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A Study on the Microscopic Fracture Characteristics of A533B-1 Nuclear Pressure Vessel Steels

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A533B-1 원자로 압력용기 강의 미시적 파괴특성에 관한연구

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Abstract

The strain rate effects on fracture toughness and fracture resistance characteristics of A533B-1 nuclear pressure vessel steels were examined in the quasi-dynamic test conditions through the microscopic investigation of the intense strain region around crack tip and the microroughness of fracture surface. J-value calculated from the recrystallization etch technique was the same as calculated from the modified-J when the crack extension is less than 1.5mm in a 1/2T-CT specimen. Local fracture strain was calculated from the fracture surface microroughness. The local strains were calculated to be the values of 1.8 and 2.0 and were much higher than the macroscopically measured values. It was nearly independent on strain rate and was regarded as a material constant in ductile dimpled rupture. The fracture toughness increased with increase in strain rate while the tearing modulus showed little variation.

요　약

준 동적 파괴가 일어나는 변형율속도 조건에서 A533B-1 원자로 압력용기강의 파괴인성 및 파괴저항특성에 미치는 변형율속도의 영향을 균열선단의 강 소성역 관찰 및 파면의 미세거칠기측정을 통해 연구하였다. 1/2T-CT 파괴시편에서 약 1.5mm 이하의 균열진전에 대해서는 소성일로 부터 구한 J와 수정 J가 거의 일치하였다. 파면의 미세거칠기로 부터 구한 국부 변형율은 1.8−2.0 정도의 값을 나타내어 거시적으로 측정된 값보다 높은 값을 보여주었다. 이들 방법은 모두 변형율속도가 증가함에 따라 파괴인성은 증가하나 tearing modulus는 큰 변화가 없음을 보여주었다.

I. Introduction

Single specimen unloading compliance method has been recommended as a standard testing method in finding fracture toughness and resistance characteristics of engineering materials.[1,2] According to the studies of Rice and Johnson[3] and McMeeking,[4] it was predicted that steep strain gradient exists around the blunted crack tip. Since the total plastic work absorbed in that zone during stable crack growth has a relationship with J-integral,[5,6] it is possible to construct J-Resistance curve of the fast loaded CT specimens without unloading.

In this paper a microscopic fracture parameter, plastic work (Wp), was measured in simply loaded compact tension (CT) specimen to examine the J-R curve and the strain rate effect on J-R curve of A533B-1 nuclear pressure vessel steels. Fracture toughness (J_{IC}) of each specimen was calculated from the microscopic fracture surface observation by using the critical fracture strain model.[7] The applicability of the microscopic fracture mechanics parameters and the relationship between them were investigated.

II. Theory and Experimental Procedure

Assuming deformation theory of plasticity with crack growth effect, J-integral value at arbitrary point i of load displacement curve is[1]

$$J_{i+1}=\left[J_i+\frac{\eta_i}{b}\left(\frac{A_{i,\,i+1}}{B}\right)\right]\left[1-\frac{\gamma_i}{b}(a_{i+1}-a_i)\right] \cdots\cdots (1)$$

where a = crack length

b = uncracked ligament

W = CT specimen width ($=a+b$)

B = CT specimen thickness

$\gamma_i = 1+0.76(b/W)i$

$\eta_i = 2+0.522(b/W)i$

$A_{i,\,i+1}$ = the area enclosed by $i, i+1$ on the load-displacement record.

Hutchinson[8] proposed the J-controlled crack growth limit corresponding to about 6% of initial remaining ligament size, beyond which the validity of the deformation theory J is lost. Recently, Ernst[9] proposed modified-J which is independent of specimen size and geometry up to considerable amount of crack growth.

$$J_m=J_d-\int_{a_0}^{a}\frac{d(J_d-G)}{da}\bigg|_{\delta_{pl}} da \cdots\cdots\cdots\cdots (2)$$

where J_d = deformation theory J(Eq.1)

G = Griffith's linear elastic energy release rate

δ_{pl} = plastic displacement

Ernst[9] concluded that J_m could be used to evaluate the J-R until crack growth proceeded to about 30% of the initial ligament although J-controlled crack growth regime was violated.

During the crack growth, the plastic strain energy of the crack is absorbed near the crack tip. When the plastically deformed zone is recrystallized at a certain condition (at 650℃ for 3 hours in this experiment), the recrystallized grains show difference in diameter according to the amount of equivalent plastic strain since the number of nucleation site increases with the degree of plastic deformation. Fig.1 and Fig.2 show the schematic shape and photograph of the intense strain region of the recrystallized and etched specimen.

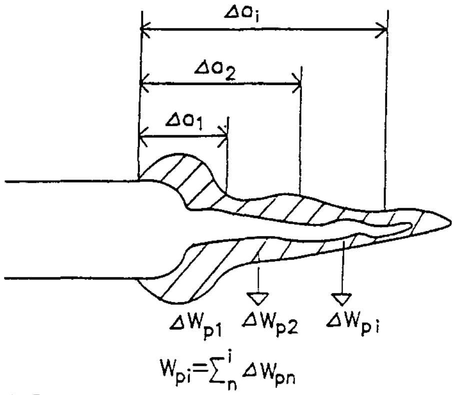

Fig. 1 Schematic of Procedure to Calculate W_p with Crack Extension in a CT Specimen

Fig. 2 Photograph of Recrystallized Intense Strain Region

Assuming that recrystallized zone corresponds to the intense strain region, total plastic work (W_p), absorbed in the region can be calculated from the optically observed recrystallized zone.[5,6]

Experimentally, Shoji[5] derived a simple relationship between J-integral (J_w) and W_p as follows.

$$J_w = \alpha \cdot \sqrt{E \cdot W_p} \quad \cdots\cdots (3)$$

where $\alpha = 0.11$

E=Young's modulus

Using this equation, it is possible that the J_w is calculated directly from W_p by measuring the recrystallized area.

In ductile fracture, crack initiation occurs when local strain becomes larger than a critical fracture strain at the position aparted by characteristic distance l_0^* from the initial sharp crack tip. Some recent studies proved that l_0^* was some multiples of the interdistance between the void initiating particles. Several methods were proposed to find critical fracture strain. Since dimple aspect ratio M =h/w (dimple height/dimple width) on fracture surface has a strong relationship with ductility and fracture strain, Thompson[11] calculated the local fracture strain by using the following relationship

$$\varepsilon_f^* = \frac{1}{3} l_n \left(\frac{M^2}{3f} \right) \quad \cdots\cdots (4)$$

Using simple relationship between J and COD, fracture toughness(J_{IC}) was given as follows.

$$J_{IC} = \text{Constant} \cdot l_0^* \cdot \sigma_0 \cdot \frac{1}{3} l_n \left(\frac{M^2}{3f} \right) \quad \cdots\cdots (5)$$

Thus fracture toughness can be determined from the volume fraction f of nonmetallic inclusion and dimple aspect ratio M of fracture surface, if yield stress (σ_0) is known.

The material used in this experiment is the ASTM A533B-1 nuclear pressure vessel steel. The chemical composition is shown in Table 1. ASTM standard chevron notched 1/2T-CT specimens were fatigue precracked until a/W reached about 0.6. Side groove of 20% was introduced to satisfy the plane strain condition. J-integral testing were performed by single specimen unloading compliance method. The test to examine the strain rate effect on the characteristics of fracture resistance were done at room temperature with various strain rate without unloading. J_d and J_m were calculated by Eq.1 and by Eq.2 respectively, then J_{IC} was calculated by ASTM regression method. The test condition of the specimens are listed in Table 2.

Table 1. Chemical Composition of A533B-1 Steel(wt.%)

Fe	C	Si	Mn	Ni	Cr	Mo	B
Bal	0.18	0.28	1.37	0.63	0.17	0.48	0.001

Table 2. Test Condition of CT Specimens

Specimen	Test condition		
	Temp.	Strain rate	Unloading
A	30℃	$0.001sec^{-1}$	Yes
B	0℃	$0.001sec^{-1}$	Yes
I	30℃	0.01^{-1}	No
II	30℃	$0.1sec^{-1}$	No
III	30℃	$1.0sec^{-1}$	No

Fractured tensile specimens were recrystallized to find the relationship between the recrystallized grain size and the equivalent plastic strain. All specimens were cut in half perpendicularly to the fracture surface by low speed cutter. One halves of the specimens were recrystallized at 650℃ for 3 hours and the other halves were fractured in liquid nitrogen.

The relationship between the recrystallized grain size and local strain was obtained from the recrystallized tensile specimens. From Fig.2 W_p was calculated by the equation in reference [5.6] and J_w was calculated from Eq.3. Then J_w was compared with J_d and J_m.

Fracture surfaces were examined carefully in a scanning electron microscope. The specimens were tilted by small angle to calculate the depth of fracture surface dimple. The depth of dimple was calculated approximately by a simple trigonometric relation.

$$h=\frac{X'-X_0\cos\theta}{\sin\theta} \quad \cdots\cdots (6)$$

where X_0=half width of dimple when untilted
X'=half width of dimple when tilted
θ=tilt angle

So local fracture strain and fracture toughness were calculated from Eq.4 and Eq.5.

III. Results and Discussion

J-R curves calculated by single specimen unloading compliance techniques are shown in Fig.3 and Fig.4 As seen in the figures, the difference between J_d and J_m increased when crack extension exceeds 0.6mm.

Since the integral in Eq.2 gives negative values, the values of the modified J are always greater than that of the deformation J. Assumming the modified J theory is more close to the practice, J_d by deformation theory underestimates the fracture resistance for 1/2T-CT small specimens. This fact indicates that J_d represents the fracture resistance characteristics in the tests with large specimens.

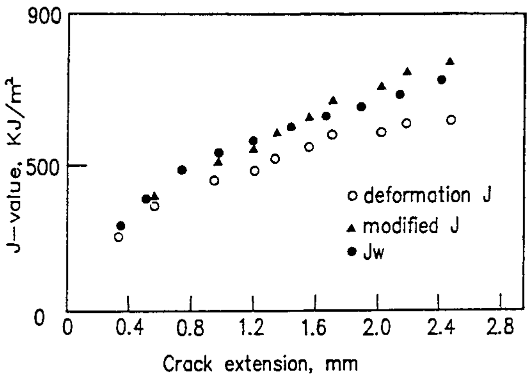

Fig. 3 J-R Curve of the Specimen A, Tested at 30℃ with Strain Rate of 0.001/sec.

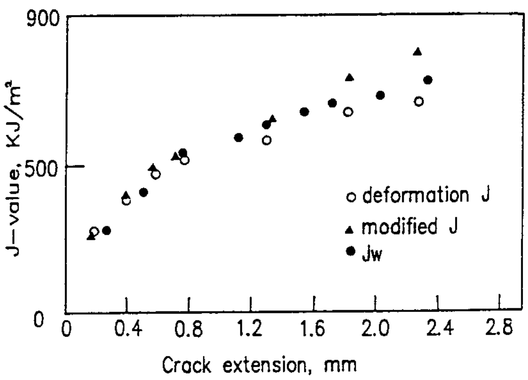

Fig. 4 J-R Curve of the Specimen B, Tested at 0℃ with Strain rate of 0.001/sec.

The correlation of local strain and recrystallized grain diameter of tensile specimen was shown in Fig.5. This result was used to calculate the local strain around the crack tip by comparison of grain diameter of tensile specimen with that of fracture specimen.

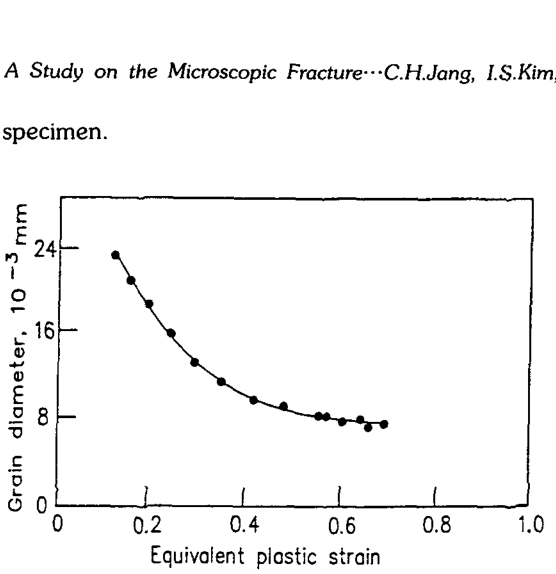

Fig. 5 Grain Size as a Function of Equivalent Plastic Strain of Recrystallized Tensile Specimen

The J_w-R curves calculated from Eq.3 are also shown in Fig.3 and Fig.4 with those from unloading compliance method. J_w are in good agreement with J_m when the crack growth was less than 1.5mm. However, the difference between them increased with further crack extension, which may be due to the fully deformed ligament and high triaxial stress state ahead of crack tip for small specimens.

J_w-R curves of simply loaded specimens with different loading rate from 0.3 MPa√m/sec to 300 MPa√msec were also calculated and J_{IC} and tearing modulus T were obtained from the J_w-R

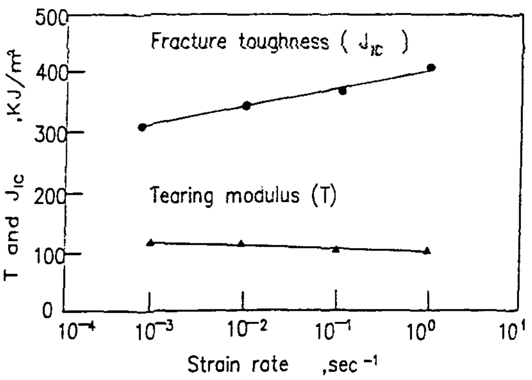

Fig. 6 Variation of Fracture Toughness (KJ/m²) and Tearing Modulus (dimensionless) as a Function of Strain Rate, in which the Values were Obtained from J_w-R Curves. The specimens were tested at 30℃.

curves. The values of T and J_{IC} are shown in Fig.6 J_{IC} increased about 40% but the slope of the curve showed no remarkable variation with strain rate in quasi-dynamic test condition. According to the results of Charpy test, at the upper-shelf energy region, the fracture toughness tested dynamically was higher than that of static test.[12]

Strain rate sensitivity could be explained by diffusion mechanisms such as the adiabatic condition ahead of crack tip and the time dependent embrittlement phenomena.[13] Bui and Ehrlacher[14] showed that damage zone (2×h) ahead of crack tip decreased with crack speed. Since fracture resistance may be proportional to the damage zone size, fracture resistance decreased with increase in strain rate. The width of intense strain region R measured in this experiment has a similar meaning to the damage zone and also decreased with strain rate increase.

The results of fracture surface observation are shown in Table 3. Characteristic distance l_0^* was in the range of 0.20mm and 0.22mm for fully dimpled rupture regardless of test condition. Thus it could be regarded as a material constant for ductile fracture to which the critical fracture strain model can be applied. Aspect ratio M varied from 0.6 to 0.8. Local fracture strain was in the range of 1.8 and 2.0 and was much higher than that of the analytical result[3] and that of the tensile test.[10] The fracture toughness increased with increasing strain rate in the upper-self region. Although this results are in contrast to the general trend that fracture toughness decreases as the strength of the

Table 3. Result of Fracture Surface Observation. J_{IC} was calculated by using the Eq.5.

Specimen	l_0^*(mm)	M	ε_f^*	J_{IC}(KJ/m²)
A	0.2128	0.594	1.79	225.38
B	0.2127	0.676	1.88	245.58
I	0.2027	0.657	1.86	230.87
II	0.2205	0.670	1.88	263.21
III	0.1972	0.799	1.99	261.63

material increases, but in agreement with the result of Kobayashi[12] for the same nuclear pressure vessel steels. This phenomenon is explainable by the fact that the flow stress can increase as strain rate increases without decreasing in the local fracture strain.

IV. Conclusions

1. J_w calculated from recrystallization technique has the same value as modified J which represents the behavior of large specimen until the crack extension reached about 1.5mm for 1/2T-CT specimens. Therefore, J_w could be used as fracture parameter up to considerable amount of crack extension althouth the J-controlled crack growth condition was violated.

2. At room temperature, which is nearly a upper-shelf region, fracture toughness increased with strain rate but tearing modulus was nearly constant.

3. Local fracture strain measured from microscopic observation was in the range of 1.8 and 2.0.

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