Evaluation of J-R Curve Test Methods on Materials for Reactor Pressure Vessels

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1. INTRODUCTION

The structural integrity assessment of nuclear reactors pressure vessels, primary pipe line and associated systems might be evaluated according to elastic-plastic fracture mechanics methodology. This practice is possible, particularly in upper shelf region, taking into account the elevated fracture toughness values of modern reactor pressure vessels, which remain high enough under neutron irradiation conditions.

The elastic-plastic evaluation methods are based on the J integral and tearing modulus procedures. In this calculation an essential element is the materials crack growth fracture resistance curve (J-R curve).

The single specimen unloading compliance technique is the most used method for determining J-R curve. This paper evaluates the standardized single specimen methodology which is compared with a direct method from load-displacement plots to obtain J-R curve. Compliance relationship to calculate crack growth and correction expressions on three point bend specimen (3P-SENB) are analized.

As regards satisfying capsules specimen size limitation for reactor surveillance programs, small specimens validity to measure fracture toughness properties are investigated.

2. MATERIAL AND METHOD

2.1 Test method

Fracture toughness tests on four pressure vessels steels were run; their chemical composition and mechanical properties are shown in Table 1. Three point bend specimens with nominal thickness B = 12,7 mm and 6,25 mm and size groove 20 % were used.

The J-R curve test procedure was performed according to the ASTM requirements (ASTM E-1152-87 and ASTM E-813-87).

2.2 Compliance technique and direct method to estimate stable crack growth

Unloading compliance method was used and two compliance relationships being applied. One of them (Wu 1984) is recommended by ASTM J-R curve standard test method and the other is given in WI J-R test procedure (Gordon, 1985).

Rotational correction expresion (Perez Ipiña and Santarelli, 1989) on measured compliance was applied.

A direct method to obtain J-R curves from load-load displacement records has been used. It was carried out by means of a developed computational program based on relationships given in elastic-plastic handbook (Kumar et al, 1981).

3. RESULTS

The measured and estimated crack growths from compliance expressions suggested by ASTM and WI, are compared in Tables 3 and 4. The J- Δa values with and without rotation correction are shown in Figure 1.

Several definitions applied to determine the values of J at initiation of crack growth on J-R curve are presented in Table 5.

However, in materials B and D the stretch zone width (SZW), employed scanning electron microscope, was measured. The SZW data has been applied to calculate an initiation J value called Ji which is also compared against conventional values in Table 5.

The influence of specimen thickness on J initiation parameters is evaluated in Figure 2.

J-R curves estimated from direct method are ilustrated in Figure 3.

4. DISCUSION AND CONCLUSIONS

The estimated crack lengths, that were calculated applying WI recommended compliance relationship, show an error around a maximum allowed value (4%) compared with measured ones but it is higher than error using ASTM suggested compliance expresion. The error on estimated stable crack growth, Δa, is lower than maximum allowed value corresponding to both procedures. These evaluations are shown in Tables 3 and 4.

An important influence takes place on determination of J-R curve when rotational correction upon calculated compliance is used, as may be observed in Figure 1. The methodologies that were applied in this paper do not take into consideration rotational correction for bend specimens. In order to account several uncertainties in testing only an effective modulus (Em) is established by ASTM. It is useful to adjust the original crack length reducing the difference between measured physical initial crack size and predicted one.

From comparative analysis between initiation values, Table 5 and Figure 2, defined according with ASTM blunting line criterion and using offset lines at 0,15 mm and 0,2 mm of crack growth applied to several geometries, it is feasible to show that J initiation values correspond to points located close or after maximum load on load-load displacement record, where crack extension is observed.

Therefore, these values should not be considered like ductil crack growth initiation.

In material D a fracture toughness initiation value, called Ji, was calculated as the J value from power law regression equation at crack extension equal to scanning measured SZW. Furthermore Ji was also obtained as the J value where the power law fit crossed the blunting line defined by SZW theorical expression (Kobayashi et al, 1983; Kiyotsugui et al, 1983; Heerens et al, 1988).

Both Ji values verify a good agreement, Figure 2.

The difference between J- initiation values at SZW for large specimens and small ones is lower than the other values calcualted according to ASTM blunting line. Consequently, small specimens might be reliable to apply, i.e. for surveillance program, whether SZW blunting line is used.

Finally, the J-R curves estimated from direct method show an acceptable agreement with unloading compliance methodology, Figure 3.

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Table 1. Chemical composition (%)

Material	C	S	Si	Mo	Cu	Cr	Mn	P	Ni
A	0,160	0,001	0,12	0,6	0,01	0,1	1,37	0,012	0,6
B	0,175	0,001	0,17	0,5	0,18	0,1	1,33	0,019	0,6
C	0,168	0,001	0,18	0,5	0,01	0,1	1,33	0,012	0,7
D	0,180	0,005	0,25	0,5	0,04	0,1	1.33	0,007	0,7

A = A533 Gr. B Cl. 1 (hot rolled)

B = A533 Gr. B Cl. 1 (hot rolled)

C = A533 Gr. B Cl. 1 (forging)

D = A508 Cl 3 (forging)

Table 2. Mechanical properties at room temperature.

Material	Rp 0.2 [MPa]	Rm [MPa]	A_5 (%)	Z (%)	$\sigma_y = \frac{Rp\ 0.2 + Rm}{2}$ [MPa]
A	476	601	25,2	73,8	538,5
B	565	677	26,6	73,8	621,0
C	473	627	29,1	72,0	550,0
D	440	580	26,4	71,0	510,0

Table 3. Estimated and measured crack growth, using suggested ASTM expression.

Specimen N°	Initial crack length (mm)		aom-ao (mm)	Error (%)	Final crack length (mm)		afm-ao (mm)	Error (%)	Crack growth Δa		Δam- Δap (mm)	Error (%)
	aom measured	ao estimated			afm measured	af estimated			Δam measured	Δp estimated		
A-1	15,30	15,54	-0,24	-1,57	17,58	17,57	0,01	0,66	2,27	2,03	0,24	10,5
A-2	15,60	15,81	-0,21	-1,34	17,58	18,06	-0,08	-0,44	2,37	2,25	0,12	5,0
B-1	15,86	16,15	-0,29	-1,83								
B-2	15,79	16,22	-0,43	-2,72								
C-1	15,02	15,55	-0,53	-3,52	16,28	16,71	-0,43	-2,64	1,25	1,16	0,09	7,2
C-2	15,61	15,92	-0,31	-2,0	17,59	17,86	-0,27	-1,53	1,98	1,94	0,04	-2,0

Specimen thickness = 12,7 mm Side groove 20 %

Table 4. Estimated and measured crack growth, using suggested WI expression

Specimen N°	Initial crack length (mm)		aom- ao (mm)	Error (%)	Final crack length (mm)		afm-ao (mm)	Error (%)	Crack growth Δa		Δam- Δap (mm)	Error (%)
	aom measured	ao estimated			afm measured	af estimated			Δam measured	Δp estimated		
A-1	15,30	14,53	0,77	5,0	17,58	16,76	0,82	4,6	2,27	2,23	0,04	4,0
A-2	15,60	14,82	0,78	5,0	17,98	17,28	0,70	3,9	2,37	2,46	-0,09	-3,8
B-1	15,86	15,19	0,67	4,2								
B-2	15,79	15,26	0,53	3,35								
C-1	15,02	14,53	0,49	3,3	16,20	15,79	0,49	3,0	1,25	1,26	-0,01	-0,8
C-2	15,61	14,94	0,67	4,3	17,59	17,05	0,54	3,0	1,98	2,11	-0,13	-6,6

Specimen thickness = 12,7 mm Side groove 20 %

Table 5. Fracture toughness values at room temperature

Material	Specimen thickness (mm)	ASTM E813-81 J_{IC} (KJ/m2)	Loss J_q 0,15 (KJ/m2)	ASTM E813-87 J_q 0.2 (KJ/m2)	J at SZW Ji (KJ/m2)
A	12,7	730	750	800	
	6,25	340	490	520	263
B	12,7	880*			
	6,25	320	310	350	
C	12,7	850	885	910	
	6,25	475	540	570	
D	33,3	350	420	460	
	12,7	785	880	920	322
	6,25	490	590	620	

* Jc, cleavage fracture

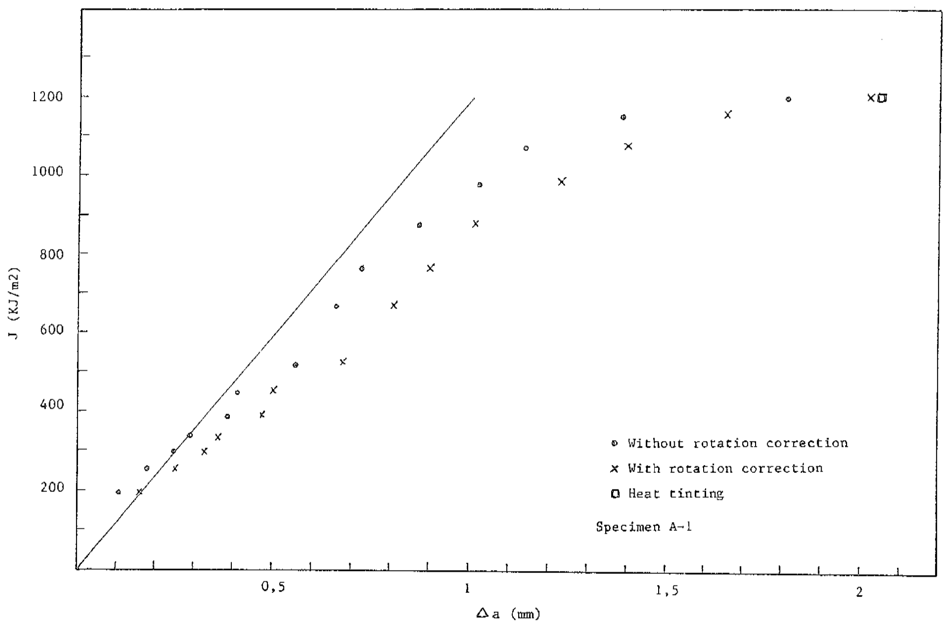

Fig. 1, Rotation correction effect on J-R curve

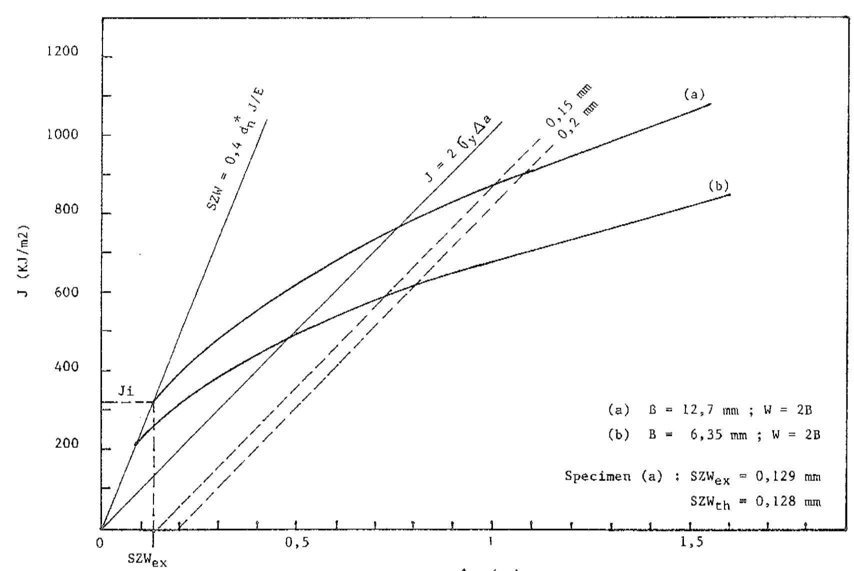

Fig. 2, J-R curves of material D, two different specimen geometries

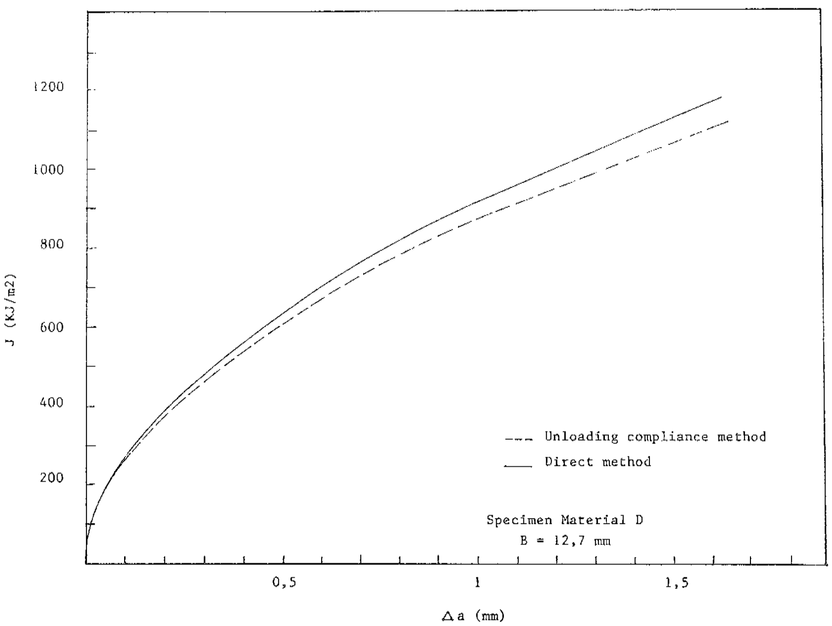

Fig. 3, J-R curve obtained by direct method