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Quantification of Notch Bluntness Effect on Fracture Toughness according to Material Ductility by FE Damage Analysis Based on Multi-Axial Fracture Strain Model

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1. Introduction

Conventionally, the fracture mechanics analysis for crack in structural component is performed assuming a sharp crack is present. But cracks generated by manufacturing process or corrosion [1-3] can exist in blunt notch form and notch shape defect has higher fracture toughness than sharp crack defect by notch bluntness effect. So, When the conventional fracture analysis is used at notch blunt assessment, the result may be excessively conservative.

From this point of view, it is necessary to quantify the notch bluntness for fracture toughness. However, the influence of notch bluntness on fracture toughness is affected by the notch radius and the ductility of the material. It is difficult to quantify the effect of notch bluntness through experimental method. On the other hand, FE damage analysis can be used usefully, if the predictive capacity of the analysis can be confirmed

In this paper, FE analysis based on multi-axial fracture strain model was used to simulate the fracture toughness. In Ref. [4], It is validated that the multi-axial fracture strain model follows the test results well. For the analysis, three materials with different ductility were used. These materials was determined from pre-strained 316 stainless steel [5]. Then fracture toughness of three materials according to notch radius simulated by FE damage analysis. From this result, the influence of the material ductility on fracture toughness according to the notch radius was confirmed.

2. Quantification of notch bluntness effect on fracture toughness according to material ductility

2.1 test data

For the following work, tensile and fracture toughness test data [5] was brought in to determine three materials with different ductility. Each material was rolled parallel to rolling direction. Tensile test was conducted with a smooth bar specimen with a diameter of 6mm and fracture toughness test used 1T C(T) specimens with a thickness of 25mm. Table 1 gives the summary of results of tensile and fracture toughness tests.

Table 1 Summary of the tensile and fracture toughness test result for 316 Stainless steel [5]

CW (%)	E (GPa)	σ_y (Mpa)	σ_u (Mpa)	Elong-ation (%)	R.A.
5	197	388	628	52.3	81.2
20	191	643	774	33.0	78.3
40	183	870	982	19.7	19.7

2.2 Determination of Multi-Axial Fracture strain

The fracture strain locus of multi-axial fracture strain model is given by

$$\varepsilon_f^p = \alpha \times \exp\left(-1.5 \times \frac{\sigma_m}{\sigma_e}\right) \quad (1)$$

Where α is material constant which can be determined by smooth bar tensile test. The smooth bar tensile test is simulated using C3D20R element with minimum size 0.1mm. The FE results were compared with the engineering stress-strain test data and it agreed well with experimental data. To determine the material constant α, the variation of the stress triaxiality with the equivalent plastic strain at the center of the specimen was calculated. To consider the history of the stress state, an mean value of the stress triaxiality is calculated by integrating over the equivalent plastic strain between the start of loading and the specimen failure. The average values of the three materials are different. In order to use the three materials with consistent ductility change tendencies in following process, the representative values of the triaxial stresses of the respective materials are assumed to be uniform as the average values of the CW5 materials. These three materials were called Mat A, Mat B, and Mat C in the following process. The fracture strain locus constants for each of the materials are shown in Table 2.

The critical damage parameter, ω_c, can be determined from initiation fracture toughness of each materials C(T) test. The fracture toughness test was simulated using 3-D FE damage analysis with quarter model considering symmetric conditions. The C3D8 element were used and the size of the element in crack propagation area was 0.2mm. The true stress-strain curves determined by tensile test FE simulation was used. As the deformation of the crack tip increase, the ductile damage accumulates in accordance with the multi-axial fracture strain locus from Eq. (1) and the ductile fracture is assumed when the total damage becomes ω_c. The J-R curves from FE damage analysis depend on the value of ω_c. By comparing with experimental data, the ω_c of each materials was determined and given by Table 2.

Table 2 Determination of multi-axial fracture strain-model constants

Mat	α	ω_c
A	3.757	1.35
B	3.432	0.89
C	3.000	0.36

2.3 1T C(T) FE analysis results

To verify the effect of material ductility on the notch radius variation, a 1T C(T) specimen with three notch radii (crack, R0.4, R0.8) was modeled. The fracture toughness test of these specimen was simulated using 3-D FE damage analysis with quarter model considering symmetric conditions. The multi-axial fracture strain parameter determined in the previous section was used.

As the results of damage analysis, the J_Q and J value linearly increased with the notch radius regardless of the material ductility. And the slope tended to increase with ductility of the material. The J_Q variation with notch radius in three materials is given by Fig. 1.

The tearing modulus as the crack progressed tended to converge on the same value in all three materials. However, at the crack growth initiation, Mat A showed a tendency to increase as the notch radius increased, while Mat B and Mat C, which had relatively low ductility, showed the opposite tendency.

3. Conclusion

This paper investigates the effect of ductility on the fracture toughness according to the notch radius by FE analysis, which is based on multi-axial fracture strain model, assuming three materials with different ductility. As a result, it was confirmed that the notch radius of the cracks linearly increases the fracture toughness and affects the slope tearing modulus. At this time, it was confirmed that the ductility of the material increases the toughness increase slope according to the notch radius with decreasing ductility, and determines the tearing modulus change tendency according to the notch radius.

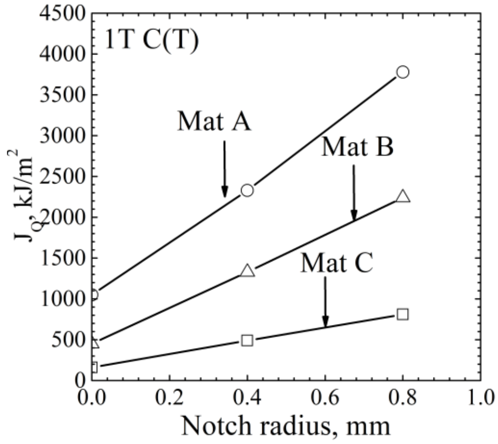

Fig. 1 The J_Q variation with notch radius in three materials

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