elastic-plastic material relationship in Equation (2) is still suitable for the remanent part. In this paper, some parameters such as aspect ratio and Gurson element height are fixed in simulation as $q_1 = 1.46, q_2 = 0.931, q_3 = 2.131$ and $D = 200 \mu m$, where D is the height of element with Gurson model property.

The boundary condition is: all node freedom in depth direction is fixed; node freedom in vertical direction for symmetric surface except crack face is fixed; in order to remove rigid displacement of the whole model, one of the nodes far from loading position and crack surface is
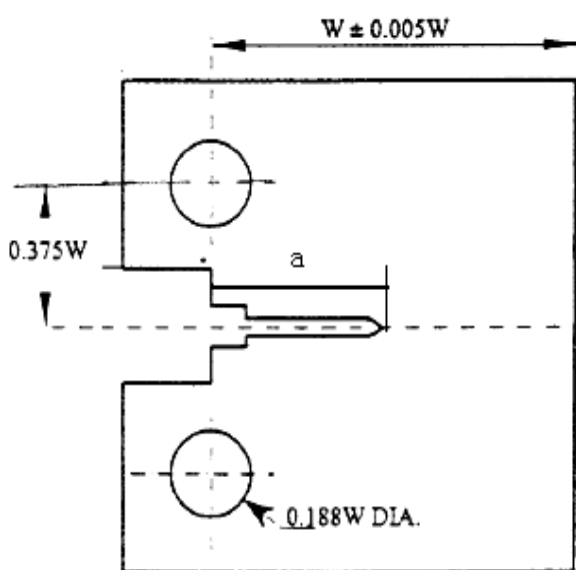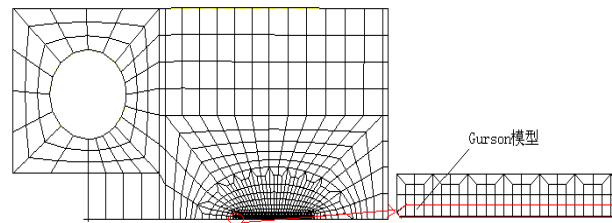

Figure 2. Finite element model of contact tension specimen.

fixed in horizontal direction. Displacement loading method is used.

3.3. Calculation Results

Software Warp3d is used to simulate fracture process of contact tension specimen. Effects of initial porosity f_0, critic porosity f_N and load control parameter α embedded in Warp3d on fracture process are studied in simulation.

1) Effect of load control parameter α on J value

For the simulation of this part, initial crack length ratio is $a/w = 0.3$, initial porosity rate is $f_0 = 0.005$, critic porosity ratio is $f_N = 0.2$ and only load control parameter is changeable. It is shown in **Figure 3** that, curve of J value vs. displacement loading is affected little by load control parameter, and the specimen is perfect now with no crack extension. As displacement Δ increasing, curves are distinct with different α: smaller α value is related with stable crack extension, such as there is a platform in curve corresponding to $\alpha = 0.005$; curves with larger α are related with unstable crack extension since there is a downtrend in these curves.

2) Effect of critic porosity

For the simulation of this part, initial crack length ratio is defined as $a/w = 0.5$, load control parameter is defined as $\alpha = 0.005$, initial porosity is defined as $f_0 = 0.003$, and only critic porosity f_N is changeable. It is shown in **Figure 4** that almost no effect of f_N on result can be observed.

3) Effect of initial porosity

For the simulation of this part，initial crack length ratio is defined as $a/w = 0.5$, load control parameter is defined as $\alpha = 0.005$, critic porosity is defined as $f_N = 0.2$, and only initial porosity f_0 is changeable. It is shown in **Figure 5** that curves of J value vs. displacement loading are coincident with smaller loading. As loading Δ increases, yielding is found around crack tip since smaller f_0 ($f_0 = 0.001$) corresponding to more perfect material, and there is an uptrend for J value because yielding zone is expanding. As f_0 increases, there is a downtrend in curve, since material with larger porosity rate is fragile, and relaxative stress can be observed around crack tip with crack surface extension.
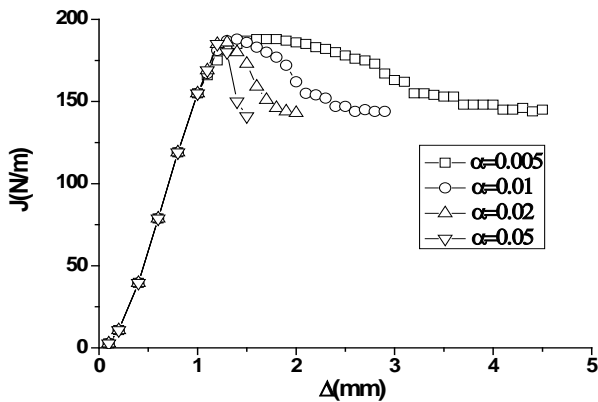

Figure 1. Schematic plot of contact tension specimen.

Figure 3. Effect of load-control parameter on calculation results.
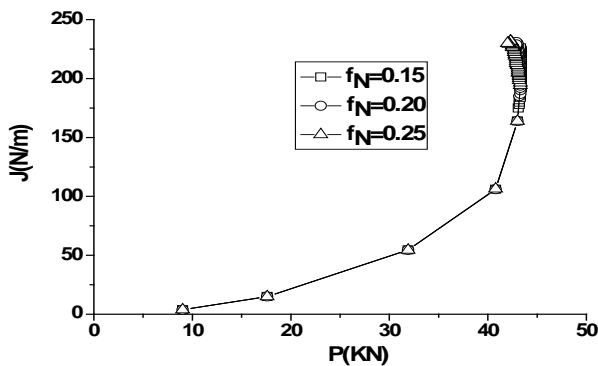

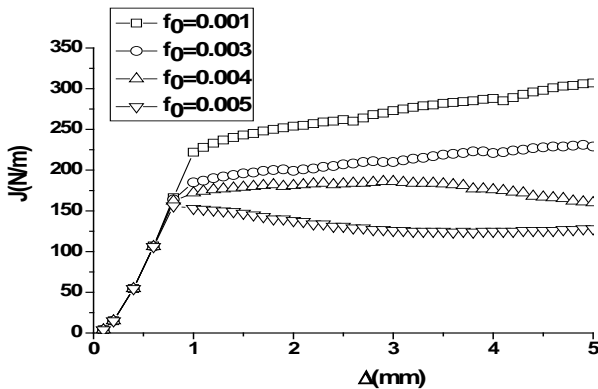**Figure 4. Effect of critic porosity on calculation.**

Figure 5. Effect of initial porosity on calculation results.

4. Conclusions

The fracture process of contact tension specimen made of ferritic steel A533B is simulated by finite element method combining with Gurson damage model, and effect of parameters in Gurson model on simulation result is studied, from which the following conclusions can be obtained:

1) The initial porosity rate is the leading role for simulation result, when f_0 increases, there is an unstable trend for crack extension, and only J value in initial loading period is affected by critic porosity rate f_N.

2) With decreasing load control parameter of α, stable and convergent crack extension can be observed.

5. Acknowledgements

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