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Cleavage Fracture Evaluation for SA508 Carbon Steel at -60℃ by Weibull Stress Model

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1. Introduction

A cleavage fracture of ferritic steels is primarily attributed to slip induced cracking of carbides followed by unstable propagation. This phenomenon becomes strong and measured fracture toughness data tend to be highly scattered in ductile-brittle transition (DBT) region. With respect to the scatter, two reasons have been offered [1]; (1) the cleavage fracture toughness in the DBT region is controlled in large part by statistical sampling (2) a level of stress triaxiality ahead of the crack-tip is a function of the crack configuration, loading situation and amount of crack growth.

So, the scatter and transferability problems for specimens with different conditions are major obstacles for integrity assessment of structural components. Recently, to address these issues, considerable concerns on the local approach adopting several damage models are being increased again in reference to a progress of computational technology. The Weibull stress model [2, 3] which is one of representative damage models provides a framework to quantify the relationship between macro- and micro-scale driving forces with respect to cleavage fracture behaviors.

In this paper, statistical evaluation on the cleavage fracture is carried out for SA508 carbon steel which is a reactor pressure vessel material. At first, the fracture toughness tests for standard 1T-CT (Compact Tension) and PCVN (Pre-Cracked V-Notched) specimens are conducted at -60℃. Secondly, Weibull parameters are calibrated through comparing basic experimental data and corresponding finite element analysis results of 1T-CT specimen. And then, a series of three dimensional finite element analyses incorporating the Weibull stress model are performed for both types of specimens. Finally, sensitivity analyses for the Weibull parameters as well as failure probability evaluation using the experimental and finite element analysis data are carried out to investigate their effects on failure probability of cleavage fracture.

2. Damage models and calibration

The Weibull stress model which adopts the weakest link theory and two-parameter statistics has been proposed [2, 3]. The model can be used for elastic-plastic structural assessment and utilizes a damage criterion computed from the history of mean stress and strain in an elementary material cell. The authors evaluated the cleavage fracture using this model previously [4]. However, two-parameter Weibull stress model gives rough estimation results. It is because two-parameter Weibull stress model does not concern minimum toughness value below which cracks arrest.

To overcome this limitation, the probability of cleavage fracture, P_f, can be estimated by the following three-parameter expression taken into account the stress and strain fields at the crack-tip:

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

where, m denotes a Weibull modulus and quantifies the scatter, σ_u is a scale parameter which sets material's intrinsic resistance corresponding to a 63.2 (1-e^{-1}) % failure probability value of σ_W when σ_u=0 and σ_{th} is threshold value of Weibull stress. The Weibull stress, σ_W, characterizes the severity of applied crack-tip loading and defined as

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

In the above equation, V_0 is a reference volume prescribing near the crack-tip area and σ_I is a principal stress. The size of V_0 is taken as arbitrarily to be representative of the material micro-structure. In this paper, V_0 is set to 8mm^2. Ω is a volume of material inside the fracture process zone, usually defined as the loci of $\sigma_I \geq \lambda\sigma_Y$, with λ=2 (σ_Y is a yield strength, $\lambda\sigma_Y$ is a reference stress). However, the values for λ other than 2 have only minor effects on the Weibull stresses.

On the other hand, to apply the Weibull stress model, the parameters such as m and σ_u should be calibrated using basic experimental data. Gao et al. [5] proposed a new calibration procedure based on fracture toughness data from two sets of specimens giving rise to different constraint levels at fracture. In the proposed procedure, Eq. 2 has rewritten as follows for numerical evaluation.

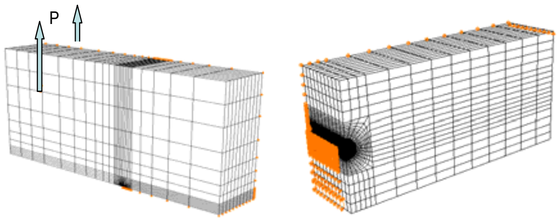
$$\sigma_W = \left[\sum_{i=1}^{n_e} (\sigma_1{}^i)^m \frac{V_i}{V_0}\right]^{1/m} \tag{3}$$

where, n_e denotes number of elements which exceed the reference stress and V_i is the volume of ith material unit in the crack-tip plastic zone experiencing a maximum principal stress σ_1^i.

3. Cleavage Fracture Evaluation

3.1 FE models and analysis conditions

Both the standard 1T-CT (a/W=0.5) and 10×10 mm PCVN (a/W=0.5) specimens were modeled and analyzed. Fig. 1 illustrates typical three dimensional finite element meshes and analysis conditions. The quarter model was generated for 1T-CT specimen considering symmetrical conditions, which consists of 19,525 nodes and 16,640 elements. Distributed tensile loads were applied at pin-hole location although it was omitted for brevity in numerical simulation. On the other hand, the half model was generated for PCVN specimen reflecting its relatively small geometry, which consists of 11,594 nodes and 9,740 elements.

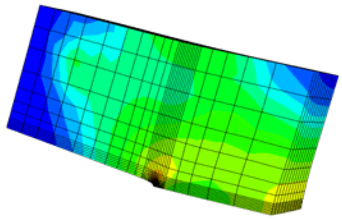


(a) CT specimen (b) PCVN specimen

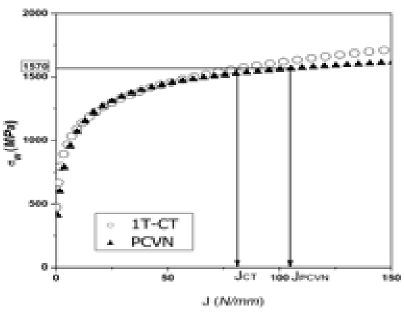
Fig.1 Three dimensional FE meshes and analysis conditions

3.2 Analysis results

Fig. 2 depicts von Mises contour plots for 1T-CT specimen and differences of resultant σ_w-J curves for the two types of specimens. Due to the different crack configurations and loading conditions, at the given Weibull stress level (e.g., 1570MPa), two specimens gave about 30% different J_c values. This phenomenon means that, in case of 1T-CT specimen, it is easier to initiate cleavage fracture than the relatively thin PCVN specimen due to its higher Weibull stress level caused by high triaxial stress state.



(a) Von Mises contour plots for 1T-CT specimen



(b) Weibull stress distribution

Fig. 2 Three dimensional FE analysis results

In this paper, the discrepancy was adjusted using a concept of ‘toughness scaling diagram’. Fig. 3 shows it to compare J-integrals between CT specimen and PCVN specimen at same Weibull stress condition. J_{pcvn} was 1.5 times to $J_{1T\text{-}CT}$.

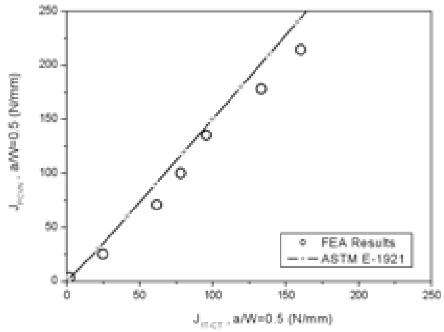


Fig. 3 Toughness scaling diagram

4. Conclusion

The cleavage fracture evaluation based on local approach has been carried out for SA508 carbon steel at -60℃ to calculate failure probabilities and following conclusions were derived.

(1) The Weibull stress model coupled with three dimensional finite element analyses estimated the cleavage fracture of 1T-CT and PCVN specimens in a satisfying manner.

(2) From sensitivity analysis results, it was proven that the priority of principal parameters affects on failure probability of cleavage fracture was in order of σ_u, m and V_0.

(3) The evaluation results can be used to correlate cumulative probabilities among cracked specimens with different crack configurations and loading conditions, after prudent calibration, and utilized to make the basis for demonstrating real safety margins of reactor components containing defect.

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