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Qualification of J-R (J-T) Curve from 1/2T Compact-Tension Specimen

Sae Hwan Jee and Sun-Pil Choi
Korea Advanced Energy Research Institute
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1/2T Compact-Tension Type 시편으로 구한 J-R (J-T) 곡선의 타당성 검토

지 세 환 · 최 순 필
한국에너지연구소
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Abstract

The change of material J-R(J-T) curve with crack extension and J-calculation method was investigated to give experimental and analytical method for reliable J-R (J-T) curve, which was adapted recently as a tool for instability analysis of Nuclear Pressure Vessel. Experiments were carried out by Single Specimen Unloading Compliance Method using 1/2″T, Compact-Tension Type fracture mechanic specimens which were the same size and material as domestic nuclear pressure vessel material surveillance specimens. The results revealed that crack extension up to 25~30% of initial uncracked ligament and JD (Deformation theory J) calculation method, currently being used in NUREG-0744, could give rather reliable material J-R (J-T) curve than the small crack extension and JM (Modified J) calculation method. But as JM results more or less higher J at instability, the application of JM should be considered regarding to the problem of power plant availability.

요 약

소형시험편(1/2″T)을 이용, 균열진전량 및 J계산식에 따른 재료의 J-R (J-T) 곡선의 변화를 조사하여 신뢰성있는 J-R(J-T) 곡선을 구하기 위한 실험 및 해석방법을 고찰하였다. 시험은 국내 원자력발전소 압력용기감시 시험에 포함되어 있는 파괴인성시편과 꼭같이 SA 533 Grade B, Classl 재료로 제작한 1/2″T, C-T 시편을 이용, Single Specimen Unloading Compliance Technique으로 수행하였다. 시험 및 해석결과 Ernst의 Deformation theory J (JD)식을 이용하여 초기 Uncracked ligament (b_0)의 25~30%까지 균열을 진전시켜 구한 J-R(J-T) 곡선이 대형시편의 결과와 가장 유사한 값을 나타내었다. 한편 Ernst의 Modified J (JM)식에 의한 J-R (J-T) 곡선은 Deformation theory J(JD)에 의한 J-R(J-T) 곡선보다 다소 높은 Instability 예측점을 얻을 수 있기 때문에 실제 압력용기 안전성 해석시에는 가동률향상 및 수명연장 측면에서 Modified J의 사용은 고려되어야 할 것이다.

Nomenclature

a : Crack length
a_0 : Initial crack length
Δa : Crack extension
A : Area under the load-displacement curve
b : Uncracked ligament size
b_0 : Initial uncracked ligament size
B : Specimen thickness
B_{Net} : Net thickness for side grooved specimen
C-T : Compact-Tension
E : Young's modulas
G : Griffith linear elastic energy release rate
J : Rice's J-integral
JIC : The J value at crack extension
JIC, Loss : The J_{IC} value determined by F.J. Loss method
J_{pl} : Plastic part of the deformation theory J
T : Tearing modulas, $T_{mat}=\frac{E}{\sigma_0^2}\cdot\frac{dJ}{da}$
T_{avg} : Average Tearing modulas within 1.5mm exclusion line.
δ_{pl} : Plastic part of displacement
δ_0 : Flow stress. (Yield stress+Ultimate tensile stress)/2
ω : Hutchinson's J-controlled growth validity assurance parameter $\omega=\frac{dJ}{da}\cdot\frac{b}{J}$

I. Introduction

The effort to get "more reliable" material J-R (J-T) curve using small size fracture mechanic specimen has been composed the core of the recent research activities in relation to the pressure vessel materials surveillance program, which is designed to monitor and evaluate the effect of neutron irradiation on nuclear reactor pressure vessel materials [1~4]. Particulary since the issuance of NUREG-0744 [5], which adapted 'tearing instability' concept under 'J-controlled crack growth condition' for the crack instability criterion, as a guide in providing analyses required by 10 CFR Part 50, APP. G, Section V.C in Oct, 1982, the problem to get reliable material J-R(J-T) curve using small specimen contained in surveillance capsule has become important "practical" problem directly related to the safety evaluation and life span dettermination of reactor. However, comparing to the significance of material J-R (J-T) curve in NUREG-0744 analyses method, several problems and difficulties have been remained in testing irradiated small size fracture mechanic specimen and analyzing the test result with limited number of specimens. Since there is no large specimen with same condition and no standard test procedure, for example, the reliability problem of J-R(J-T) curve from limited number of small size specimens has been the subject of debate [6]. Of these, discussions relating to the amount of "allowable crack length" is an example that should be considered theoretically or practically (experimentally) in testing and analyzing the result regarding the reliability; i.e, several errors can become important when stable crack extension are carried well beyond the presently suggested limits.

At some point in crack extension, especially in small size specimen, the surface opposite the crack(the back surface) influence the strain field around the tip, the deformation pattern changes, and the analytical expression no longer describes the crack tip conditions. For the J-R(J-T) curve to be meaningful, crack extension is intentionally limited to the region "dominated" by J.

In this respect, several criteria has been proposed as to the allowable crack extension for different materials, geometry and J-equations. For example, Hutchinson and Shih et al. [7] suggested limiting the crack extension to less than $0.06b_0$ and tentative ASTM procedure [8] suggested up to $0.1b_0$ while Carlson [9] and Druce [10] $0.15b_0$. In particular, Ernst recently proposed $0.3b_0$ with Modified $J(JM)$ [11]. It should be mentioned here that one reason of the importance of "allowable crack extension" lies in the fact that, when a curve is fitted for the J-Δa data points, extrapolation from small crack extension data would give non-conservative values for J and T comparing to large crack extensions [12].

In this respect the author investigated the change of material J-R(J-T) curve with different crack extension beyond J-controlled crack growth regime and the effect of J-calculation method from load-displacement curve on J-R (J-T) curve to give experimental and analytical method for reliable material J-R (J-T) curve, which is critical especially when the curve is determined with small size fracture mechanic specimen contained in surveillance capsule and is used for safety analyses of pressure vessel materials.

II. Experimental Procedure

Material and Preparation of Specimens

7 specimens as shown in Fig. 1 were machined from the Japan Kobe Steel made SA 533 Grade B, Class 1 (Thickness: 120 mm) steel plate. Coupons for specimens were prepared following the test coupon obtaining procedure of ASME Code Section III, NB-2222 [13] and machined to the same size and geometry as domestic nuclear pressure vessel material surveillance specimens.

All notch-tips were machined by E.D.M for good fatigue pre-cracking condition. Fatigue precrack was prepared by load control with dynamic universal testing machine (M. T. S, Load cell capacity: 10ton) up to $a_0/w=0.60\sim0.65$ following the ASTM-E 813 procedure [14]. Table 1 shows parameters used for fatigue precrack preparation. After fatigue pre-cracking all the specimens were side-grooved up to 20% of the thickness to ensure a straight crack front through prevention of shear-lip formation on both side of specimen [15]. Chemical composition and heat-treatment history of the plate is shown in Table 2.

Table 1. Fatigue Precracking Condition

Load	P_{max}=500kg, P_{avg}=270kg, P_{min}=40kg
ΔK	ΔK=97.02 kg/mm$^{3/2}$ (up to 50% of precrack) ΔK=57 kg/mm$^{3/2}$ (for final 50% of precrack)
Fatigue Cycle	150,000~200,000 cycle (13~15Hz) SINE WAVE
a_0/w	0.60~0.65 side grooved after fatigue precracking (20%)

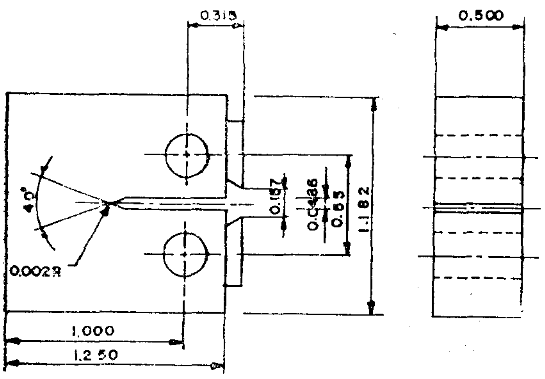


Fig. 1. Specimen Geometry and Dimension (Unit: inch)

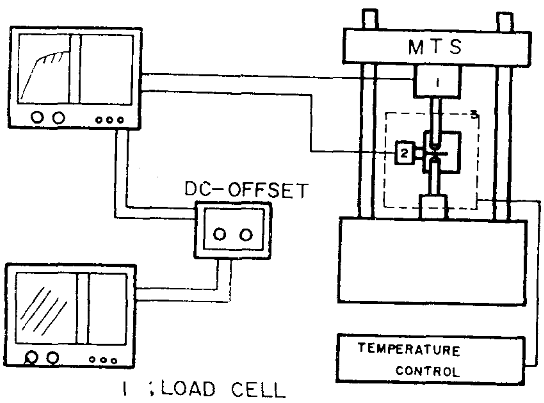


Fig. 2. Apparatus for J-Integral Testing

Table 2. Composition and Heat Treatment of SA 533B-I Steel (wt. %)

C	Si	Mn	P	S	Ni	Cr	Mo	V
0.1812	0.2757	1.37	0.0083	0.0099	0.6272	0.1695	0.4799	0.004
Al	Cu	Ti	Co	As	Sn	Sb	B	Fe
0.0326	0.0218	0.001	0.0208	0.0051	0.0028	0.003	0.0009	Balance

Quenched: 880±10°C×69Min. W.Q. (Water Quenching)
Tempered: 650±10°C×165Min. A.C. (Air Cooling)

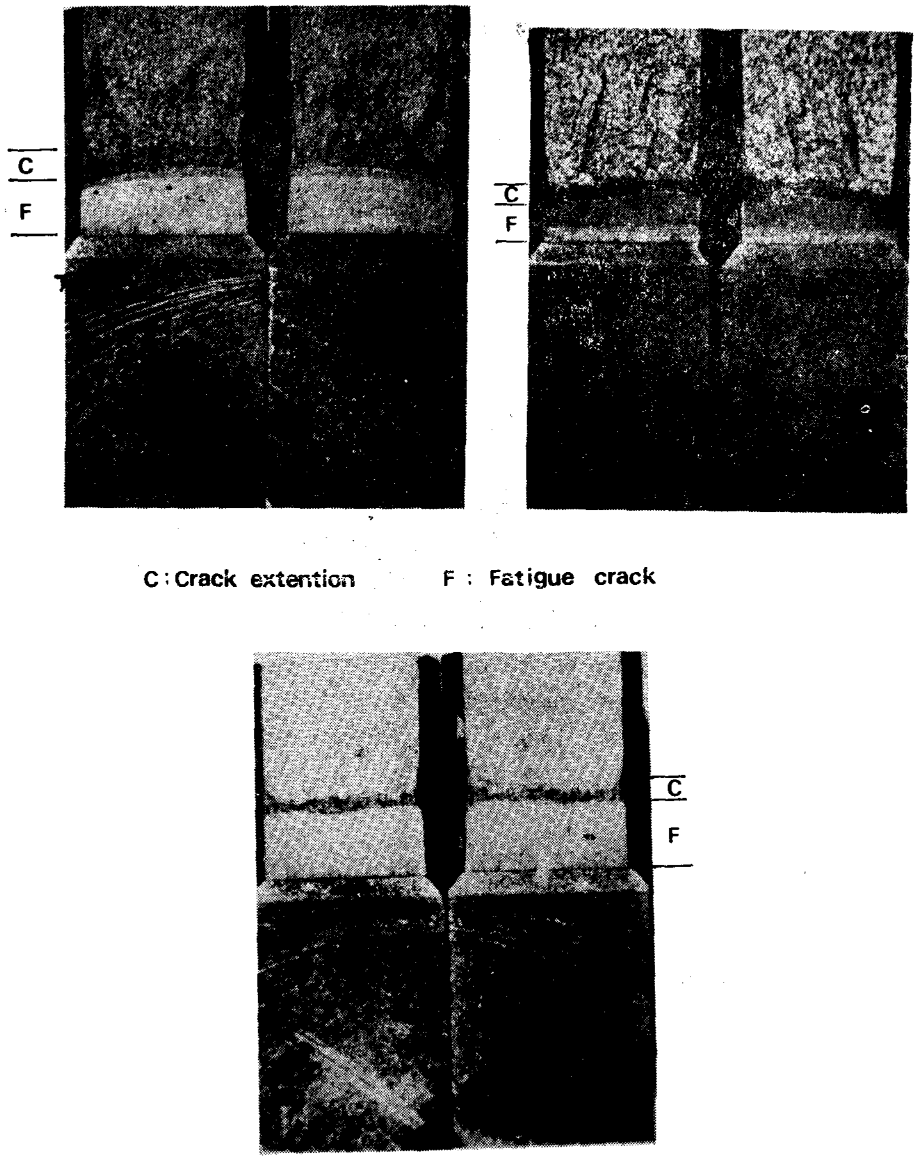


Fig. 3. Fracture Surface of Test Specimens

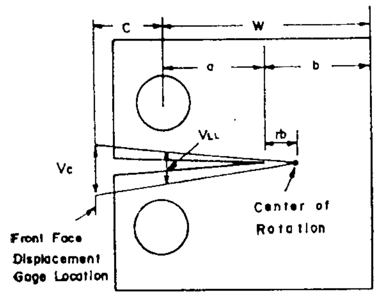
J-Testing for J-R(J-T) Curve

At present there is no standard test method for J-R(J-T) curve for material characterization and structural instability analyses. In 1982, however, ASTM Committee E24. 08. 03 issued tentative procedure for determining the plain strain J-R curve on which, partly on single specimen unloading compliance method of ASTM E-813, this experiment was based. Load-displacement curve for *J*-calculation and amplified unloading compliance curve (amplified up to ×10~25) for prediction of crack extension during test were obtained by stroke control with 2 *X-Y* record. Fig. 2 shows schematics of apparatus used for *J*-testing. After testing all specimens were heat tinted, at about 350°C, in electrical furnace for 10 minutes and fractured for the determination of initial and final physical crack length after chilling the specimens to a temperature low enough for brittle fracturing in liquid nitrogen. Crack length was measured up to 0.001mm compling with 9 point method of ASTM E-813 using projector profile. Fig. 3 shows examples of fracture surface.

J-Calculation and Prediction of Crack Extension

J-integral calculation made from any of the estimation formulas require an area under a load-displacement curve, as a measure of work done on the specimen. For the Compact-Tension specimen, this area is a measure of work only when the displacement is measured along the load line. In ASTM-E 813 and tentative procedure for plain strain J-R curve, measurement of load line displacement is simple and routine. However, for conventional surveillance fracture mechanic specimen as in Fig. 1, a load line measurement of displacement is either very difficult or impossible due to the size limitation.

In order to avoid this problem, measurements near the front face (8.077mm from the load line) with fixtures for C.O.D gage installation



Schematic of compact specimen show'ng method of linear extrapo'ation for displacement mesurement

V_c = front face displacement measured at a distance c from the load line

V_{LL} = load line displacement

a = crack length

b = uncracked ligament length

c = distance from the load line to the point of front face displacement measurement

r = the distance from the crack tip to the point of rotation divided by b

w = specimen width

$$V_{LL} = V_c\left(\frac{a + rb}{a + rb + c}\right)$$

ASTM — E813 $r = 0.1 \sim 0.16$

Fig. 4. Prediction of Crack Extention from Front Face Displacement

Table 3. Comparison of Physical/Predicted Crack Length [Unit: mm]

Specimen No	Specimen Orientation	Testing temp.	Initial Crack Length			Final Crack Length			Crack Extension		
			phy.	pre	error, %	phy.	pre	error, %	phy.	pre	error, %
1	L-T	Room	14.900	14.915	+0.10	16.404	16.500	+0.59	1.504	1.585	+5.40
3	L-T	Room	14.070	14.127	+0.40	14.972	15.122	+1.00	0.902	0.995	+10.31
5	L-T	Room	15.500	15.589	+0.57	16.252	16.438	+1.14	0.752	0.849	+12.90
6	L-T	Room	13.125	13.237	+0.85	14.076	14.151	+0.53	0.951	0.914	−3.89
7	L-T	Room	14.859	14.977	+0.79	16.073	16.026	−0.29	1.214	1.049	−13.59
8	L-T	Room	15.164	15.191	+0.18	17.666	17.495	−0.97	2.502	2.304	−7.91
9	L-T	Room	15.000	15.009	+0.06	18.000	17.809	−1.06	3.000	2.800	−6.670

Table 4. Test Result

		JIC, ASTM (kgf/mm)	JIC, LOSS (kgf/mm)	T_{avg}	Power fit Parameter ($J=A\Delta a^B$)		
					A	B	DEV(%)
	J	20.60	22.00	184.38	44.3504	0.47667	4.64
1	JD	20.70	21.13	165.29	42.4483	0.46400	4.62
	JM	21.84	22.00	158.03	44.4854	0.47939	4.83
	J	19.64	19.48	214.23	48.3694	0.63379	25.19
3	JD	19.79	18.94	204.07	47.4558	0.63009	25.02
	JM	19.51	19.32	217.80	48.7329	0.63679	25.24
	J	15.66	23.56	263.76	45.6070	0.4743	6.31
5	JD	16.26	22.38	249.24	44.5776	0.4704	5.81
	JM	15.55	23.56	269.41	46.0181	0.4793	6.40
	J	16.97	20.07	223.25	49.1386	0.5634	9.19
6	JD	18.37	21.72	204.07	48.1400	0.5583	9.25
	JM	16.96	22.31	226.39	49.5610	0.5659	9.26
	J	18.80	28.82	219.13	47.4509	0.4842	6.56
7	JD	19.22	27.79	204.07	46.2222	0.4777	6.10
	JM	18.80	28.73	222.64	47.8479	0.4871	6.62
	J	18.19	27.32	132.07	38.7249	0.3626	12.04
8	JD	19.04	25.25	111.32	35.5611	0.3348	10.86
	JM	17.96	27.21	138.48	38.9600	0.3719	12.95
	J	15.37	26.38	143.50	36.8183	0.3389	12.25
9	JD	14.93	24.68	129.30	34.2615	0.3206	11.68
	JM	13.81	26.49	155.36	37.2043	0.3461	13.38

were carried out and, later, converted to load line displacement for J-integral calculation using a linear interpolation. See Fig. 4. Crack extension was predicted from the amplified unloading compliance curve using Ashok Saxena's elastic polinominal compliance- crack length expression [16].

J-Calculation Equation

One of the purpose of this experiment was to investigate actual differences in J-R(J-T) curve when different J-calculation equations were used for the same load-displacement curve. J-calculation equation from the load-displacement curve can be differ depending on the specimen geometry, loading condition, amounts of crack extension and whether the J-controlled crack growth condition is considered or not. Several J-calculation equations have been suggested with some limitations. Of these equations, the following three equations were selected for comparison and the differences were discussed on the base of Tearing modulas and ω value.

1) Merkle-corten J (J) [17]

$$J=\frac{1+\alpha}{1+\alpha^2}\cdot\frac{2A}{B\cdot b}$$

$$\frac{1+\alpha}{1+\alpha^2}=1+0.261\left(1-\frac{a}{w}\right) \qquad (1)$$

$$\alpha=\left[\left(\frac{2a}{b}\right)^2+2\left(\frac{2a}{b}\right)+2\right]^{\frac{1}{2}}-\left[\left(\frac{2a}{b}\right)+1\right]$$

2) Ernst Deformation theory $J(JD)$ [18]

$$JD=J_{i+1}=\left[J_i+\left(\frac{\eta}{b}\right)_i\cdot\frac{A_{i,i+1}}{B_{Net}}\right]$$

$$\left[1-\left(\frac{r}{b}\right)_i(a_{i+1}-a_i)\right] \qquad (2)$$

$$\eta=2+0.522\left(\frac{b}{w}\right)$$

$$\gamma=1+0.760\left(\frac{b}{w}\right)$$

3) Ernst Modified $J(JM)$ [11]

$$JM=JD-\int_{a_0}^{a}\frac{\partial(JD-G)}{\partial a}\Big|_{\delta pl}\cdot da$$

$$=JD+\int_{a_0}^{a}\frac{r}{b}\cdot J_{pl}\cdot da \text{ for} \qquad (3)$$

$C-T$ specimen

Specific characteristics and limitations (or meaning) of these equations can be found in Ref [17], [18], [11] respectively.

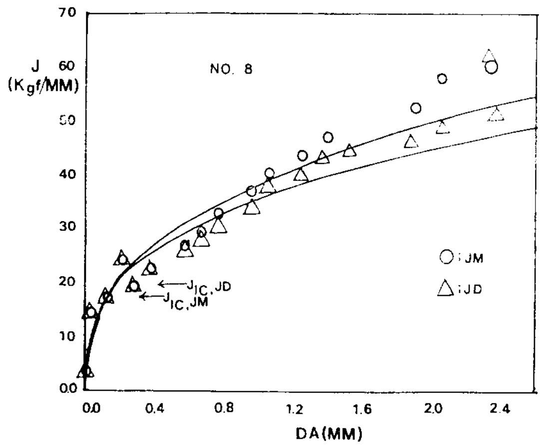


Fig. 5. J-R Curve (No. 8)

Table 5. ω Value with Crack Extension

	JD(kgf/mm)	a(mm)	JM(kgf/mm)
#1	20.00(0.176)	ATJ	19.38(0.185)
	9.88	0.4	10.10
	4.46	1	4.60
	2.79	1.6	2.89
#3	31.90(0.168)	ATJ	30.85(0.166)
	14.56	0.4	15.05
	6.57	1	6.54
	6.21	1.05	6.32
#8	15.78(0.162)	ATJ	18.86(0.152)
	7.14	0.4	7.87
	3.05	1	3.43
	1.31	2.3	1.44
#9	19.60(0.127)	ATJ	24.65(0.117)
	7.01	0.4	7.80
	3.04	1	3.27
	2.00	1.5	2.14
	1.61	2.8	1.73

III. Results and Disscusion

Table 3 compares physical crack length with predicted crack length. As shown in Table 3, different crack extensions were attained to compare the effect of crack extension on J-R (J-T) curve. In the following disscusion, results from Specimen No 1, 3 and 8, 9 will be compared and discussed as a representative of small and large crack extension respectively. All the resulting J-Δa datas were power fitted to $J=A(\Delta a)^{\wedge}B$ equation because analytical method of stable crack growth applicable to nuclear pressure vessel steels must be based on the premise that material J-R curves are continuously non-linear and this equation has been revealed best fit result and so accepted widely [6], [19]. Table 4 shows power fit parameter A and B with deviation for each J-calculation equation and Fig. 5 shows an example of power fitted curve with J-Δa datas for Secimen NO. 8.

Change of T and w with Crack Extension

Within the limited crack extension, the change of T and ω was investigated, on the basis of suggested J-controlled crack condition to set minimum allowable crack extension for 1/2″T, C-T specimen [20]. Table 5 shows ω values with crack extension. At Δ a JIC, ω shows somewhat large variation from 15 to 40, but give almost same value as crack extended.

Here, regarding to the allowable craak extension, if we remember Hutchinson's suggestion [20], say, $\omega>1$ for J-controlled crack growth, it might say theoretically that experiments was stopped before Δa reach the allowable crack extension range. In other words, it imply that crack can extened further (even thought it is impractical for 1/2″T C-T specimen).
And in contrast, if we consider Paris $\omega=5$[21] and Shih's $0.06b_0$ suggestion for ensured J-controlled crack growth, all the results violate Paris' and Shih's suggestion.

Practically if we apply Shih's $0.06b_0$ suggestion for 1/2″T C-T specimen (In this case, allowable crack extension is less than 0.7mm), it become impossible to get reliable J-R curve for safety analyses from 1/2″T C-T specimen. Discussions will be made on this point later. As shown in

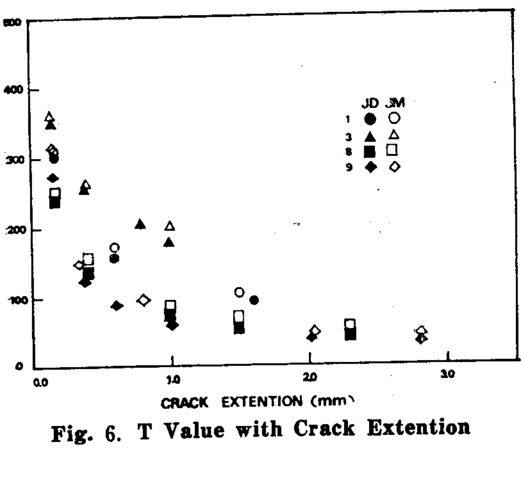


Fig. 6. T Value with Crack Extention

Fig. 6, Tearing modulus, a parameter of materials resistance for crack extension, decrease rapidly and reach almost a half value of T at Δ a, JIC after only a small crack extension of 0.5~1mm. It implies that SA 533, Cl 1 material show rapid decrease in the rate of increase in materials resistance to fracture just after crack initiation.

The Effect of J-Calculation Method on J-R Curve

Fig. 7 and Fig. 8 show the effect of J-calculation method on J-R curve. For all case

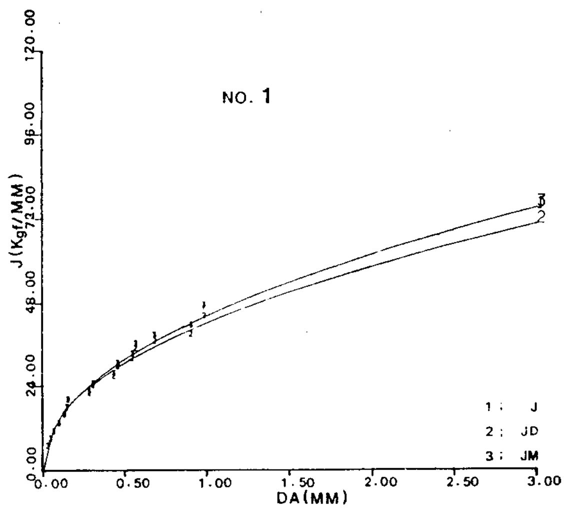


Fig. 7. Power Fitted J-R Curve (No. 1)

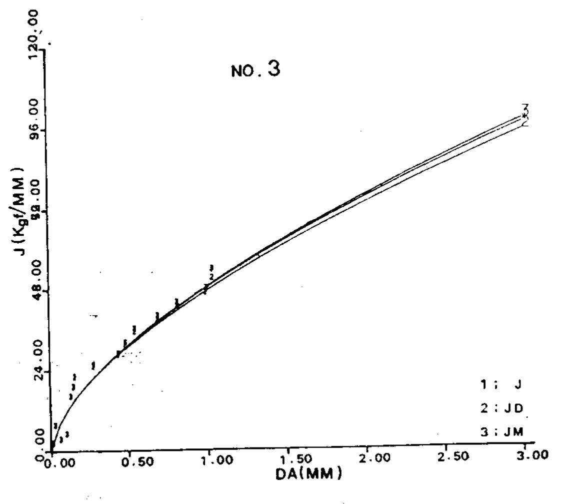


Fig. 8. Power Fitted J-R Curve (No. 8)

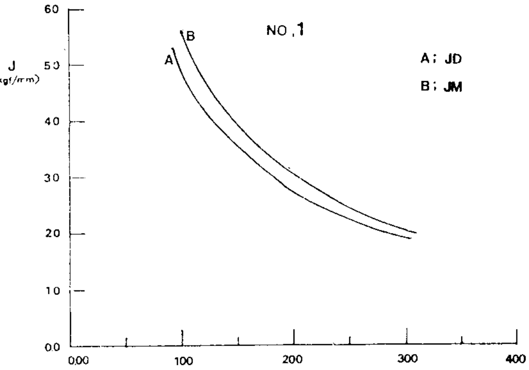


Fig. 9. J-T Curve (No. 1)

there are nearly no difference between J (Merkle-Corten J) and JM (Modified J) curve within the limited crack extension and both curve were above the JD(Modified J) curve as expected as in Ref[22].

These results shall lead to different J-T curves as in Fig. 9 implying different instability prediction if we use these curve for safety analyses. Regarding instability prediction, it is clear that JD gives more conservative prediction than JM as JM-T curve locates above JD-T curve as in Fig. 9.

Qualification of J-R Curve

Together with the suggestions of Hutchinson, Paris and Shih, ASTM Tentative method for J-R curve also provide a measure qualifying J-R (J-T) curve. Fig. 10 show four J-T curve from JD equation (Specimen 1, 3, 8, 9) with Paris' $\omega=5$ line (A) and ASTM's qualification criteria.

As amount of crack extension increase, J-T curve move downward. Since Paris $\omega=5$ results from the testing of thick specimens with crack extension satisfying J-controlled crack growth condition and/so somewhat conservative, $\omega=5$ line can be used as a criteria for qualifying J-R curve from small size specimens; i.e, if a J/T loading line with $\omega=5$ intercepts a J/T curve

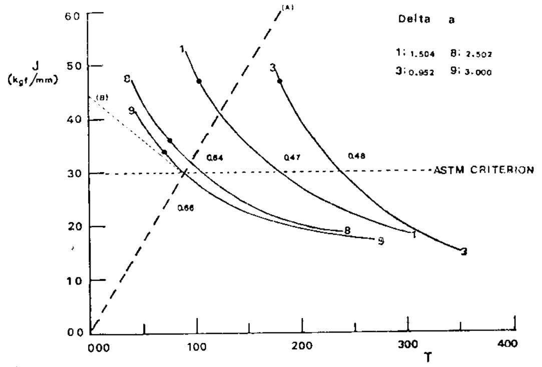


Fig. 10. Qualification of J-T Curve

from small specimen at the crack extension of J-dominated, say $\Delta a=0.6b_0$, this J/T curve can be regarded as a reliable one as it shows similar result from thick specimen.

For SA 533 Class 1, Grade B steel, a J/T loading line with $\omega=5$ is

$$J/T=\frac{\sigma_0^2 \cdot b}{E \cdot \omega}=\frac{(85)^2 \cdot 1}{30.5}=50\ lb \cdot in/in^2$$
$$=0.89 Kgf/mm$$

and this conservative loading line intercepts J/T curves from Specimen 8 and 9 at the crack extension of 0.64mm and 0.66mm, which fall nearly under $\Delta a=0.06b_0$ respectively.

Two measurement capacity criteria of Tentative ASTM procedure, Δa max$=0.1b_0$ and Jmax$=(B_{Net}\cdot\sigma_0)/20$, also can be used as a qualification criteria for J-R(J-T) curve. Here J-R curves which are fitted through the data points in a region bounded by the coordinate axis, the Jmax and Δa max limit are qualified. Fig. 10 shows these two criteria, Jmax=30 kgf/mm and Δa max=1mm, which intercept J-T curves from Specimen 8 and 9 at the crack xtension about $0.06b_0$ and near this value.

From the above discussion curves from Specimen 8 and 9, whose crack extension range about $0.25\sim0.30b_0$, can be regarded as reliable ones that can be used for structural instability analyses. If instability prediction is performed following NUREG-0744 procedure, J-T curve for this purpose can be constructed through the linear extrapolation of J-T curve to the *J*-axis from the intercept point with the $\omega=5$ loading line(B) [5].

Conclusion

Conclusions from the experiment to investigate the change of material J-R (J-T) curve with different crack extension beyond *J*-controlled crack growth regime and the effect of *J*-calculation methods on J-R(J-T) curve are as follow.

1. From the front face displacement measurement it was possible to predict the amount of crack extension exactly for 1/2″T, C-T specimen using Saxena and Hudak's compliance-crack equation.

2. Regarding the effect of *J*-calcaulation method on J-R(J-T) curve, there were no apparent difference between JD-R and JM-R curve for the crack extension up to approximately 15% of initial ligament. Accordingly no relative big difference for JIC and T_{avg} value, which are determined from the data points within 1.5 mm exclusion line, were resulted.

3. In order to get reliable material J-R(J-T) curve for instability prediction using 1/2″T, C-T specimen, it seems that amount of crack extension (Δa) shall be over at least 25～30% of initial ligament.

4. Since instability prediction with JD-R curve is more or less conservative than JM-R curve, the application of JM should be considered regarding the availability of reactor.

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