Prediction of Weibull Stress Distribution and Cleavage Fracture Probability of SA508 Steel

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1. Introduction

For the simulation of cleavage fracture, usually, it is necessary to perform a series of finite element (FE) analyses and experiments of standard specimens. However, since these investigations may prove unduly conservative or available plant specific data and/or archive material may be very limited, it is not easy to apply directly to real three dimensional structure. Considering these situations, many scientists and engineers have suggested a local approach to predict the fracture characteristics.

From microscopic point of view, the cleavage fracture can be regarded as rapid propagation of crack along a particular crystallographic plane in which the fracture toughness data tend to be widely scattered. Due to this reason, statistical approaches to predict cleavage fracture have been used to calculate cleavage fracture probabilities.

The Beremin model[1] is a good mathematical model to simulate the cleavage fracture. For the prediction of cleavage fracture probabilities using the Beremin model, the Weibull stress distribution around the crack tip area were calculated based on FE analyses results for 1T-CT(Compact Specimen) and PCVN(Pre-Cracked V-Notched specimen) specimens and used to determine the probabilities of cleavage fracture of SA508 steel.

2. Micromechanical Model of Cleavage Fracture

The Beremin model which adopts two parameter Weibull stress distribution can be used to predict the cumulative probability of cleavage fracture. Also, Lei et al.[2,3] proposed a mathematical solution for Weibull stress distribution of CT specimen that need not to perform FE analyses. The Beremin model adopts a two-parameter description of the cumulative probability of cleavage fracture utilizing weakest link statistics. The cumulative probability of fracture, P_f, is given by

$$P_f = 1 - \exp\left[-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right] \qquad (1)$$

where, m denotes the Weibull modulus which quantifies the statistical scatter, and σ_u is a scale parameter which sets the value of σ_W at 63.2% failure probability.

The Weibull stress, σ_W, is defined as

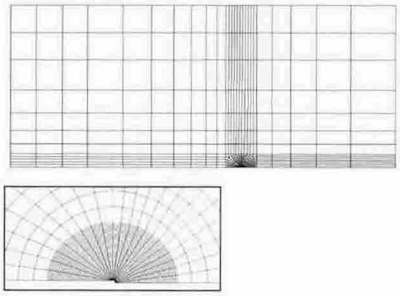
$$\sigma_W = \left[\frac{1}{V_0}\int_\Omega \sigma_1^m d\Omega\right]^{1/m} \qquad (2)$$

During this process, we have to fix the material parameters such as m and σ_u, and, for the calibration of material parameters, the experimental data of cleavage failure probability should be provided. Gao et al.[4] recently proposed a new calibration procedure based on fracture toughness data measured from two sets of specimens giving rise to different constraint levels at fracture, where m is assumed invariant of constraint at a fixed temperature.

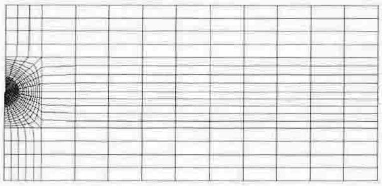
3. Analyses and Results

2-D elastic-plastic FE analyses for 1T-CT and PCVN specimens have been carried out to calculate the Weibull stress distribution and cumulative cleavage failure probabilities around crack tip area. For predicting cumulative probabilities, we used various material parameters which were calibrated by finite element analyses data and experiment data.

ABAQUS 6.4-1 and a post-processing program were utilized to calculate automatically the Weibull stress distribution at the crack tip. We used material properties of SA508 steel at -60℃ and load-displacement data of 1T-CT and PCVN specimens. Fig. 1 depicts representative 2-D finite element models and Fig. 2 shows tensile test results of SA508 steel.



(a) 2-D FE model of 1-CT specimen



(b) 2D FE model of PCVN specimen

Fig. 1 2D FE models of two specimens

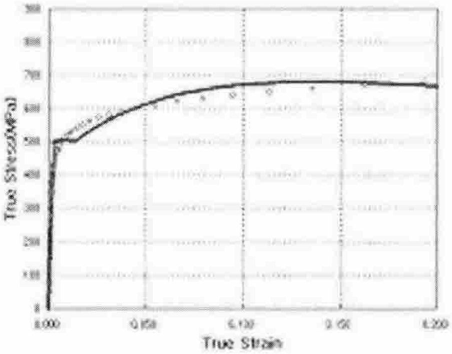


Fig. 2 tensile test results of -60□ SA508 steel

For the calculation of the Weibull stress distribution, we set a reference volume in front of crack tip and get stress distribution of elements inside the reference volume from FE analysis results. By summing up all the elements exceeding reference stress (or yield strength), the Weibull stress distribution with specific Weibull modulus ‘m’ was determined. Here, the maximum principal stress was defined as two times of yield strength[5].

In other hand, Lei et al.[2] suggested a mathematical solution of 1T-CT specimens to calculate the Weibull stress distribution. So, we choose an example case and compare mathematical solutions with post-processing results. Fig. 3 shows the analyses results of this example case in which we can find two results exactly same(m = 13, σ_u= 2050MPa). From this process, the Weibull stress distribution and cumulative probabilities of cleavage fracture were calculated. Fig. 4 shows the relationship between J-integral and cumulative probability.

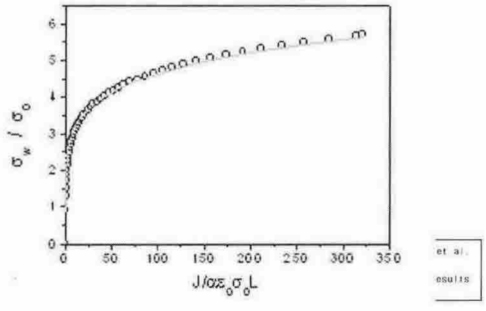


Fig. 3 Comparison FE results and Analytical solution of Weibull stress at compact tension specimen

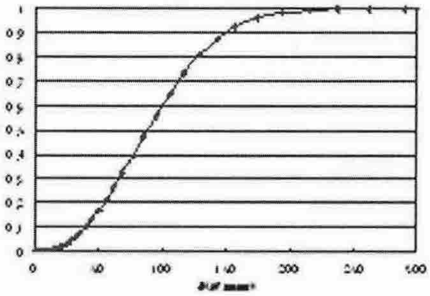


Fig. 4 cumulative Probability of CT specimen

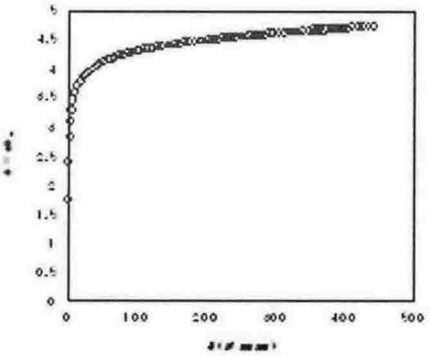


Fig. 5 FE results of Weibull stress at SA508 steel (Compact Tension specimen)

4. Conclusion

The Weibull stress and cumulative probability of SA508 steel were estimated using FE analysis and post-processing. In this research, the determination of material parameters of the Beremin model was very important part to calculate the cumulative probabilities. Also, the calibration of each material parameter was very difficult and time-consuming work. The post-processing program developed in this research can be utilized as a useful tool and the procedures can be referenced as a guideline for FE calibration as well as material parameter determination.

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