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Fracture Toughness Test with Modified 1X-WOL Specimens in The Ductile-to-Brittle Transition Region

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1. Introduction

The nuclear reactor surveillance program of Kori-1 contains 1X-WOL (wedge opening loading) type fracture mechanics specimens. The 1X-WOL specimen was developed at Westinghouse Research Laboratories [1] during the late 1960s and many of 1X-WOL specimens were included in surveillance capsules by the early 1970s. The 1X-WOL specimen was originally designed to obtain the linear elastic K_{IC} values on highly embrittled materials. In the ductile-to-brittle transition (DBT) region, the material can behave with either low or high toughness so that some tests will result in elastic-plastic deformation with a small amount of stable crack growth. The 1X-WOL specimens have another possible restriction that the plastic deformation can be occurred in the long loading arms caused by lower strength in the arms rather than in the uncracked ligament ahead of the crack tip.

In this work, the original 1X-WOL specimens were modified in geometry to avoid the possible plastic deformation in the loading arms. After then, the modified 1X-WOL specimens were tested in the transition region by the ASTM E 1921-05 [2] which is a standard test method to measure the fracture toughness in DBT region. The K_{Jc} values taken from the modified 1X-WOL specimens were compared with the results from standard 1T-CT specimens.

2. Experimental Procedure

The material used in this work was SA508-Gr.3 taken from actual scale reactor pressure vessel forging thicker than 200mm. The 1T-CT specimens and the 1X-WOL specimens were sampled from the 1/4T location of the forging block. The specimen orientation was T-L direction as described in ASTM E 399-87 [3].

The original 1X-WOL specimen is shown in Fig. 1. This specimen has a higher bending stress in the loading arms than in the uncracked ligament of the specimen. To weaken the remaining ligament strength, the width of the original 1X-WOL specimen was reduced by machining some material from the back side of the specimen from 28.575mm to 24.13mm and side grooves of 20% were machined as shown in Fig. 2.

Because free specimen rotation is restricted by the rigid loading stud used as the bottom attachment in the 1X-WOL specimen, an adapter stud was introduced to allow the rotation of the specimen, as shown in Fig. 3.

Specimen preparation including fatigue pre-cracking and test procedure to measure the fracture toughness in transition temperature were followed in accordance with ASTM E 1921-05 [2] standard procedure. The load-line displacement rate in the test was 0.15min/min. Eight specimens were tested at eight different temperatures.

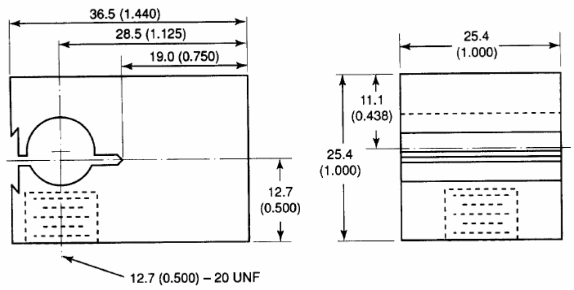

Figure 1. Standard 1X-WOL specimen. (All dimensions in millimeters. Number in parenthesis indicates dimensions in inches.)

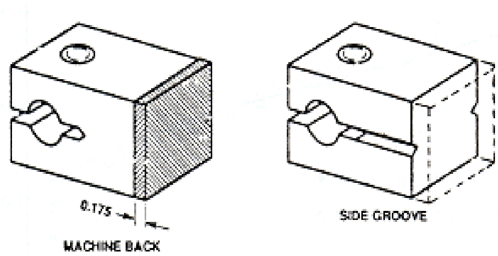

Figure 2. WOL specimen modification.

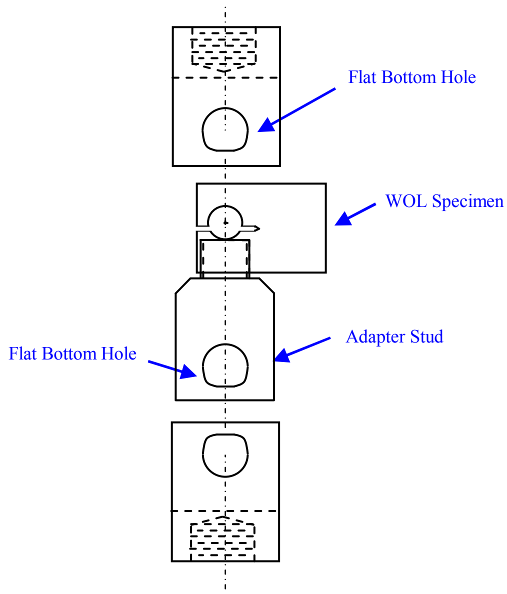

Figure 3. Fixtures for gripping the modified 1X-WOL specimen.

3. Experimental Results and Discussion

Equations in ASTM E 1921-05 [2] were used to calculate the fracture toughness Master Curve and reference temperature, T_0. Fracture toughness K_{Jc} is calculated from the J-integral at onset of cleavage fracture as the sum of elastic and plastic components:

$$K_{Jc} = \sqrt{J_c E/(1-\nu^2)} \quad (1)$$

$$J_c = J_{elastic} + J_{plastic} \quad (2)$$

where $J_{plastic} = \eta A_{pl}/(B_N b_0)$ and E is Young's modulus, ν is Poisson's ratio, $\eta = 2 + 0.522 b_0/W$, b_0 is the initial uncracked ligament, A_{pl} is the plastic area under the load-displacement curve, B_N is the net thickness. $J_{elastic}$ is calculated from the elastic K expression. Due to the reduction of specimen width the elastic K expression should be changed for the modified specimen geometry. Three different K expressions were considered for the modified 1X-WOL specimen geometry in this work.

ASTM E 1921-05 [2]:

$$K = (2+\alpha)(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)P/(B\sqrt{W}(1-\alpha)^{3/2}) \quad (3)$$

BAW-2086, Rev. 1 [4]:

$$K = (99.966 - 757.69\alpha + 2363.2\alpha^2 - 3227.5\alpha^3 + 1681.1\alpha^4)P\sqrt{a}P/(BW) \quad (4)$$

Wilson [5]:

$$K = (30.96 - 195.8\alpha + 730.6\alpha^2 - 1186.3\alpha^3 + 754.6\alpha^4)P/(B\sqrt{a}) \quad (5)$$

The experimental results evaluated with three different equations are listed in Table 2. The T_0 values from 1X-WOL specimens are -60.4 ~ -63℃. T_0 for 1T-CT specimens was -62.7℃. The T_0 values calculated from the three different K expressions were with ±2℃. Fig. 4 shows K_{Jc} data comparing to the 1T-CT results. A solid line represents the median K_{Jc} master curve for 1T-CT specimens and dotted lines show the 5% and 95% K_{Jc} master curves for 1T-CT specimens. It is shown that K_{Jc} values of the modified 1X-WOL specimen are well placed between the 5% and 95% limit curves of the 1T-CT master curve.

4. Conclusion

The modified 1X-WOL specimens were tested to measure the K_{Jc} and T_0 values in DBT region. All the test results calculated from the three different K expressions were in good agreement with the results from 1T-CT. From these facts we can conclude that the 1X-WOL type specimens were very useful for the master curve fracture toughness tests after the specimen dimensions and the loading jig alignment were modified to prevent arm bending and non-symmetric strain field in front of the crack tip.

Table 1. Comparison of K_{Jc} (MPa√ m) and T_0 (℃) for three different elastic K equations

Specimen	Temp. (℃)	ASTM	BAW	Wilson
GS8801	-60	135.0	134.0	137.9
GS8802	-50	122.2	121.2	125.1
GS8803	-40	152.0	150.9	154.1
GS8804	-70	99.4	98.3	103.0
GS8805	-80	87.4	86.2	90.8
GS8806	-90	62.8	61.9	65.5
GS8807	-100	39.4	38.7	41.3
GS8808	-30	125.0	123.7	127.3
GS8809	-196	33.7	33.2	35.2
T_0 (℃)		-61.1	-60.4	-63.0

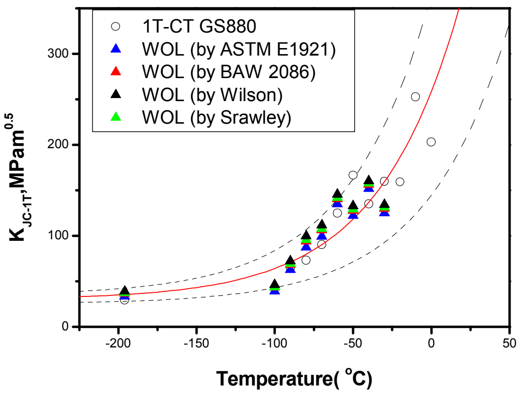

Figure 4. K_{Jc} values calculated from three different equations and 1T-CT master curves.

Acknowledgement

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