Evaluation of Fracture Toughness Applicability of Small-scale Cruciform Bend Specimen

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1. Introduction

The structural integrity assessment of reactor pressure vessels (RPV) for continued operation of nuclear power plants (NPPs) is carried out using specified specimens as set forth surveillance test procedure of ASTM standard. These specimens should be satisfied small-size geometry due to the limitation of surveillance capsule space. In general, during the in-service inspection, a detected defect size is shallower than that of ASTM standard considered, and biaxial loading is subjected in RPV structure. To overcome a conservatism of ASTM and to satisfy the limitation of the surveillance capsule space, the small-scale cruciform bend specimen is proposed and its fracture toughness applicability is discussed in the present work.

2. Fracture Toughness Evaluation

2.1 Cruciform specimen testing

Fig. 1 depicts the geometry of SA508 Gr. 3 small-scale cruciform bend specimen (CRB). While ORNL have developed basic geometry of specimen for the simulation of biaxial loading condition [1], small size of specimen was proposed to satisfy the term as described in the section of introduction in present study. Geometry of small scale CRB specimen is basically identical to the PCVN specimen but have two more loading legs, and three load-diffusion control slots in each arms were machined. The CRB specimen subjected to a biaxial loading by 5-point bending and a/W=0.3 straight crack was generated by the pre-cracking process. Fracture toughness tests were performed according to ASTM standard E 1921 [2] at four test temperature (T= -80°C, -100°C, -110°C, -120°C) in a chamber filled with liquid nitrogen. Two geometry related functions, $f(a/W)$ and $\eta(a/W)$, are determined to calculate K_{Jc} based on preliminary FE analyses as summarized in Table 1.

2.2 Fracture Toughness Test Results

The Wallin master curve approach was used to characterize the toughness-temperature relationship of ferritic materials [3]. Fig. 2 shows the results of the 11 cruciform bending tests with PCVN specimen data sets of SA508 Gr. 3 material for comparison. The cruciform data set demonstrates a similar pattern as the PCVN data, but reference temperature T_0 was lower than PCVN with a/W=0.3 data. T_0 was -83.4°C for the PCVN with a/W=0.3 and 0.5 and -100.6°C for the cruciform bend specimen with a/W=0.3. In the FE analyses, the test section was fully yielded, which means small scale yielding and full constrained crack-tip condition was not satisfied, and it result in higher fracture toughness and lower reference temperature of CRB specimens compared with PCVN specimens. It is notable that the remaining ligament of the CRB specimen is to be a longer value for the fully contained constraint condition.

2.3 Constraint and Biaxial Effects

Biaxial loading has the potential to increase constraint at the crack-tip and thereby reduce some of the shallow flaw, fracture toughness elevation. Calculations of the crack-tip constraint characterizing parameters were performed for a more detailed review. To quantify the stress state at the crack tip, the Q-stress is often used, as defined by [4]. However, the reference value for the HRR field, $(\sigma_{\theta\theta})_{HRR}$, for the plane strain is different from that for plane stress, and thus the application of the Q-stress in a 3-D structure is not clear. A better parameter to quantify the out-of-plane constraint effect is the stress triaxiality parameter, defined by [5]. As this parameter includes all three components of principal stress, it can accommodated the three-dimensional (out-of-plane constraint) effect.

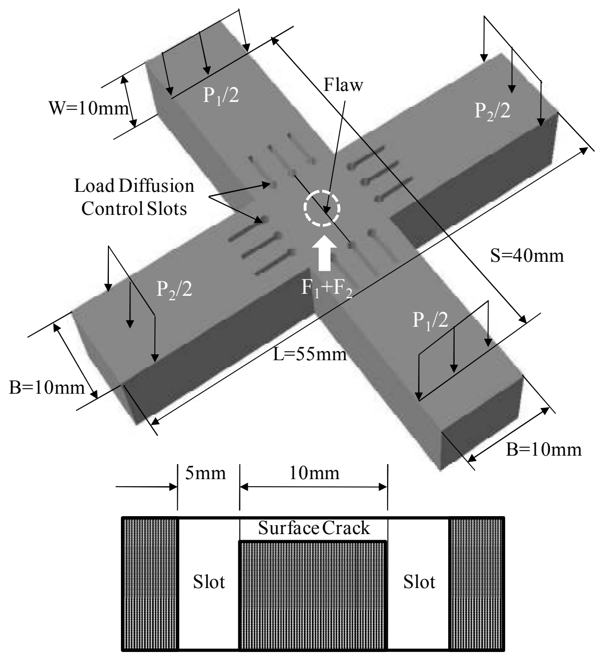

Fig. 1. Geometry of small-scale CRB specimen.

Table 1: Geometry factors for the different crack depth ratio

a/W	$f(a/W)$	$\eta(a/W)$
0.1	0.00928	1.10716
0.3	0.01632	0.95404
0.5	0.01600	0.49500

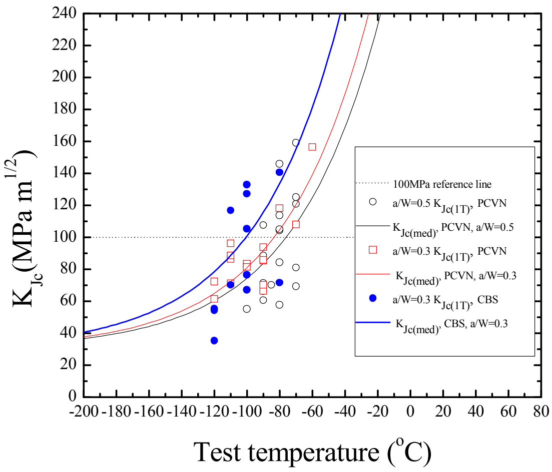

Fig. 2. Master curve (median) plot of cruciform specimen data with PCVN specimen data.

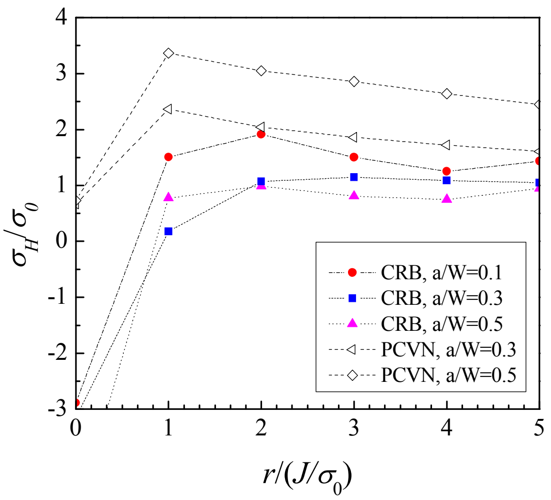

Fig. 3. The crack-tip stress field analysis at T=-100°C and J≈58 kJ/m^2

Fig. 3 shows normalized hydrostatic stress profiles with increasing distance from the crack tip. The constraint of PCVN specimens are higher than that of CRB specimen, the triaxiality is increasing with decreasing a/W ratio. These result come from that the effect of increasing crack tip constraint with increasing biaxial loading ratio was significantly greater than the effect of decreasing crack tip constraint with decreasing a/W ratio. The biaxial loading ratio were 0.96, 0.74 and 0.48 for a/W=0.1, 0.3 and 0.5 in the FE analyses, respectively. From the constraint effect analysis which is not presented herein, cruciform bend specimen have greater triaxiality compared with a PCVN specimen at a small load, but gradually approaches the plane stress condition. Based on the investigation, it can be concluded that biaxial fracture toughness tests show that fracture toughness was reduced at T=-120°C due to a full constraint, which can create a biaxial effect, which can lead to increase in the reference temperature, T_0, for a cruciform bend specimen. For a higher test temperature, specimen geometry B and W should be modified to have and maintain full constraint and the plane strain conditions. Specimen geometry has a more significant effect than biaxial loading and crack size.

3. Conclusions

In the present study, a small-scale cruciform bend specimen was designed, the reference temperature, T_0, and fracture toughness values, K_{Jc}, were obtained through the fracture test and simulation technique for a cruciform bend specimen, and were compared with those of PCVN specimens. Based on the FE results, constraint at the crack tip was evaluated for a cruciform bend specimen with shallow and deep cracks. In contrast to the PCVN specimen, cruciform bend specimen had a low constraint condition with increasing a/W ratio by the effect of biaxial loading ratio that was significantly greater than the effect of decreasing crack tip constraint with decreasing a/W ratio. From the analysis of the crack tip constraint stress, relatively high triaxiality was shown for the CRB specimens at low load by comparing PCVN specimens but triaxiality of cruciform bend specimen was approached plane stress condition with increasing load.

Thus, to obtain current ASME spirit, full constraint should be maintained for satisfying small scale yielding and plane strain conditions. From this point of view, CRB specimen should be modified to have sufficient cross section and distance between crack tip and crosshead. Fracture toughness values of CRB specimen considering biaxial loading can be used when these points considered and after the quantification of constraint effect. The authors continue in effort to develop appropriate specimen design.

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