FRACTURE TOUGHNESS EVALUATION OF PRESSURE VESSEL STEEL BY SMALL THREE-POINT-BEND SPECIMENS

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ABSTRACT

J_c fracture toughness tests by three point bending were conducted using several pre-cracked CVN specimens made from HAZ of pressure vessel steel materials. The test temperatures ranged from ambient temperature to 290°C, and the deformation speed was 0.25 mm/min. The test procedure adopted was based mainly on the multi-specimen standard practice for J_{IC} testing recommended by ASTM E813:81, even though it was recognised that the requirements of specimen size would hardly be met, especially for unirradiated materials. This paper discusses the results and suggests a suitable equation for the blunting line in the R-curve method and the procedure for determination of J_{IC} for irradiated specimens using such small specimens.

KEYWORDS

J_c fracture toughness evaluation; CVN specimens; pressure vessel steel; three point bend; blunting line; irradiated specimens.

INTRODUCTION

From the view point of the quantitative evaluation on the structural integrity of nuclear pressure vessels, it is important to collect the fracture toughness data of reactor pressure vessel steels. However, the current fracture toughness test based on linear elastic fracture machanics requires quite large and expensive specimens with added limitations of irradiation facility in some existing reactors. The present work has been carried out to establish a suitable procedure for the determination of J_c values using pre-cracked CVN specimens by three point bending which could be either irradiated inside the reactor loop with ease, or are readily available from existing reactor pressure vessel surveillance programmes and need to be pre-cracked before testing.

MATERIALS AND EXPERIMENTAL PROCEDURES

Weldments in A 533B Cl 1, A 508B Cl 3 and equivalent A 533B Cl 2 steels were used in all the tests. Table 1 gives the yield strength and the ultimate tensile strength of these weldments as determined from the load-load point displacement plot of specimens prepared from them.

Table 1 Tensile Properties Estimated for Weldments in A 533B Cl 1 (5XX), A 508B Cl 3 (6XX) and eqv. A 533B Cl 2 (7XX)

Origin	Temp. (°C)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
5 XX	20	578	638
	150	524	589
	290	503	597
6 XX	20	592	642
	150	540	603
	290	521	609
7 XX	20	564	640
	150	544	570
	290	512	566

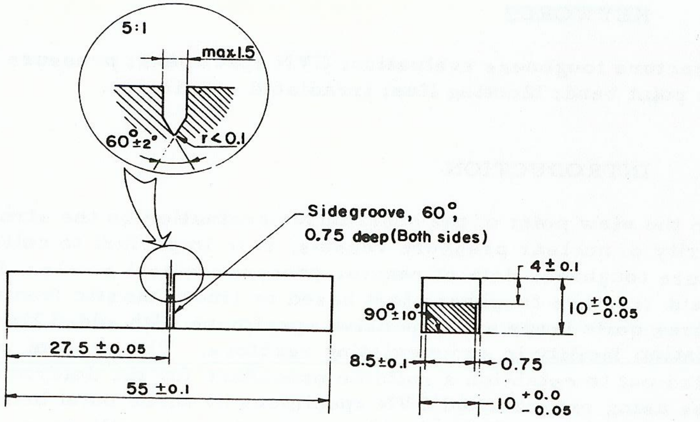

Fig. 1 Fatigue pre-cracked CVN specimen of minimum 1.5 mm precrack.

These specimens were cut from the weldment blocks at locations 1/4 T and 3/4 T parallel to the rolling direction. Fatigue pre-cracking was conducted at room temperature and in general 150, 000 cycles were required for about 2 mm of crack extension, and subsequently 15% side groove were machined out. Figure 1 shows the details of the specimen dimensions.

Fracture toughness tests on these specimens were carried out in a small screw driven testing machine designed and evaluated at RISΦ. It was instrumented with a 50 KN load cell and a dual LVDT system of ± 5 mm travel. The machine was equipped with a furnace for tests upto 300°C and has been remotised for hot cell use. Load-load point displacement plots were obtained using this set up.

The test procedure for the determination of fracture toughness, J, and final crack extension, Δa was the same as recommended in ASTM E 813:81, except with the modification that maximum ductile tearing obtained in any of the specimens tested was nominally below 0. 3 mm, or, typically below 7% of the remaining ligament length, and only data points lying between the blunting line and a 0. 3 mm parallel off-set line were used to obtain the regression line equation. Blunting lines were established on J(Δa) plots by introducing:

$$J = S.\sigma_o.\Delta a$$

Where S was the slope factor, and σ_o the stress defined as the average of yield strength and ultimate tensile strength.

Critical value of toughness, J_c, was determined as the value of J at the intersection of the regression line and the blunting line as determined above.

Tearing modulus T was determined on the basis of the slope dJ/da of the regression line as:

$$T = (E/\sigma_o^2).(dJ/da)$$

Where E was the youngs modulus.

RESULTS

A total of 66 unirradiated specimens were tested. All specimens originated from weldment blocks in A533B Cl 1 (designated as 5XX), A508B C13 (6XX) and eqv. A 533B C12 (7XX) and were used to obtain J_R curves at ambient temperature, 150°C and 290°C for these weldments. Each curve was designated by a two digit number (RXX). The coefficients of the regression line given in Table 2 were determined by using all available (J, Δa) data on the same material at the same test temperature.

Figure 2 shows the regression lines and the corresponding blunting lines used for J_c determination of specimens from one of the weldment blocks (5XX), tested at different temperature.

TABLE 2 Coefficients of Regression Line $J = M.\Delta a+N$, including R^2, for all J_R -Curves obtained for the Materials and Test Temperatures

Origin	Temp. (°C)	R-Curve No.	No. of specimens used	M	N	R^2
5 XX	20	R 01 - R 04	14	677	79	.94
	150	R 07 - R 08	5	790	36	.99
	290	R 13 - R 14	6	582	60	.96
6 XX	20	R 21 - R 24	12	785	76	.90
	150	R 27 - R 28	6	535	95	.91
	290	R 33 - R 34	6	603	51	.97
7 XX	20	R 41 - R 42	8	764	78	.85
	150	R 43 - R 44	6	451	67	.98
	290	R 45 - R 46	6	356	52	.99

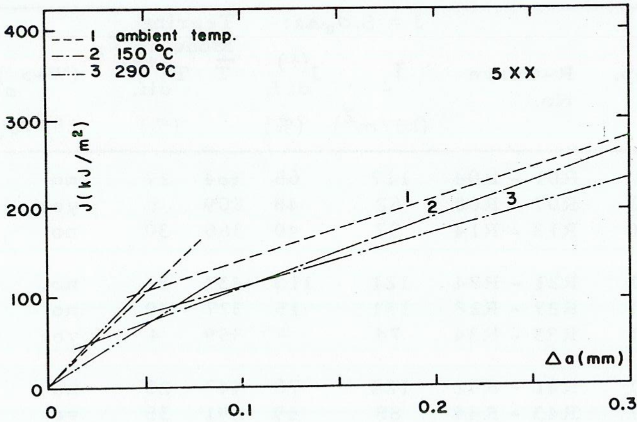

Fig. 2 J_c determined from regression line and blunting line.

EVALUATION OF TEST DATA

It has been demonstrated that ASTM E813:81 recommendations with blunting line slope factor S = 2 yields a value of J_c corresponding to the value of J at a crack extension of 0.5 mm, for a standard bend specimen (WxB = 40x20 mm^2), of a typical low alloy steel (Garwood, 1979). Consequently this blunting line hardly indicates the real crack extension due to blunting (the stretching of the crack tip). In previous studies of CVN sized specimens, slope factors S = 4 and S = 3.7 has been determined (Neale, 1982; Kodaire, 1979).

In table 3 values of $\bar{J}_c$ determined are presented as obtained by intersection of J_R curves with blunting lines using these three slope factors. $\bar{J}_c$, the average value, is evaluated by using the regression line as determined in Table 2.

TABLE 3 Comparison of J_c as determined using Various Blunting Lines (Neale, 1982; Kodaire, 1979; ASTM E813) and Regression Lines Established in Table 2

Origin	Temp. (°C)	R-Curve No.	$J = 2\sigma_0 \cdot \Delta a.$		$J = 4\sigma_0 . \Delta a$		$J = 3.7\ \sigma_Y \cdot \Delta a.$	
			$\bar{J}_c$ (kJ/m^2)	$J_{dif}^{(+)}$ (%)	$\bar{J}_c$ (kJ/m^2)	$J_{dif}^{(+)}$ (%)	$\bar{J}_c$ (kJ/m^2)	$J_{dif}^{(+)}$ (%)
5 XX	20	R01 - R04	178	55	109	67	116	66
	150	R07 - R08	124	48	56	46	61	48
	290	R13 - R14	127	20	82	49	87	59
6 XX	20	R21 - R24	209	44	111	121	118	116
	150	R27 - R28	178	8	124	17	130	15
	290	R33 - R34	109	2	70	4	74	4
7 XX	20	R41 - R42	213	91	114	73	123	76
	150	R43 - R44	113	39	84	50	86	49
	290	R45 - R46	78	10	62	11	64	11

(+): $J_{dif.} = (J_{max.} - J_{min.})/\bar{J}_c$.

It is readily noted that ASTM E813:81 based slope factor S = 2 generally yields much larger values of J compared to the values generated by the more steep lines. The former values often exceed the latter two values by 100% whereas the latter two estimates are usually in good agreement. It should also be recognised, however, that the scatter in J_c values as obtained by more steep blunting lines most often far exceed the scatter of ASTM E813:81 based J_c data, Table 3.

As a consequence of the descrepencies demonstrated above, an original blunting line was searched for by measuring the size Δa_b of the stretch zone on the fractured surface of several of the specimens tested. Presuming that the stretch zone represents the ultimate amount of blunting prior to initiation of ductile tearing, values of $\bar{J}_c$ are calculated from the respective regression equations, Table 2. Subsequently, values $\bar{J}_c(\Delta a_b)$ were used for obtaining the slope factors by:

$$S = \bar{J}_c(\Delta a_b) / \sigma_0 . \Delta a_b .$$

The results are presented in Table 4.

TABLE 4 Establishment of Blunting Line $J = S.\sigma_0 . \Delta a_b$ on the Basis of Stretch Zone Measurement

Temp. (°C)	Ori-gin	R-Curve No.	Δa_b (mm. 10^2)	$\bar{J}_c(\Delta a_b)$ (kJ/m^2)	σ_0 (MPa)	S	$\bar{S}$	$\bar{\bar{S}}$
+20	5XX	R01 - R04	60	120	608	3.29	3.31	3.40
	6XX	R21 - R24	60	123	617	3.32		
	7XX	R41 - R42	-	-	-	-		
+150	5XX	R07 - R08	60	83	557	2.48	3.52	
	6XX	R27 - R28	50	122	572	4.27		
	7XX	R43 - R44	40	85	557	3.82		
+290	5XX	R13 - R14	50	89	550	3.24	3.34	
	6XX	R33 - R34	50	81	565	2.87		
	7XX	R45 - R46	30	63	539	3.90		

From Table 4 it is seen that S has a mean value of 3.40. Comparisons of the results in Table 3 and Table 5 readily qualify the blunting line slope factor S = 3.40 finally employed for determination of J_c.

TABLE 5 Comparison of $\bar{J}_c$ as determined from Measurement of Stretch Zone, Table 4, and from the Blunting Line Established in Table 6

Ori-gin	Temp. (°C)	R-Curve No.	Comparison of $\bar{J}_c$ Est. from (kJ/m^2): Δa_b (+)	blunting line (++)	deviation (%)
5XX	20	R01 - R04	120	117	+3
	150	R07 - R08	83	62	+25
	290	R13 - R14	89	87	+2
6XX	20	R21 - R24	123	121	+2
	150	R27 - R28	122	131	-7
	290	R33 - R34	81	74	+9
7XX	20	R41 - R42	-	-	-
	150	R43 - R44	85	88	-4
	290	R45 - R46	63	65	-3

(+) : $\bar{J}_c$ estimated from measured maximum values of stretch zone, Table 4.

(++) : $\bar{J}_c$ estimated from blunting lines, Table 6.

SIZE REQUIREMENT

As seen in Table 6, ASTM E813:81 size requirement criterion of $(W-a_o) \geqslant 25 \bar{J}_c / \sigma_0$ and $\sigma_Y > d\bar{J}/da$ could be hardly met. Typically $(W-a_o)$ value fall short of $25 J_c / \sigma_0$ values by 20% in worst cases. $\bar{T}$, the average tearing modulus, is evaluated by using the regression line as determined in Table 2.

TABLE 6 $\bar{J}_c$ and $\bar{T}$ determined from J_R -Curve with Slope S, as derived in Table 4

Ori-gin	Temp. (°C)	R-Curve No.	$J = S.\sigma_0.\Delta a$: $\bar{J}_c$ (kJ/m^2)	$J^{(+)}_{dif.}$ (%)	Tearing Modulus T: $\bar{T}$	$T^{(++)}_{dif.}$ (%)	$(W-a_o) \geqslant 25\bar{J}/\sigma_0$?	$\sigma_Y > d\bar{J}/da$?
5XX	20	R01 - R04	117	65	384	27	no	no
	150	R07 - R08	62	48	509	1	yes	no
	290	R13 - R14	87	40	366	30	no	no
6XX	20	R21 - R24	121	113	433	81	no	no
	150	R27 - R28	131	15	327	40	no	no
	290	R33 - R34	74	4	359	4	yes	no
7XX	20	R41 - R42	124	76	443	23	no	no
	150	R43 - R44	88	49	291	35	yes	yes
	290	R45 - R46	65	11	233	3	yes	yes

(+) : $J_{dif.} = (J_{max.} - J_{min.}) / \bar{J}_c$ (++) : $T_{dif.} = (T_{max.} - T_{min.}) / \bar{T}$

However, for small specimens not meeting this size requirement, dJ/da values have been found to be high, but valid J_{IC} value could be determined, (Huang, 1981). Moreover, keeping in mind that CVN sized specimens are finally to be used for irradiated materials only, the decreased values of $25 J_c / \sigma_0$ due to irradiation are very likely to be more than $(W-a_o)$ values, thus qualifying CVN specimens for valid J_{IC} determination.

CONCLUSIONS

For irradiated materials, with a suitably established blunting line slope factor, valid J_{IC} values would probably be obtained by using CVN sized specimens, and a modified ASTM E813:81 multispecimen method.

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