BIAXIAL TESTING OF NUCLEAR PRESSURE VESSEL STEEL USING SMALL SCALE CRUCIFORM SPECIMENS

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ABSTRACT

Biaxial loading exists in pressure vessel components in both U.S. Navy pressure vessels and in pressure vessels of commercial nuclear power plants. Failure of these vessels by material fracture processes has generally not taken into account the biaxial loading. The ductile-to-brittle transition is generally defined using uniaxially loaded bend specimens even though the conditions in the pressure vessel are often 1 to 1 biaxial loading conditions. The development of the Master Curve approach of ASTM E1921 has suggested that safety margins can be reduced because of the increased rigor that this method has brought to the definition of the ductile to brittle transition in ferritic steels. Reductions in the safety margins requires taking a further look at other aspects that might shift the master curve reference temperature, and one possibly important feature is the presence of biaxial loading. Work done on biaxially loaded, cruciform geometry bend specimens at Oak Ridge National Laboratory (ORNL) appeared to demonstrate a substantial increase in the Master Curve T_o reference temperature due to the presence of the biaxial stress field established in the cruciform test geometry. Because the ORNL specimens were very large (about 1 m by 1 m) and the test apparatus very complex, the cost of the ORNL tests was very high and only a few specimens could be run. For this reason full statistical support of the shift of the ductile-to-brittle transition due to the "biaxial effect" could not be demonstrated.

With this in mind a series of tests have been conducted on small-scale cruciform specimens of an A533B steel obtained from the decommissioned Shoreham nuclear power station. The overall objective of this work is to compare the results of these biaxial cruciform tests to the results of standard and shallow crack fracture toughness tests to assess the effect of biaxial loading on the measured master curve and the T_o reference temperature as defined by ASTM E1921. A second goal is to demonstrate that smaller size specimens, and hence lower cost tests, can be used to evaluate the magnitude of the biaxial effect in nuclear reactor pressure vessel materials and other ferritic steels. The basic results are that low cost procedures can be developed to obtain statistically significant data sets of 10 to 12 repeat tests using cruciform specimens with shallow cracks in 0.25x0.25 m cruciform specimens with 50x50 mm scale cross-sections. Present results for the A533B material investigated here demonstrates very little shift of the T_o reference temperature due to the biaxial loading in comparison with shallow crack, uniaxially loaded three point bend specimens.

INTRODUCTION

The Master Curve introduced by Wallin and coworkers[1-3] has become accepted for characterizing the fracture toughness transition of ferritic steels. ASTM standard, E1921, prescribes a methodology to measure the Master Curve index temperature T_o based on as few as six replicate fracture tests[4]. This procedure provides the potential for characterizing the entire ductile-to-brittle transition from tests on surveillance capsule Charpy size specimens, and for this reason has become very important to the commercial nuclear power industry. The small size of these specimens, and the relatively low constraint of the three point bend loading, has caused concern as to whether the resulting T_o is accurate for applications involving large cross-sections, shallow crack geometries, and biaxial loading. A series of large (102 x102 mm or 153 x 153 mm cross section by 0.91 m square span) cruciform specimens have been tested by Oak Ridge National Laboratory[5-6] (ORNL) that seem to demonstrate an effect of the biaxial loading on the Master Curve reference temperature, T_o. Specifically, T_o of shallow crack specimens increased in the presence of biaxial loading and the scatter in toughness was reduced. The biaxial loading effect offset part of the reduction in T_o normally attributed to a loss of constraint in shallow cracked specimens. Because of the complexity and the large cost of these tests, too few large cruciform specimens have been tested to give full statistical support to the concept of a "biaxial effect". In this program smaller specimens (203 x 203 mm bend span) have been utilized to dramatically reduce the cost of specimen preparation and testing so that the reference temperature can be obtained in the spirit of ASTM E1921. Basically 1T plan, 50.8 mm (2 inch) thick cross-sections were used for the cruciform geometry which was loaded in biaxial bending using a dual bend fixture. Most other features of the ORNL design have been retained including the stress control grooves and the shallow crack with a/W = 0.11.

DESCRIPTION OF THE EXPERIMENTS

The cruciform specimen geometry is shown in the left photograph in Figure 1. Specimens were machined from the center 100 mm of the 150 mm thick Shoreham plate with the crack in the L-S orientation. A initial plunge EDM notch was fatigue sharpened to a/W = 0.11 to 0.12. To test these specimens in biaxial loading a simple 5 point bend apparatus was constructed, shown in the right photograph of Figure 1. With two rollers removed, the fixture can be used for uniaxial loading of the test samples. Details of the test apparatus and specimen preparation are available in reference [7].

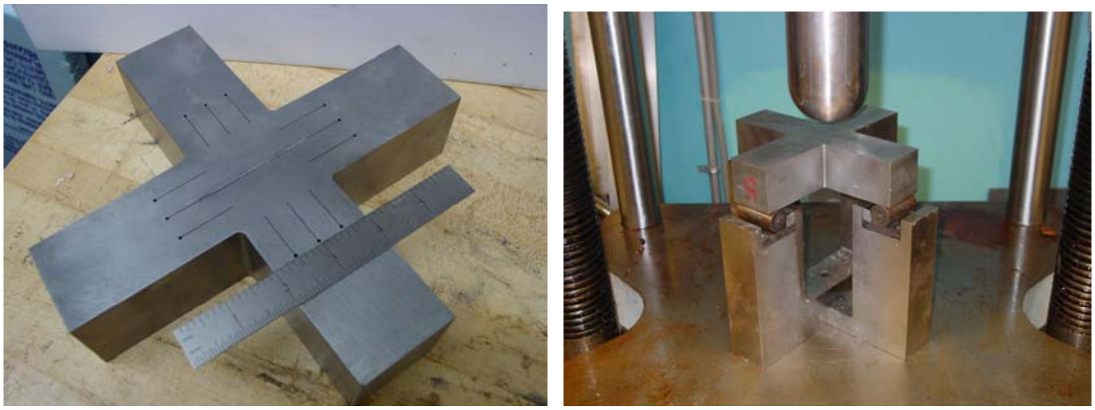

Figure 1 Cruciform specimen and bend apparatus shown without environmental chamber.

Fatigue precracking was done at ambient temperature using standard compliance procedures using 3 point bending with a "ring gage" installed on integral corners in the crack mouth to measure the crack mouth opening displacement. The ring gage measures the crack mouth opening displacement across the plunge EDM notch at the specimen surface without further modification of the specimen geometry. Specimens were tested at -100^{o}C, enclosed in a lab-built environmental chamber cooled by a liquid nitrogen spray system. Three or more self-adhesive thermocouples were mounted at various locations on the specimen and were used to measure the specimen temperature and control the specimen temperature.

ANALYSIS

The cruciform specimens were modeled using finite element analysis to predict the deformation behavior and the crack driving force as a function of applied loading[7]. One quarter-symmetric, three-dimensional models of the specimen were developed for several crack lengths with a stress-strain curve for the Shoreham A533B steel at –100°C estimated by interpolating between experimental stress strain curves obtained at –80°C and -120°C. The general purpose finite element code, ABAQUS, was used to perform all analyses. A full elastic-plastic analysis of the biaxial specimen with contact conditions at the load point was used to determine the crack driving force, K_J, as a function of crack mouth opening displacement, and to predict the evolution of plasticity in the specimen. The variation of driving force along the crack front, J(z)/J(z=0), is plotted in Figure 2. The crack driving force is very uniform over the center 75% of the crack front. As the slot is approached, the driving force increases by up to 20% (in terms of J, or about 10% in terms of K_J) and then falls off dramatically. This is due in part to shielding of the slot-crack region by the adjacent slots in the transverse arm. There is considerable plasticity at the adjacent slots that may be redistributing the stresses away from the crack tip and leading to a concentration where the shielding breaks down. Despite the variation in J along the crack front, the fatigue precracks remained remarkably straight, as shown in Figure 3, with only a slight indication of accelerated crack growth near the root of the stress control slot.

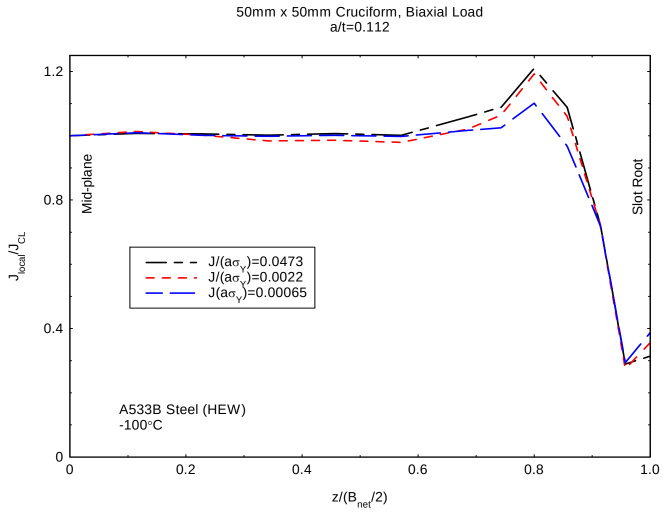

Figure 2 J-integral driving force distribution through the cruciform specimen thickness.

EXPERIMENTAL TESTING

Considerable ductile-to-brittle transition data is available on the Shoreham vessel material. Work by Tregoning and Joyce[9-10] has shown that this material has a high upper shelf toughness and has very uniform fracture toughness and tensile properties. The Master Curve reference temperature depends quite dramatically on specimen geometry [8], being approximately -77°C for the C(T) geometry, -92°C for the deep crack bend (SE(B)) geometry, and -118°C for the shallow crack SE(B) geometry with a/W = 0.1 to 0.15. The results for the deep crack SE(B) specimen were verified by the thesis work of Rathbun[11] for a wide range of B, W, and b specimen dimensions. The objective here is to test near the expected T_o temperature, so it was decided to use a test temperature of -100°C for this series of cruciform specimens. Several sets of deep crack and shallow crack specimens have been tested at similar temperatures, including 1T SE(B), 1/2T SE(B), and 1/2T SE(B) with a square cross section. Data was acquired and calibrated using VisualBASIC software, presented graphically on the monitor and stored on the PC hard drive. High-energy fractures caused nearly full separation of the specimen, while low energy fractures resulted in no observable cracking, being identified only by a sudden load drop during the test. Most specimens were given a heat tint and then immersed in liquid nitrogen prior to being broken open to expose the crack surface. The critical J integral at onset of cleavage was estimated by using the centerline finite element analysis. A spreadsheet was then used to evaluate the critical J_c at onset of unstable fracture for each specimen at the critical CMOD at onset of cleavage. Individual specimen results are presented in [7].

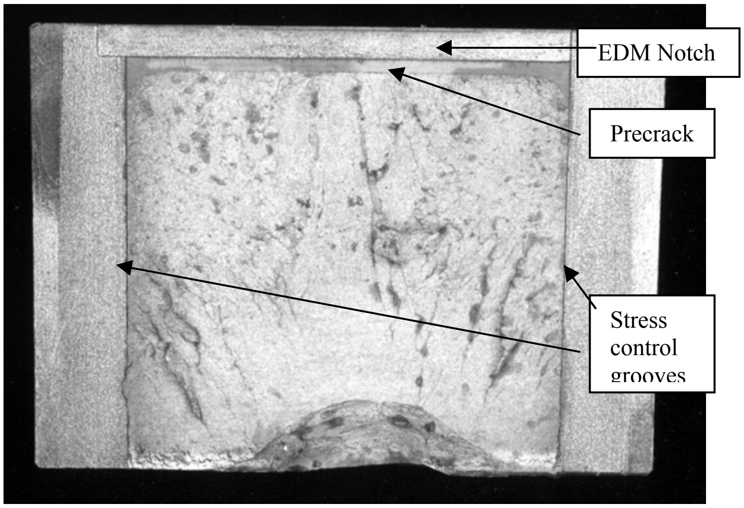

Figure 3 Fracture surface form a typical cruciform specimen test.

DISCUSSION

The results of the cruciform tests are compared with other data sets obtained from the Shoreham plant material in Figure 4 and presented in Tables 1 and 2. The Master Curve and confidence bounds plotted on Figure 4 correspond to the deep crack 1T SE(B) data presented with the open circle data points on the figure. While the standard deep crack data sets generally correspond well with these confidence bounds, shallow crack data generally has a larger variability as shown in Figure 4 and are concentrated above the confidence zone described by the deep cracked SE(B) test results. The cruciform data set demonstrates the same pattern as the shallow crack data sets with a larger scatter and an elevation of the measured toughness in comparison with the deep crack data sets, resulting in a much lower T_o reference temperature. Tables 1 and 2 summarize 15 deep crack SE(B) data sets and 6 shallow crack data sets, and include the results of the biaxial cruciform data sets obtained in this project. $M_{Avg} = Eb_o\sigma_{ys}/K_{JcAvg}^2$ is included in this table as a measure of data set constraint. For shallow crack data sets M_{Avg} calculated based on crack depth is also included.

The cruciform combined data set with a T_o = -118°C corresponds closely to the shallow crack data sets with an average T_o = -117°C in contrast with the deep crack data sets with an average T_o = -91.1°C. The T_o obtained from the larger 1T SE(B) specimens demonstrate an even larger difference with an average T_o = -86°C. Only a small biaxial effect of approximately 1°C is measured with the combined data set, with the result of the biaxial tests being essentially identical to the average result of the shallow crack uniaxial specimen data sets.

CONCLUSIONS

Cruciform specimens can be machined, precracked, and tested to develop shallow crack, biaxial loading E1921 T_o reference temperature data at a reasonable cost, at least if specimens with a 50x50 mm cross section are acceptable. Straight precracks of a repeatable size were readily obtained using a plunge EDM starter notch sharpened using uniaxial three point bending fatigue. The resulting T_o reference temperature does not show the presence of a “bi-axial” effect. The measured T_o is essentially identical to the average result obtained using shallow notch SE(B) tests loaded using uniaxial three point bending. The scatter in cleavage initiation toughness observed from the cruciform data set is also consistent with what is generally observed from shallow notch ductile to brittle transition data sets.

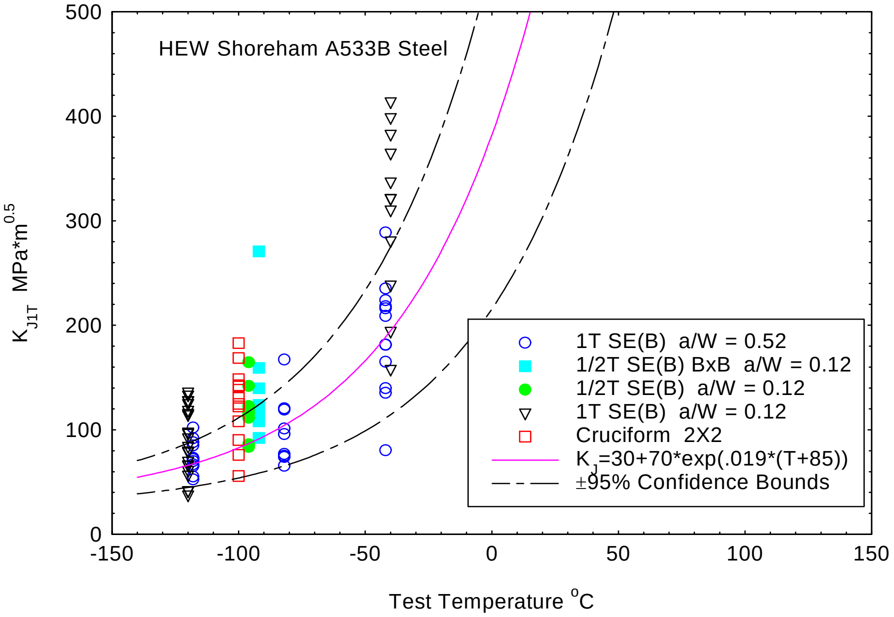

Figure 4 Comparison of cruciform specimen results and standard fracture specimen results.

Table 1 Summary of Shoreham T_o measurements – deep crack.

Specimen Configuration	**Test Temp. °C**	**T_o °C**	**N**	**r**	**a/W**	**M_{Avg}**
1T	-12	-80.2	7	4	0.53	31
1T	-27	-84.2	7	7	0.53	46
1T	-42	-86.5	12	12	0.53	100
1T	-82	-87.7	9	9	0.51	368
1T	-118	-94.1	12	12	0.50	592
1/2T	-40	-97.5	8	2	0.53	21
1/2T	-50	-94.	6	3	0.53	46
1/2T	-60	-82.2	6	6	0.53	58
1/2T	-116	-87.1	8	8	0.55	303
1/2T	-81	-94.1	8	6	0.74	50
1/2T	-115	-98.5	7	7	0.76	101
1/2T	-79	-101.1	8	7	0.51	116
1/2T BxB	-118	-93.8	8	8	0.51	413
1/2T BxB	-76	-93.6	8	8	0.51	99
1/2T BxB	-50	-90.5	12	9	0.54	56
Average		**-91.1**[A]				

[A] Average taken of data with r > 5 only.

Table 2 Summary of Shoreham T_o measurements – shallow crack.

Specimen Configuration	**Test Temp. ^{o}C**	**T_o ^{o}C**	**N**	**a/W**	**M_{Avg} (b)**	**M_{Avg} (a)**
1T	-120	-117.9	23	0.15	1001	179
1T	-40	-112.4	12	0.12	77	10
1/2T	-115	-127.7	15	0.12	323	42
1/2T	-96	-108.5	8	0.12	83	24
1/2T BxB	-120	-109.3	8	0.12	650	92
1/2T BxB	-92	-126.0	8	0.12	165	23
Average		-117.0				
Cruciform	**-100**	**-118.**	**12**	**0.11**	**516**	**192**

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