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DESIGN OF A CRUCIFORM BEND SPECIMEN FOR DETERMINATION OF OUT-OF-PLANE BIAXIAL TENSILE STRESS EFFECTS ON FRACTURE TOUGHNESS FOR SHALLOW CRACKS

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ABSTRACT

Pressurized-thermal-shock loading in a reactor pressure vessel (RPV) produces significant positive out-of-plane stresses along the crack front for both circumferential and axial cracks. Experimental evidence, while very limited, seems to indicate that a reduction in toughness is associated with out-of-plane biaxial loading when compared with toughness values obtained under uniaxial conditions. A testing program is described that seeks to determine the effects of out-of-plane biaxial tensile loading on fracture toughness of RPV steels. A cruciform bend specimen that meets specified criteria for the testing program is analyzed using three-dimensional elastic-plastic finite-element techniques. These analysis results provide the basis for proposed test conditions that are judged likely to produce a biaxial loading effect in the cruciform bend specimen.

1 INTRODUCTION

The service life of commercial nuclear reactor pressure vessels (RPVs) can be limited by safety requirements related to postulated pressurized-thermal-shock (PTS) accident conditions. In analyses of PTS transients, the fracture initiation resistance for an RPV is based on the American Society of Mechanical Engineers Section XI fracture toughness curve, which was developed through testing of compact specimens that exhibit essentially plane-strain conditions. However, PTS loading produces biaxial stress fields in an RPV wall with a significant positive out-of-plane stress aligned parallel to postulated surface cracks oriented in either the longitudinal or the circumferential directions. These out-of-plane stresses have the potential to influence conditions that could alter the material fracture toughness. Experimental evidence is very limited, but some data (described below) seem to indicate that a significant toughness reduction is associated with out-of-plane biaxial loading when compared with toughness values obtained under uniaxial conditions. This paper summarizes essential elements of a testing program being conducted by the Heavy-Section Steel Technology (HSST) Program at Oak Ridge National Laboratory to determine out-of-plane biaxial tensile stress effects on fracture toughness for shallow cracks in RPV steels.

2 RECOMMENDATIONS FOR A BIAXIAL TESTING PROGRAM

A recent HSST investigation (Bass et al. 1992) concerning the potential impact of far-field out-of-plane stresses and strains on fracture initiation toughness focused on existing experimental

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data and on predictions from advanced analytical models. That study identified a very limited quantity of existing biaxial test data (Aurich et al. 1977; 1979; 1984) indicating a significant decrease of fracture toughness under out-of-plane biaxial loading conditions when compared with the uniaxial loading case. At Bundesanstalt für Materialprüfung, Germany, a nominal biaxial stress state was attained in the 50- by 80-mm (1.97- by 3.15-in.) cross section of double-T-shaped specimens via a transverse bending stress that develops in conjunction with the uniaxial tension component (Aurich et al. 1977). The ratio of the tensile component to the transverse component of stress along the crack front had a maximum value of 1:0.3 and a mean value of 1:0.15. Fracture toughness (K_C) values measured with the biaxially loaded specimen were reported to be ~25% lower than those of single-edge-notch specimens fabricated from the same material (22 NiMoCr 37 steel).

Unpublished data from the Central Research and Development Institute of Machinery, Russia, concerning fracture toughness under biaxial loading conditions were reported by M. Brumovsky.* Biaxial loading was produced in a spinning-disk test facility that utilized a circular disk with a diameter of 450 to 600 mm (17.7 to 23.6 in.), a thickness of 150 mm (5.9 in.), and a surface crack of 40-mm (1.6-in.) maximum depth and 200-mm (7.9-in.) length located in the face of the disk. In these experiments, an estimated 37% reduction in K_C was reported for the biaxially loaded spinning disks, as compared with data from uniaxially loaded specimens.

Because of conflicting results from analytical studies (Bass et al. 1992) and the absence of suitable confirmatory experimental data, a testing program was initiated within the HSST Program to (1) determine the effects of out-of-plane biaxial loading on fracture toughness and (2) provide a basis for development of prediction models. Biaxial fracture toughness data obtained from this testing program can potentially impact assessment of RPVs under PTS transient loading conditions. Probabilistic fracture-mechanics analyses of an RPV have shown that shallow cracks dominate the conditional probability of vessel failure in a PTS evaluation (Cheverton et al. 1985). Test data (Theiss et al. 1992) indicate a significant increase in the fracture toughness of shallow-crack uniaxial beam specimens compared with deep-crack specimens in the transition region for unirradiated A533 grade B class 1 steel. In Fig. 1, the increase in fracture toughness for HSST shallow-crack beams is quantified in terms of a temperature shift. The shallow-crack lower-bound curve for essentially one crack depth was estimated by using the deep-crack lower-bound curve shifted by T_S = 35°K (63°R). This temperature shift, which is crack-depth dependent, could be greater for shallower cracks that are also important in PTS analysis. However, any increase in crack-tip constraint resulting from tensile out-of-plane biaxial stresses could act in opposition to the in-plane constraint relaxation for the uniaxial shallow-crack data. Potentially, this could lead to a reverse temperature shift (T_B in Fig. 1) of the lower-bound toughness curve

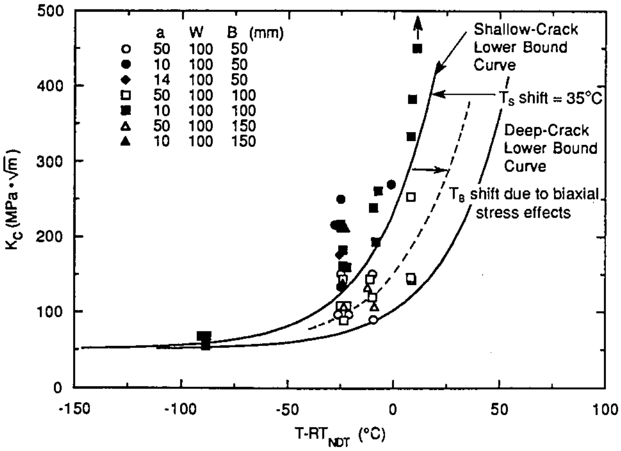

Fig. 1. Toughness (K_C) data vs normalized temperature for shallow- and deep-crack specimens with shallow- and deep-crack lower-bound curves.

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*Personal communication to W. E. Pennell, Oak Ridge National Laboratory, from M. Brumovsky, Skoda Works, Czechoslovakia, May 11, 1992.

that offsets the uniaxial "shallow-crack" effect by an undetermined amount. Clearly, the existence and magnitude of a temperature shift due to biaxial stress effects must be determined from data generated in the transition region of the fracture toughness curve.

3 A CRUCIFORM BEND SPECIMEN FOR BIAXIAL FRACTURE TOUGHNESS TESTING

A biaxial bend specimen (Fig. 2) designed for the testing program has a cruciform-shaped geometry with a cross section of dimensions 9.1 by 10.2 cm (3.6 by 4.0 in.) and a straight through-crack of uniform depth 1.02 cm (0.4 in.) in the test section (Bass et al. 1993). Three slots are machined in each loading arm to minimize diffusion of the load around the test section containing the through-crack. The crack is cut between two opposite central load diffusion control slots [see Fig. 2(b)]. The test section is fabricated from A533 grade B class 1 steel plate previously employed in the HSST shallow-crack testing program. The specimen is notched and precracked after the two longitudinal arms are electron-beam (EB) welded to the test section. Then the transverse arms are EB welded to the specimen. Instrumentation is placed on the specimen to monitor crack-mouth-opening displacement (CMOD), load vs load-line displacement, surface strain, and temperature at various locations. A special loading system (Theiss et al. 1993) has been constructed for applying biaxial or uniaxial bending loads to the arms of the specimen in a statically determinant manner.

Three-dimensional (3-D) elastic-plastic finite-element stress and fracture mechanics analyses have been performed on the cruciform specimen depicted in Fig. 2 to confirm the design and to investigate loading conditions. An important element in the design of the cruciform specimen concerns the optimal positioning of the center load diffusion slots to minimize peak K values at the ends of the crack. Results from 3-D finite-element analysis indicate that locating the center and outer load-diffusion control slots at different distances from the specimen midplane can be effective in controlling these peak K values. In Fig. 3(a), the edge of the center slot is positioned

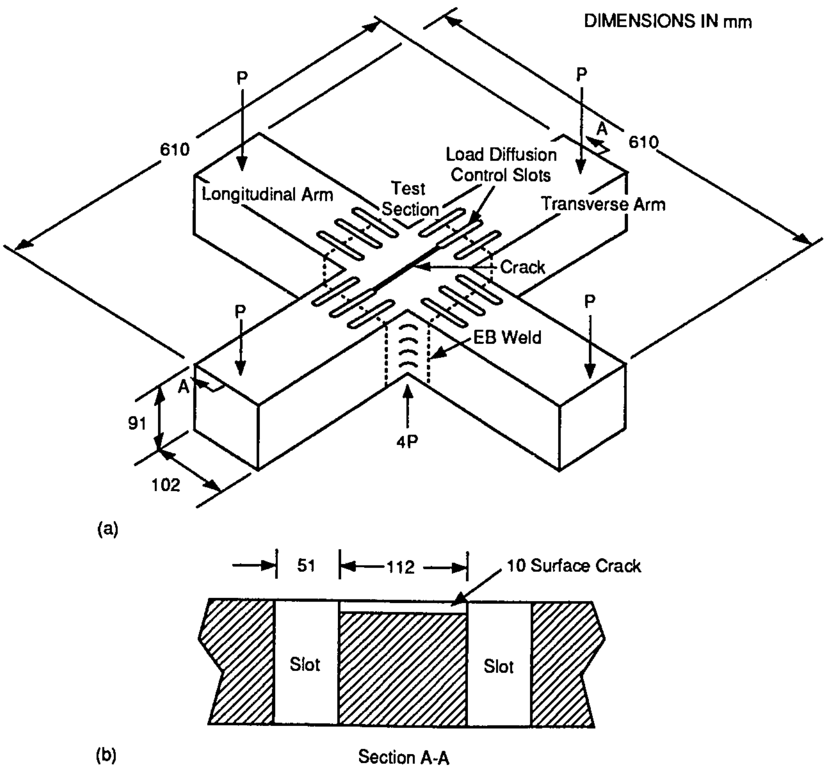
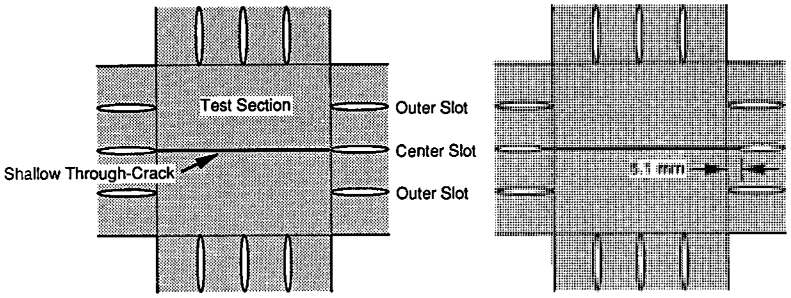


Fig. 2. Cruciform bend specimen used in HSST biaxial testing program: (a) dimensions of cruciform specimen and (b) details of crack plane.



(a) (b)

Fig. 3. Two slot configurations employed in analyses of cruciform bend specimen: (a) uniform slots on test section boundary and (b) center slot contracted away by 5.1 mm (0.2 in.) from test section boundary.

at the boundary of the specimen test section (Configuration A). Figure 3(b) shows a configuration (B) for which the center slot contracts away from the test section boundary a distance of 5.1 mm (0.2 in.).

Figure 4 depicts the applied $K_J = \sqrt{EJ/(1-\nu^2)}$ vs distance from the specimen centerline corresponding to applied longitudinal bending load of 1 MN for the two slot configurations A and B. Here, applied J-values are converted to K_J for comparison with existing shallow-crack beam data, even though nonplane strain conditions and substantial inelastic effects for higher loads are present in the cruciform specimen. The results in Fig. 4 indicate that K_J near the center slot is significantly elevated over the midplane value for slot configuration A. The slot configuration B effectively removes this elevation in K_J. These predictions of a reduction in K_J near the slot for configuration B are consistent with results for opening-mode stress contours (not shown). The differential slot configuration B leads to substantial reductions in the stress concentration near the edge of the slot when compared to the uniform slot configuration A.

Analyses of the specimen geometry incorporating the slot configuration B were performed for loading conditions corresponding to five biaxiality ratios, namely, 0.0, 0.25, 0.5, 0.75, and 1.0 to 1.0 (ratio of transverse to longitudinal arm loads). Results for the five load cases are depicted in

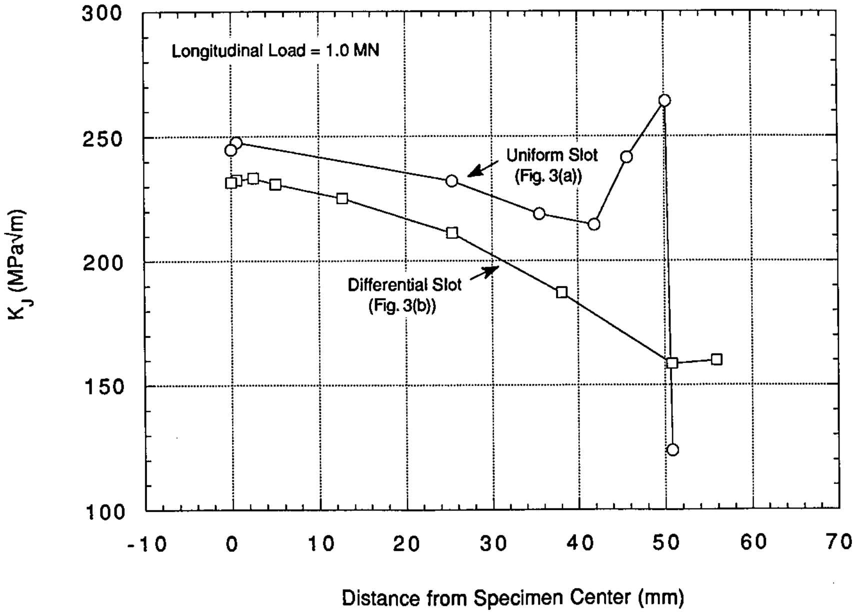


Fig. 4. Distribution of K_J vs distance along crack front for applied longitudinal arm load of 1 MN and biaxial loading ratio of 0.5:1 applied to HSST cruciform bend specimen using slot configurations in Fig. 3.

Fig. 5, where the applied load on the longitudinal arms is plotted vs applied K_J. Effects of the biaxial loading ratio on applied K_J values are not monotonic because K_J values for loading ratios of 0.5 and 1.0 fall, respectively, below and above the uniaxial K_J value for longitudinal arm loads >778.5 kN (175 kips). The variation of longitudinal arm load vs CMOD (not shown) was found to be consistent with the variation of load vs applied K_J depicted in Fig. 5. Of the load cases examined herein, results imply that significant biaxial loading effects are likely to be observed in the specimen for a loading ratio of 0.5 to 1.0, assuming that failure of the specimen occurs in the nonlinear response region depicted in Fig. 5.

Additional details concerning design, analysis, test plans, and results for the biaxial testing program are provided by Bass et al. (1993) and Theiss et al. (1993).

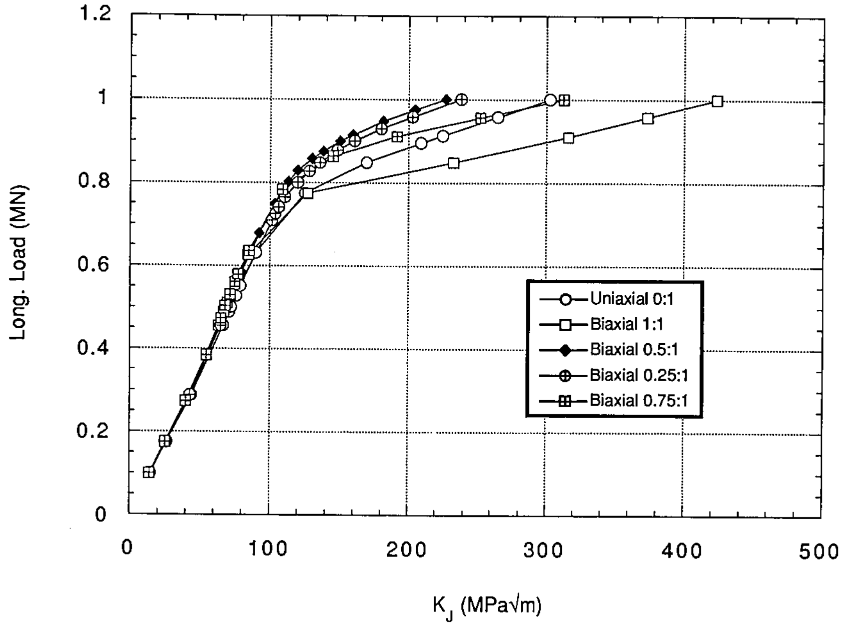


Fig. 5. Variation of longitudinal applied load vs applied K_J for five biaxial loading ratios applied to HSST cruciform bend specimen.

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