◉ 論 文

JIC Evaluation of the Smooth and the Side-Grooved CT Specimens in the Reactor Pressure Vessel Steel(SA508-3)

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원자력압력용기강 (SA508-3)의 평활 및 측면홈 CT시험편을 이용한 J_{IC} 평가

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Key Words : Elastic-Plastic Fracture Toughness(탄소성 파괴인성), Blunting Line(둔화직선), R-curve(R-곡선), Stretched Zone Width(스트레치존 폭), Transgra-nular Dimple Fracture(입내 딤플파괴)

요 약

원자력 압력용기강의 탄소성 파괴인성값 J_{IC}를 CT형 시험편을 이용하여 검토하였으며, 평활 시험편 및 측면홈 시험편의 두께는 각각 B_o=25.4mm, B_N=20.4mm 이다. 측면홈의 깊이는 19.7% 이며, 홈의 각도는 90°로 가공하였다. 탄소성 파괴인성시험은 ASTM E813-81과 JSME S001-81의 추천방법에 따라 실시하였다. 두 추천방법으로 실험한 결과 ASTM방법에 의한 J_{IC}값이 과대평가됨으로써 부대조건에 만족되지 못하였지만 JSME방법은 만족되었다. 측면홈 시험편은 R곡선법에 의한 ductile tearing의 결정이 평활 시험편보다 용이하였으며, 이에 따른 J_{IC}값의 정확성을 배가 할 수 있었다. 또한 임계 스트레치존 폭(SZW_C)은 측면홈에 의한 높은 3축응력이 발생되어 평활시험편보다 적게 나타났으며, 이러한 복합적인 원인에 기인하여 스트레치존법에 의한 J_{IC} 평가는 R곡선법에 의한 평가보다 약간 과대평가됨을 알 수 있었다.

1. INTRODUCTION

Safety and integrity are required for nuclear reactor pressure vessel. Actually, the fracture behavior of machine components and structures are estimated mainly by the analysis of fracture mechanics. This is

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true because most of surface crack initiation and growth take place in three dimension.

In the linear elastic fracture mechanics, the fracture toughness J_{IC} is represented by the energy release rate (G) and stress intensity factor (K) in case of small scale yielding. Crack Opening Displacement(COD) and the J-integral are generally applied in case of large scale yielding.

Rice[1] in 1968 defined the J-integral as the potential energy difference per unit thickness between two identically loaded bodies having neighboring crack size. The critical value J_{IC} is known to characteristic of material. The material can be safe when J-integral value is smaller than the critical value $J_c(J<J_c)$. J_c value varies with the fracture mode, the material thickness, the specimen shape and the test temperature.

Begly and Landes[2] have proposed that elastic-plastic plane strain fracture toughness J_{IC} is related to the plane strain fracture toughness K_{IC}. The usability of J_{IC} has been confirmed by many investigators[3,4]. The determination of fracture toughness is recommended in JSME S001-81[5] and ASTM E813-81[6]. The method of JSME S001-81 is not proposed the limitation of the small crack length. But a crack initiation point should be measured as accuracy as possible. J_{IC} values can be obtained only through experiment, and the experiment methods are provided in ASTM and JSME.

This paper compares with two methods by using the smooth CT specimen and side groove CT specimen; one is the elastic-plastic fracture toughness determination method by R-curve of ASTM E813-81[6] and the other is that by R-curve of JSME S001-81[5], SZW. The side grooved-specimen is very useful in estimation of the elastic-plastic fracture toughness, because it is much easier than the smooth CT specimen to determine the onset of the ductile tearing by the R-curve method. Besides, it improves the accuracy of toughness values, decreases the scattering of them and prevents tunneling and shear lip by the side groove.

2. MATERIAL SPECIMEN AND TESTING PROCEDURE

The testing material is SA508-3 forging steel commonly used for the nuclear reactor pressure vessel. Table 1 and 2 show their chemical composition and mechanical properties. Fig. 1 shows the geometry of the compact tension specimen (width=50.8mm and thickness=25.4 mm) in accordance to ASTM E813 and JSME S001-81 specification. The thickness of the smooth specimen is B_o=25.4mm, the side-grooved specimen is B_N=20.4mm and the side groove depth is 19.7% and the groove angle is 90°.

The experimental procedures of fatigue precracking and fracture toughness estima-

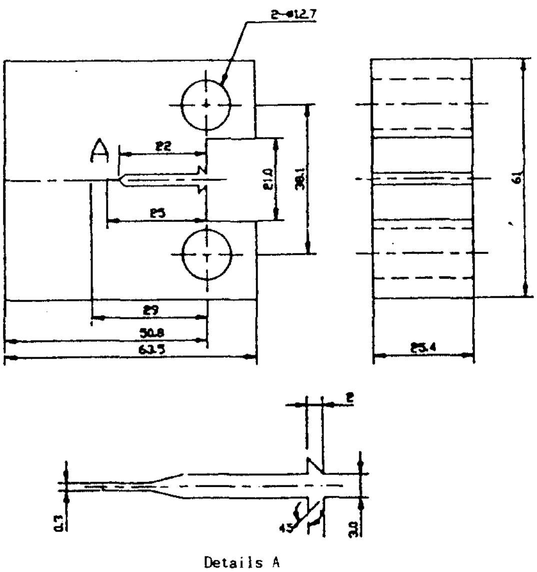
Table 1. Chemical composition of the SA508-3 steel(W_t.%)

C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu
0.17	1.42	0.004	0.003	0.04	0.98	0.22	0.58	0.003	0.045

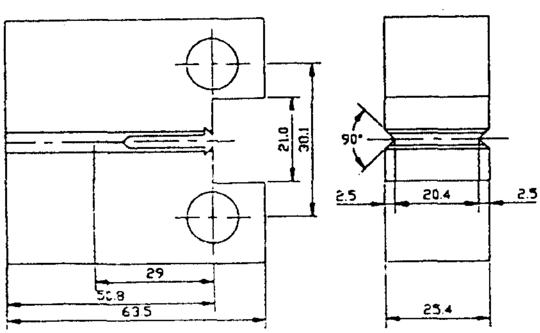
Table 2. Mechanical properties of the SA508-3 steel

Temp. (°C)	Tensile strength (kgf/mm²)	Yield strength (kgf/mm²)	Elongation (%)	Young's modulus (kgf/mm²)
RT	59.89	45.51	27.8	20930

tion follows ASTM E399[7] and E813. An electro-hydraulic fatigue testing machine (INSTRON 1331) is used in the experiment.



(a) Smooth specimen



(b) Side-grooved specimen

Fig.1 Configuration of the compact tension specimens(Uint:mm)

An environment for the fatigue precracking was room temperature and a loading waveform was sinusoidal under a constant load.

The crack ratio is a/W=0.6 and the maximum stress intensity factor(SIF) K_{max} is 104.17kgf $mm^{-3/2}$. The stress ratio is R=0.05 and the frequency is 20HZ and the stress intensity factor range is $\Delta K=98.96kgfmm^{-3/2}$. The cross head speed at the fracture toughness test was 0.1mm per minute. After unloading, the specimens are precracked for the marking and then tested. The clip gage with 3mm gage range represented 0.00228mm maximum standard deviation, which satisfied the limit specified in ASTM E399. The stretched zone width was measured by using the SEM (Scanning Electron Microscope).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3-1. Estimation of the fracture toughness by the R-curve method.

Fig.2 shows the relation between J and Δa_{ASTM} obtained by the ASTM standard in the the smooth compact tension specimen. The procedures described in the ASTM standard are as follows, The J-integral values was expressed in formulation of Rice's[8,9] and Landes[10] simplified by the Mercle-Corten's[11].

$J=(2A/B \cdot b)$ ——————(Rice's)

$J=(A/B \cdot b)f(a_o/W)$ ——(Mercle-Corten's)

$f(a_o/W)=2(1+\alpha)/(1+\alpha 2)$

$\alpha = [2(a_o/b)+(2a_o/b)+2]1/2-[(2a_o/b_o+1)]$

Where

A : area under load, load-point displacement record in energy

B : specimen thickness

b : initial uncracked ligament

a_o : original crack size, including

fatigue precrack
W : specimen width

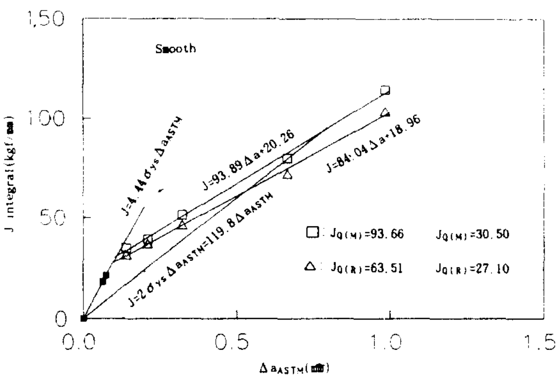


Fig. 2 Determination of J_Q by the ASTM R-curve method

The specimen thickness is divided into eight equal sections and the crack length Δa_{ASTM} from the fatigue precrack tip to the tip of the marked crack is measured at each dividing point. The average value of the two surface measurements is used as a single point along with the remaining seven crack extension values to determine the average crack extension. The crossing point between the regression line and the crack blunting line is J_{IC}.

The intersection point between a linear regression line($J=93.89\Delta a + 20.26$ or $J=84.04\Delta a+18.96$), which fit to the data, and the blunting line ($J=2\sigma_{ys}\Delta a_{ASTM}=119.8\Delta a_{ASTM}$) obtained as for the ASTM recommendation determines J_Q. The values of J_Q are $J_{Q(M)}=93.66$ kgf/mm and $J_{Q(R)}=63.51$ kgf/mm.

It was found that the J_Q values from determination J_Q satisfied both the size-requirement ($b.B > 25J_Q/\sigma_{ys}$) and the slope-requirement of the regression line ($dJ/da<\sigma_{ys}$). Thus, these values can not be taken as J_{IC}. As a consequence, It should be mentioned that Δa is equal to SZW before the crack growth occurs. The crack length Δa of blunting line should be measured for accurate estimation of J_{IC}. The blunting line obtained in this manner is $J=4.44\sigma_{ys}\Delta a_{ASTM}$ and the values of J_Q are $J_{Q(M)}=30.50$ kgf/mm, $J_{Q(R)}=27.10$ kgf/mm by the blunting line with the actual measurement.

J_Q values are satisfied both the size-requirement and the slop-requirement of the regression line, so that these values can serve as J_{IC}. The blunting line is very important in the evaluation of elastic-plastic fracture toughness(J_{IC}).

Fig.3 shows the relation between J and Δa_{ASTM} obtained by the ASTM standard at the side groove compact tension specimen. The Δa_{ASTM} of side groove specimen was measured as the same method as that of smooth CT specimen.

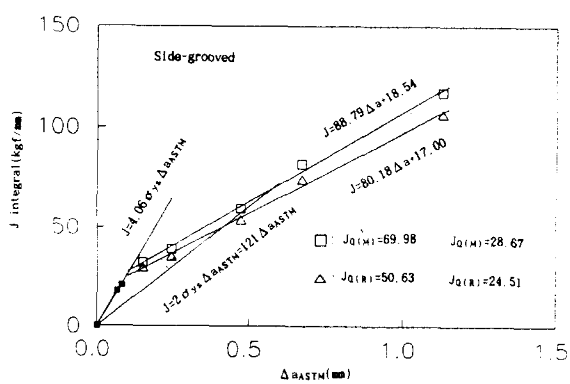


Fig. 3 Determination of J_Q by the ASTM R-curve method

The values of J_Q are $J_{Q(M)}=69.98$ kgf/mm, $J_{Q(R)}=50.63$ kgf/mm with the blunting line obtained as for the ASTM recommendation, and $J_{Q(M)}=28.67$ kgf/mm, $J_{Q(R)}=24.51$ kgf/

mm by the blunting line ($J=4.06\sigma_{ys}\Delta a_{ASTM}$) with the actual measurement.

In evaluation J_{IC}, ASTM standard is suitable for the material with the characteristics of middle-strength and high-strength. Therefore, JSME standard is appropriate method to evaluate J_{IC} of SA508-3 steel, low-strength and high-toughness rather than ASTM standard.

Kobayashi et al.[12] have proposed that the method of JSME standard is more reliable than the method of ASTM standard in A533B-1 steel. The results of this study are similar to their suggestion that J_{IC} of the JSME standard is better.

3-2. Estimationn of the fracture toughness by the JSME R-curve method

Fig.4 and 5 show the relation between J and Δa_{JSME} in the smooth and side-grooved compact tension specimen. In accordance with JSME standard the values of the crack growth, Δa, for the R-curve determination are obtained in the range of (3/8-5/8) thickness of the specimen. Where plane strain is assumed to exist. Δa was given by the average value of three

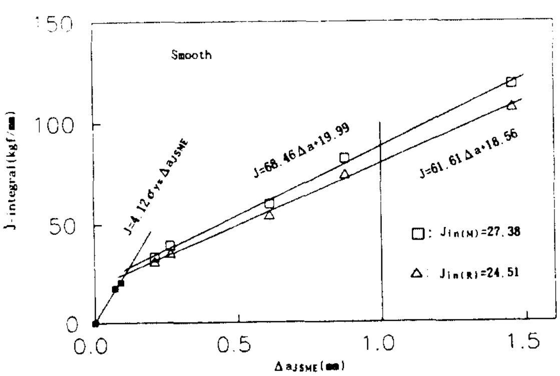


Fig. 4 Determination of J_{in} by the JSME R-curve method

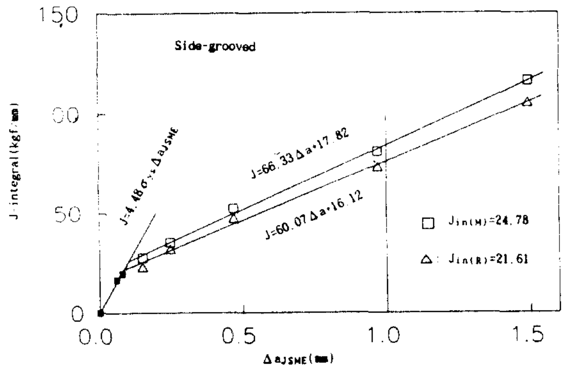


Fig. 5 Determination of J_{in} by the JSME R-curve method.

readings. The linear regression line is determined by least squares method with point of Δa_{JSME} less than within 1mm.

The blunting line by the actual measurement are $J=4.12\sigma_{ys}\Delta a_{JSME}$, $J=4.48\sigma_{ys}\Delta a_{JSME}$, and a linear regression line $J=68.46\Delta a+19.99$, $J=61.61\Delta a+18.56$, $J=66.33\Delta a+17.82$ and $J=60.07\Delta a+16.12$ respectively. The values of J_{in} are $J_{in(M)}=27.38$ kgf/mm, $J_{in(R)}=24.51$ kgf/mm, $J_{in(M)}=24.78$ kgf/mm and $J_{in(R)}=21.61$ kgf/mm respectively.

In Fig.4 and Fig.5, the value of J_{in} are satisfy both the slop-requirement of the regression line $(dJ/da)_R<(dJ/da)_B$ and requirement of the crack length $(\Delta a_{max}-\Delta a_{in})>3(\Delta a_{min}-\Delta a_{in})$. Thus, these values can serve as J_{IC}.

The values of the elastic-plastic fracture toughness J_{IC} obtained by the method of ASTM are compared with those by the method of JSME in both specimens: the values measured by the the method of ASTM R-curve are slightly higher than those by the method of JSME. This is due to the difference in the slope of the blunting line and that of the regression line.

K.W.carlson et al.[13] have proposed that the J_{IC} is not value expressed as linear approximate equation by R-curve and it is not difference between J_Q and J_{in}. But the test was not the efficient method because many specimens is required.

3-3. J_{IC} estimation by the stretched zone width (SZW) method.

Fig.6, Fig.7 shows the relation between SZW and J in the both specimens. SZW was measured at the third, fourth, and fifth dividing points of eight sections, and was given by the average value of three readings. The boundary between the SZW and the dimple region was locally observed, but it was not clear.

The average value of the SZW are SZW_c

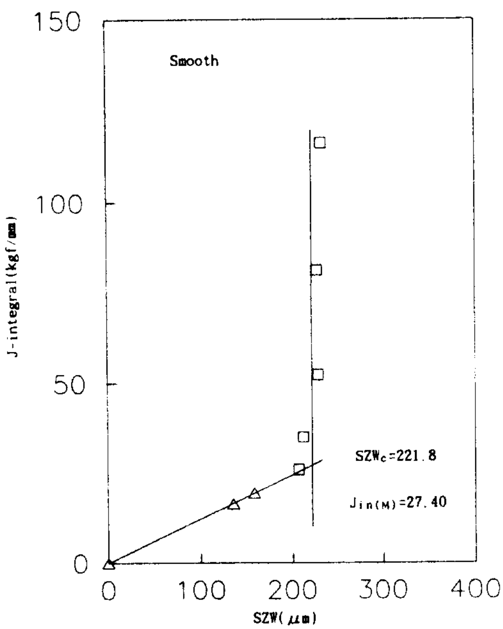


Fig. 6 Determination of J_{in} by the SZW method

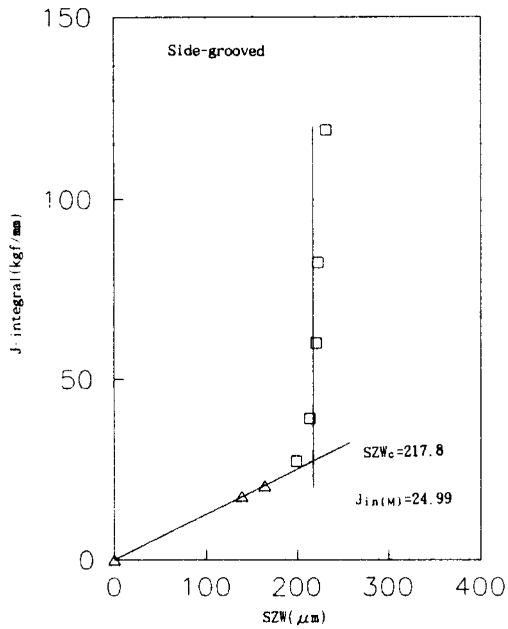


Fig. 7 Determination of J_{in} by the SZW method

= 221.8μm, SZW_c= 217.8μm in the smooth and side groove compact tension specimens respectively. The critical stretched zone width(SZW_c) of the side-grooved specimen has observed to be smaller than that of the smooth specimen. This was attributed to higher triaxiality stress caused by the side-groove.

J_{IC} can also be obtained by intersecting the so-called critical stretched zone width line with the blunting line. The value of J_{in} are J_{in}=24.99 kgf/mm and J_{in}= 27.40 kgf/mm in Fig.6 and Fig. 7. Also, the change coefficient of the SZW is within ±25% in the both specimens.

In Fig.8, 9 the symbols (▲, ◨, ▲, and ■) indicate the stable crack growth, and the elongated dimple adjacent to the stretch zone is local at the first two symbols and extensively at the other two symbols, Which it caused by the plastic blunting and the crack opening in the fatigue precracking.

Fig.8 and Fig.7 show the relations of SZW-J/E, and SZW-J/σ_{ys}. The specimen dose not affect the slop of the blunting line as shown in Fig.6 and 7. The slope of the blunting line are SZW=167.07J/E and SZW=362.47J/σ_{ys}. So, we concluded that the slopes of the blunting line, obtained by each relationship, SZW-J, SZW-J/E and SZW-J/σ_{ys} are almost independent on the specimen shape in the region of the blunting line in this study.

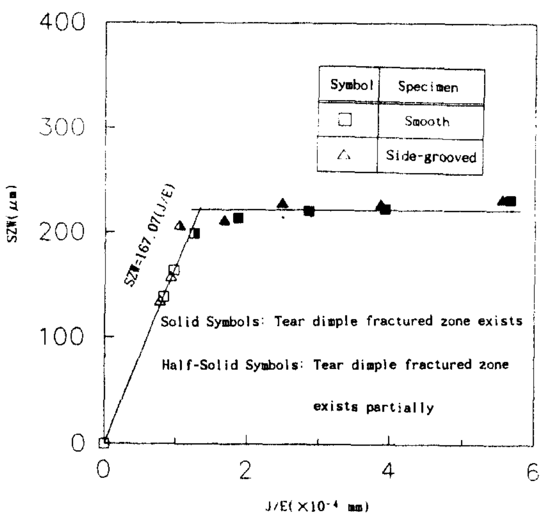


Fig. 8 Relation between SZW and J/E in the both specimens

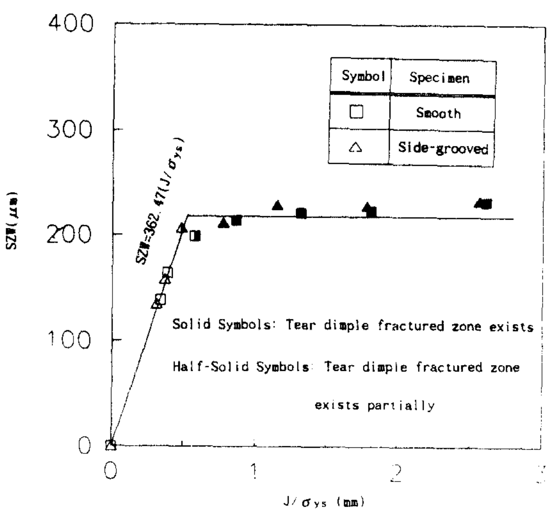


Fig. 9 Relation between SZW and J/σ_{ys} in the both specimens

Ohji et al.[14] have proposed that the strecthed zone width variable in accordance with the ductile crack growth for the middle strength steel and the low strength steel with high toughness. It is noticeable for the low strength steel with high toughness and SZW_c be observed larger than actual measurement, and strecthed zone width is variable according to increase of J-integral value. Therfore, J_{in} value obtained by strecthed zone width method rather than R-curve method are overestimated. Because this is the high toughness material.

Mutoh et al.[15] stated that the strectched zone width is variable in accordance with the plastic blunting and the ductile partition occurring in the plastic blunting region, that the elongated dimple is usually treated as a portion of the stretched zone, and thus that J_{IC} values are estimated larger by the stretched zone width method than them by the R-curve method.

Fig.10, Fig.11 show fractographs obtained by the SEM in the smooth and the side-grooved compact tension specimens. A, B, C and D at upper picture are the fatigue precrack zone, strectched zone, dimple zone and fatigue crack marking zone respectively. The fracture features show the transgranular dimple fracture pattern in the both specimens.

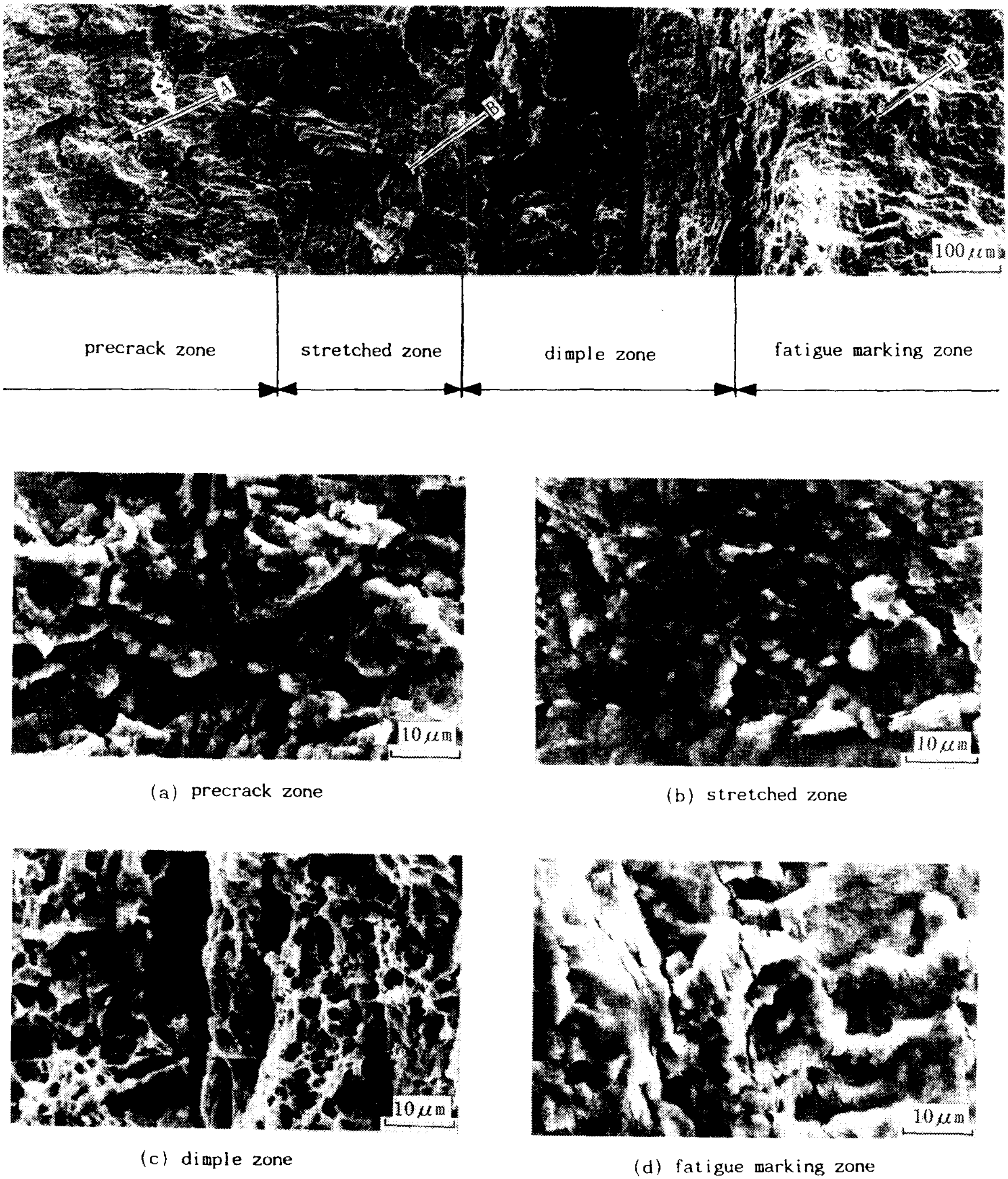
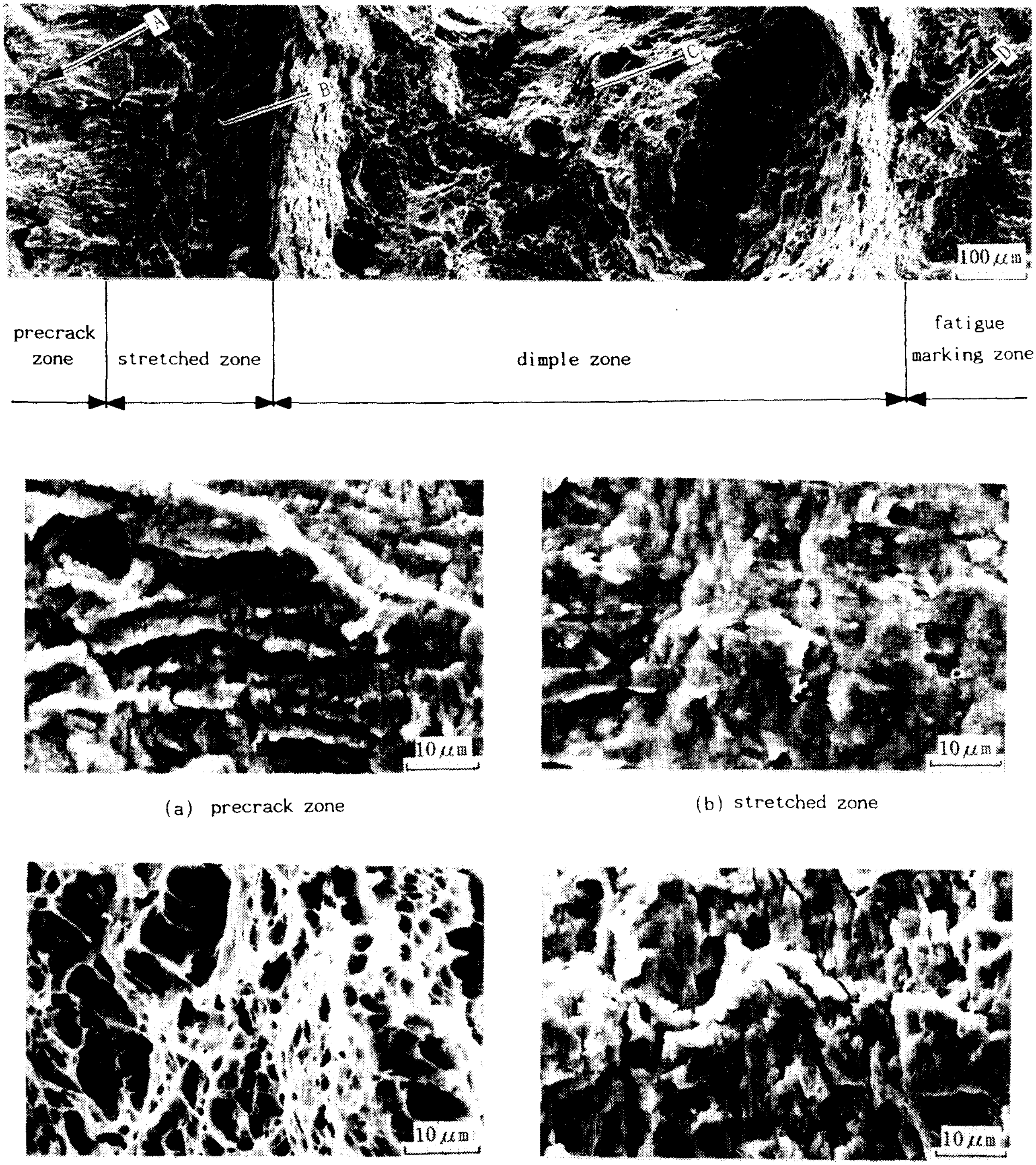


Fig. 10 S E M fractographs showing the fracture surface of the SA508-3 steel in the smooth specimen



(a) precrack zone

(b) stretched zone

(c) dimple zone

(d) fatigue marking zone

Fig. 11 S E M fractographs showing the fracture surface of the SA508-3 steel in the side-grooved specimen

4. THE COMPARISON OF J_{IC} ESTIMATION VALUES

Table 3 shows comparison the ASTM R-curve method with the JSME R-curve, SZW methods by the smooth and side-grooved specimens. J_{IC} values are not observed with the ASTM standard method. But when blunting line are decided by actual measurement, J_{IC} value will be estimated by the ASTM R-curve, JSME R-curve and SZW methods.

And J_{IC} measured values of the side-grooved specimen was smaller than that of the smooth specimen because of the difference of the crack length due to higher triaxiality or relaxation of the plastic restraint in the crack tip of the side-grooved specimen, which occured the shear lip and the tunneling phenomenon.

As a results, it was recognized that the blunting line slop and the R-curve slope are affected by the crack length. Therefore J_{IC} values are small estimated the side-grooved than the smooth specimen by the ASTM, JSME R-curve and SZW methods and the stretched zone width method gave slightly larger J_{IC} values than those by the R-curve method for SA508-3 steel. As a consequence, side-grooved specimen should be used for accurate estimation of the elastic-plastic fracture toughness J_{IC} for the SA508-3 steel with high toughness.

Otsuka et al.[16] have proposed that the critical strectched zone width SZW_c varies with the specimen shape in the initiation point of the ductile fracture. The material of the specimen is the SA50A steel and the specimen shapes are the three point bending(BEND), the center crack tension (CCT) and the two side notch specimen (SN). Particularly, the critical strectched zone width SZW_c in the CCT specimen varies with ligament. The value of SZW_c was small quantitatively due to the higher triaxiality stress with icrease in the crack tip.

5. CONCLUSION

The elastic-plastic fracture toughness J_{IC} of the nuclear reactor pressure vessel forging steel(SA508-3) was investigated by using the smooth and side-grooved compact tension specimens. The results of this study can be summarized as follows;

1. The elastic-plastic fracture toughness values was not estimated by the ASTM R-curve method. But it is estimated when blunting line was actual measurement and the values are approximate to those by

Table 3. The comparison of the fracture toughness values

Specimens \ Method	ASTM J_Q(kgf/mm)	JSME J_{in}(kgf/mm)	SZW J_{in}(kgf/mm)
Smooth	$J_{Q(M)}$ = 93.66 $J_{in(M)}$=30.5 $J_{Q(R)}$ = 63.51 $J_{in(R)}$=27.1	$J_{in(M)}$ = 27.3 $J_{in(R)}$ = 24.51	$J_{in(M)}$ = 27.40
Side-grooved	$J_{Q(M)}$ = 69.98 $J_{in(M)}$=28.67 $J_{Q(R)}$ = 50.63 $J_{in(R)}$=24.51	$J_{in(M)}$ = 24.78 $J_{in(R)}$ = 21.61	$J_{in(M)}$ = 24.99

JSME R-curve method.

2. J_{IC} values are estimated small in the side-groove CT specimen rather than the smooth CT specimen by the ASTM, JSME R-curve and SZW method. The side-grooved CT specimen became differently of the crack length due to relaxation of the plastic restraint in the crack tip, which decreased the shear lip and the tunneling phenomenon.

3. J_{IC} values by the the strectched zone width(SZW) method gave slightly larger than by the R-curve method in the both specimens.

4. The side-groove specimen may be used as the testing specimen for accurate estimation of the elastic-plastic fracture toughness of the nuclear reator pressure vessel forging steel with high toughness.

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