§ 8. Fracture Toughness Evaluation of Reduced Activation Materials with Miniaturized Specimen

Kurishita, H. (IMR, Tohoku Univ.),
Yamamoto, T. (IMR, Tohoku Univ.),
Nagasaka, T., Nishimura, A., Muroga, T.,
Jitsukawa, S. (JAERI)

Fracture toughness is a key engineering property of structural materials. The first wall and blanket of a fusion reactor are thin wall structures, several millimeters thick. Furthermore, irradiation volumes available in IFMIF are limited to approximately 500cc for displacement damage above 20dpa/year. This volume of 500cc corresponds to that occupied by only six standard compact tension (CT) specimens or two standard 3-point bending (3PB) specimens for fracture toughness testing. Overcoming these limitations require miniaturization of fracture toughness test specimens. Previous specimen miniaturization for fracture toughness testing has mainly concentrated on CT specimens because the load-line displacement can be precisely measured with a clip gage for CT specimens, but not for 3PB specimens. However, 3PB specimens have many advantages over the CT specimens. Therefore, it is desirable to develop test techniques for reliable evaluation of fracture toughness using miniaturized 3PB specimens. In this study, miniaturized 3PB specimens with thickness of 7.0, 5.0 and 3.3 mm and well defined pre-crack length of 0.5~0.6W (W: specimen width) and side grooves of 0.4B (B: specimen thickness) were prepared from a reduced activation ferritic steel, JLF-1. Plane-strain fracture toughness tests at 77 K and elastic-plastic fracture toughness tests by the unloading compliance method at room temperature were performed. The data were combined with plane-strain FEM analysis, aiming at developing miniaturized test techniques for reliable fracture toughness evaluation.

At 77K all the miniaturized 3PB specimens of JLF-1 fractured in a completely brittle manner and the plane-strain fracture toughness, K_{IC}, was estimated to be 13-16 $MPam^{1/2}$ regardless of specimen size, indicating that K_{IC} does not show appreciable dependence on specimen size.

On the other hand, at 290K all the miniaturized 3PB specimens exhibited slow stable crack extension. Therefore, the unloading compliance method was applied to measure J-integral. It is shown that the initial part of the J-R curve is much steeper than the calculated blunting line. Therefore, a straight line was fitted by eye through the initial portion of the data and a second line was drawn parallel to the first but offset by an amount corresponding to a crack extension of 0.2 mm. The candidate toughness value J_Q determined by the intersection of the data with this offset line was in the range of 222 to 273 kJ/m^2

In the initial linear portion clear jumps in the crack extension were observed, which may correspond to the onset of pre-crack extension. Therefore, the value of J_{IN}, defined here as the J-value at the onset of pre-crack extension, was determined from the intersection of the straight line and a linear approximation of the data falling between approximately 0.1 and 0.3 mm of crack extension. The determined J_{IN} value was in a small range of 103 to 123 kJ/m^2 indicating that no significant differences in J_{IN} between the specimen sizes.

The above determination of J_{IN} by the compliance method is difficult to apply to dynamic tests and to tests of highly irradiated specimens with less ductility. Therefore, a different method was developed in this study. The method is based on the finding that the plane-strain FEM analysis can reproduce the measured load-displacement record until the pre-crack starts to extend because the FEM analysis assumes no extension of pre-crack. Above that point, the FEM curve should go higher than the measured record. Therefore, we can say that the pre-crack may start to extend at the point where appreciable deviation of the FEM curve from the measured record starts to occur. This means that the area, A, under the load-displacement record up to the deviation point is related to J_{IN} for crack initiation by

$$J_{IN} = 2A/b_0B_N \qquad (1)$$

where b_0 is the original ligament size ($b_0 = W - a_0$) and B_N is the net specimen thickness.

Comparison of the load-displacement curves calculated by the plane-strain FEM analysis with the measured record for the 5 mm^B x 5 mm^W specimen showed that there is a good agreement until the displacement reaches about 0.7 mm. Above 0.7 mm appreciable deviation of the FEM-curve from the measured one clearly occurred. Calculation of the area up to 0.7mm, which corresponds to A, and substitution of the calculated value for A in eq. (1) gives the J_{IN} value of approximately 130 kJ/m^2, which is nearly equal to the measured value of J_{IN}. Since this method only requires measurements of load-displacement curves, it is applicable to static and dynamic tests and also to heavily irradiated materials with less ductility.

These results show significant progress toward reliable evaluation of fracture toughness using miniature specimens. Efforts should be continued to establish test techniques for reliable fracture toughness evaluation using the miniaturized 3PB specimens.