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Recrystallization–etch approach to study the plastic energy absorbtion at crack initiation and extension of pressure-vessel steel A533B-1

X. MAO, T. SHOJI*
Department of Mechanical Engineering, The University of Calgary, Calgary, Alberta, Canada T2N 1N4

To evaluate the elastic–plastic fracture toughness parameter of nuclear pressure-vessel steel A533B-1, a newly developed technique (the recrystallization–etch technique) for plastic strain measurement was applied to different sizes of compact tension specimens with a crack length/specimen width of 0.6–0.5 that were tested to generate resistance curves for stable crack extensions. By means of the recrystallization–etch technique, the plastic energy dissipation or work done within an intense strain region at the crack tip during crack initiation and extension was measured experimentally. Furthermore, the thickness effects on this crack tip energy dissipation rate were examined in comparison with other fracture-parameter J integrals. Thickness effects on critical energy dissipation and energy dissipation rate during crack extension were obtained and the energy dissipation rate $\mathrm{d}W_p/\mathrm{d}a$ in the mid-section shows a constant value irrespective of specimen geometry and size, which can be used as a fracture parameter or crack resistance property.

1. Introduction

Rice and Johnson [1] showed theoretically that the region corresponding to the intense stress region (ISR) allows ductile fracture processes to operate there. McMeeking [2] analysed the stress and strain fields around smoothly blunting crack tips in infinitely extended elastic–plastic materials under contained plane-strain yielding and subject to mode I opening loads, using a finite-element method formulated to admit large geometry changes. His theoretical analysis was concerned with the crack tip shape and near-tip deformation field, and the crack opening displacement (COD) as a function of the J integral, which was found to be path-independent except very close to the crack tip. Moreover, McMeeking and Parks [3] demonstrated that the J integral can be used as a unique parameter characterizing the near-tip deformation in deeply cracked bend specimens even under large geometry change and large-scale yielding.

The J-integral defined far from the crack tip is a globally measurable parameter which is proportional to the total strain energy absorbed in the whole specimen, the COD is a locally measurable parameter which represents directly a degree of damage in material near the crack tip.

Existing fracture mechanics analysis procedures tend to overestimate the risk of failure in a flawed nuclear pressure vessel. At service temperatures crack extension is accompanied by large-scale yielding. This allows a significant amount of stable crack growth to occur under rising load before general failure. Hence, to develop a flaw–structure interaction analysis suitable for describing accurately the behaviour of flawed ductile material, it is necessary to predict the conditions for crack initiation and stable crack extension, and also to predict the condition for structural instability which is the limit of stable crack extension. Under large-scale yielding conditions a large geometry change at the crack tip is accompanied by crack tip blunting and by stable crack initiation and extension.

In this study, the plastic energy dissipation within the intense strain region is chosen as the characterizing parameter of crack tip stress and strain fields even under large-scale yielding. The plastic energy dissipation or work done in an intense strain region at the crack tip accompanying stable crack initiation and extension were measured experimentally by the recrystallization–etch technique [4, 5]. The specimen size effect on this energy dissipation for stable crack initiation and extension were examined.

2. Experimental procedure

The material used for the present investigation was the nuclear pressure vessel steel A533B-1 for light water reactors (LWR). The original plate thickness of the A533B-1 was 125 mm; this material was post-weld heat-treated for 40 h at 868 K. The chemical composi-

* *Present address*: Research Institute for Fracture Technology, Tohoku University, Aza Aoba, Sendai 980, Japan

tion and the mechanical properties at room temperature of this material are given in Tables I and II.

Compact tension specimens of 25, 10, 5 and 3 mm thickness were prepared. Detailed geometries and dimensions are shown in Fig. 1 and Table III. All specimens had a longitudinal loading direction and transverse crack direction (L–T). Most of the compact specimens had an a/W value of 0.6. Only the 0.2 CT specimens had an a/W value of 0.5. After fatigue cracking the specimens were loaded monotonically to various displacement levels at room temperature; these correspond to different levels of crack extension.

After the specimen displacement had reached the desired level, the specimen was unloaded and heated to 400 °C for 30 min to heat-tint the cracked area. After fracturing the specimens at room temperature, the length of crack growth Δa (simple average value of nine points from the front to back surface) was measured optically. In order to measure a local effective plastic strain at the crack tip, some of the unloaded A533B-1 specimens were heated for 3 h at 700 °C in a vacuum to induce recrystallization [4, 5]. Around the crack tip, the original bainitic microstructure changed to ferrite in the region where the equivalent plastic strain exceeded 20%. A typical example of the region is shown in Fig. 2, obtained at the mid-section of 1CT specimen thickness. In the figure, the white region is the recrystallized region where the plastic work has been absorbed. Photographs of recrystallized grains were taken by optical microscopy with $\times 100$ magnification from which the grain size was measured. The relationship between recrystallized grain size and plastic strain was determined from multiple normal tensile tests up to different plastic strains, in which recrystallized grain sizes of the corresponding specimens were measured. Fig. 3 gives the relationship between recrystallized grain size and equivalent plastic strain, the latter defined as follows:

$$\bar{\varepsilon}_q = \left(\frac{2}{3}\right)^{1/2}\left(\frac{\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2 + \gamma_{xz}^2\,2 + \gamma_{yz}^2}{2 + \gamma_{yz}^2 \qquad\qquad 2}\right)^{1/2} \quad (1)$$

After measurement of grain size, plastic strain distribution around crack tip can be calculated by use of Fig. 3. The values of J were calculated from the

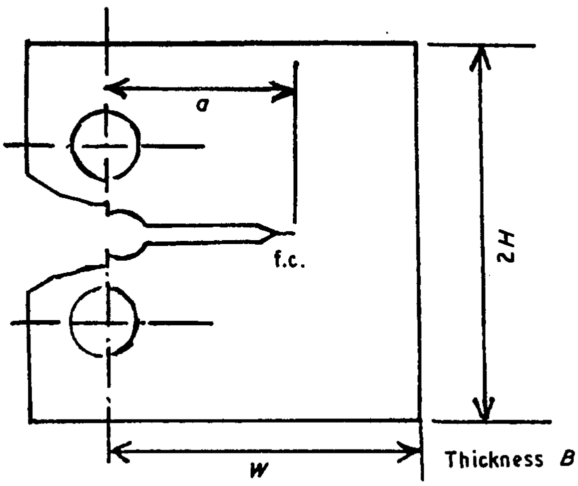

Figure 1 Specimen geometries and dimensions.

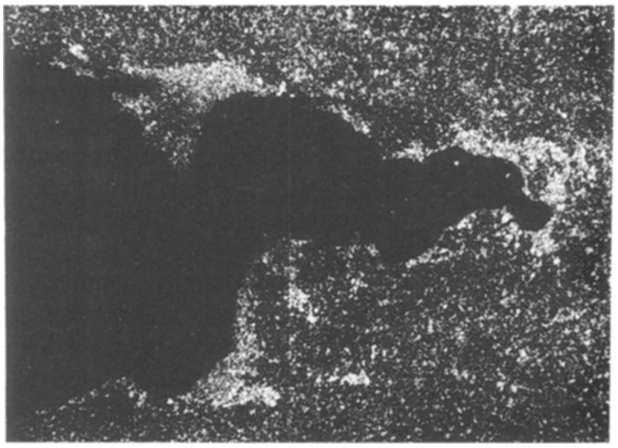

Figure 2 Example of intense strain-region at the crack tip with a 25 mm (ICT) thick specimen (white region is recrystallized area).

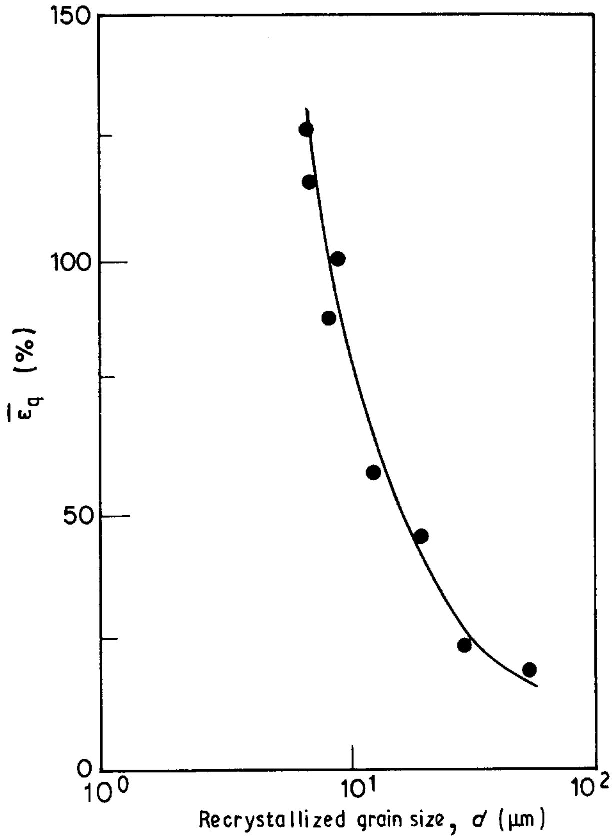

Figure 3 Relationship between recrystallized grain size and equivalent plastic strain of A53313-1 steel.

Merkle–Corten relationship

$$J = \frac{A}{Bb} f(a/W) \quad (2)$$

where A is the area under the load versus load-line displacement curve, B is the specimen thickness, b is the initial uncracked ligament length, a is crack length and $f(a/W)$ is a dimensionless coefficient value.

3. Results and discussion

Shoji [5] has investigated the significance of the crack tip energy dissipation for the material's resistance againt stable crack growth by means of the recrystallization–etch technique. The total plastic work W_p within the recrystallized region per unit thickness was defined as follows:

$$W_p = \int_S w_d \, dS = W_d S = \left(\frac{4S}{\pi + 4}\right)\frac{\pi}{2}\left[\left(\frac{\sigma_{ys}^* \bar{\varepsilon}_0}{2 - m} + \frac{H' \bar{\varepsilon}_0^2}{4(1 - m)}\right) + \left(\frac{\sigma_{ys}^* \bar{\varepsilon}_0}{1 - m} + \frac{H' \bar{\varepsilon}_0^2}{2(1 - 2m)}\right)\right] \quad (3)$$

where S is the total area of the recrystallized–etched region obtained from a direct measurement and W_d is the plastic strain energy density. W_p can be calculated from Equation 3 with the following values determined experimentally through tensile properties: $\sigma_{ys}^* = 645$ MPa (pseudo-yield stress), $\bar{\varepsilon}_0 = 0.20$ (critical equivalent plastic strain for recrystallization), $m \simeq 1.0$ (slope of strain distribution at crack tip [5]) and $H' = 480$ MPa (strain-hardening rate). Here σ_{ys}^* and H' were obtained from the true stress–strain curve for A533B-1 as shown in Fig. 4.

By use of Equation 3, the plastic energy absorbed at the crack tip for different-sized specimens was calculated. Fig. 5 shows the variation of critical energy dissipation W_p at crack initiation with specimen thickness. The crack initiation points were determined from the J–Δa curve which has been reported [6]. It can be found that W_p^c remains constant when the specimen thickness is larger than 10 mm. W_p means the energy absorbed at the crack tip for crack initiation. W_p^c can be considered as a fracture parameter for crack initiation.

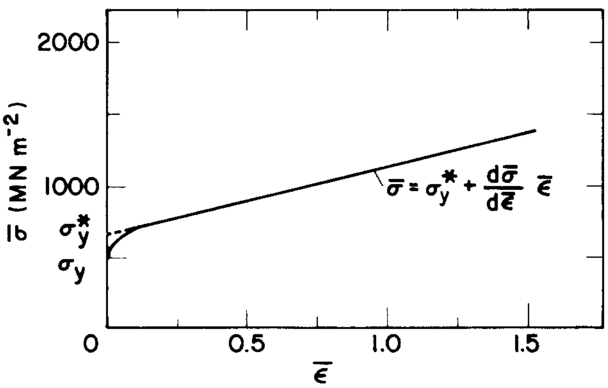

Figure 4 True stress–strain curve of A533B-1 at room temperature. $\sigma_y^* = \sigma_y + \Delta\sigma_y = \sigma_y + 150$ MN m^{-2}; $d\bar{\sigma}/d\bar{\varepsilon} = 480$ MN m^{-2}.

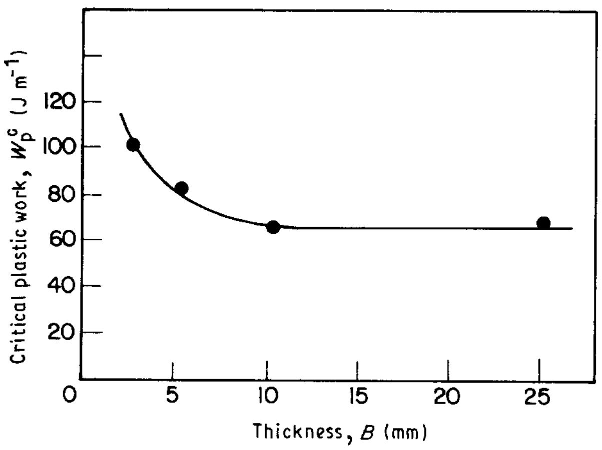

Figure 5 Thickness effect on critical energy dissipation W_p^c.

It is well known that the J_{1c} integral has been established as the ductile fracture parameter. Fig. 6 shows the relationship between W_p and the J integral in A533B-1 steel as cracks propagated for different sizes of specimen. From this figure, this relationship can be expressed as

$$J = \alpha W_p^{1/2} \quad (4)$$

where α is a constant determined experimentally, depending on specimen size or stress conditions:

$\alpha = 27$ and 50 for specimen thickness 3 and 25 mm, respectively. (5)

α increases with increasing specimen thickness, while the critical energy dissipation W_p^c decreases with increasing thickness as shown in Fig. 5. Consequently, the thickness effect on J_{IC} can be estimated from Equation 4 as $J_{IC} = 320$ and 390 kJ m^{-2} for specimen thicknesses 3 and 25 mm, respectively, which means that J_{IC} decreases with decreasing thickness; this result is consistant with the J_{IC} testing results [6].

In theoretical studies Hutchinson [7] and Shih *et al.* [8, 9] investigated the relationship between the J integral and the plastic work done at the crack tip in small-scale yielding. From their results, in the small-scale yielding region, the strain energy W_p within the area of radius r_0 around the crack tip is expressed as

$$W_p = \left(\frac{1}{n + 1}\right)\left(\frac{J}{I_n}\right) E_n r_0 \quad (6)$$

where n, I_n and E_n are material constants. Here, the area of the recrystallized region formed by the crack tip blunting approximately corresponds to the area of a circle that has a radius of $\delta_t/2$. Therefore, r_0 in Equation 6 can be expressed as

$$r_0 = \delta_t/2 \quad (7)$$

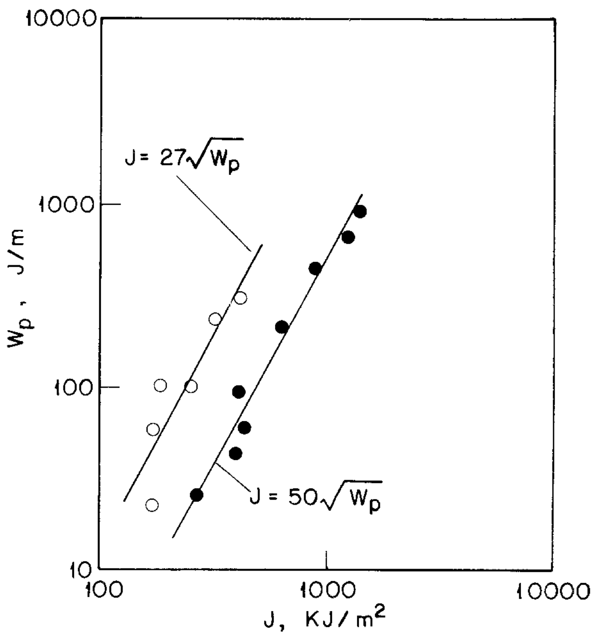

Figure 6 Relationship between energy dissipation W_p at crack tip and J integral. Thickness B: (○) 3 mm, (●)25 mm.

where δ_t can be correlated with the J integral as

$$\delta_t = d_n J/\sigma_f \tag{8}$$

where

$$\sigma_f = (\sigma_y + \sigma_{UTS})/2$$

Substituting Equations 7 and 8 into Equation 6, J is represented by

$$J = \left(\frac{2}{d_n}\right)^{1/2}\left(\frac{n+1}{n}\right)^{1/2}\frac{I_n}{E_n}\sigma_f^{1/2}W_p^{1/2} \tag{9}$$

where $n = 6.6$ [8], $I_n = 4.85$ [8], $E_n = 1.41$ [8], $d_n = 0.5$ [9], and $\sigma_f = 540$ MPa for A533B-1 steel. Using these values, Equation 9 becomes

$$J = 93\ W_p^{1/2} \tag{10}$$

This theoretical relationship agrees qualitatively with the form of Equation 4 that is determined experimentally. From this analysis it can be reasonably concluded that the relationship between W_p and the J integral (Equation 4) is valid even under small-scale yielding conditions as well as large-scale yielding conditions.

Fig. 7 shows the relationship between W_p and crack extension at mid-section Δa_{mid} obtained from various specimen thicknesses. A good linear and size-independent relationship exists with $dW_p/da = 290$ kJ mm^{-2}. The results obtained permits the evaluation of the specimen size-independent crack resistance property dW_p/da in A533B-1.

Saka *et al.* [10] introduced a new tearing modulus (T_w) parameter expressed in terms of the rate of crack tip energy dissipation in the form

$$T_w = \frac{1}{R}\left(\frac{E}{\sigma_{fs}^2}\right)\frac{dW_p}{da} \tag{11}$$

where E is Young's modulus, σ_{fs} is the flow stress and R is the radius of the intense strain region at the growing crack tip. Therefore the specimen size-independent fracture resistance T_w can be determined uniquely from the crack extension.

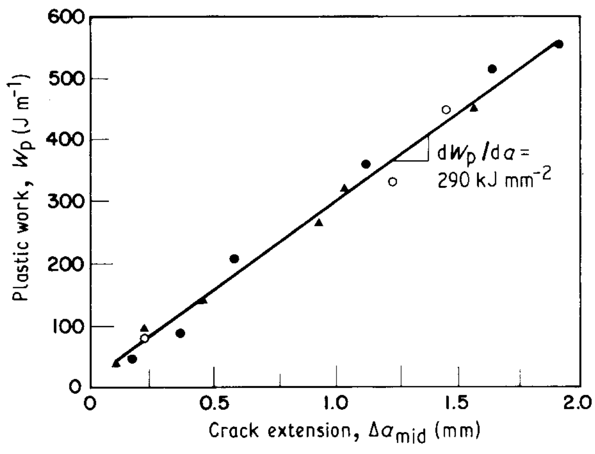

Figure 7 Relation between plastic work at crack tip and extended crack length at mid-section for various specimen thicknesses B: (▲) 3 mm, (○) 5 mm, (●) 25 mm.

4. Conclusions

To study the ductile crack initiation and propagation criteria for nuclear pressure vessel steel, the crack tip energy dissipation W_p and its variation with ductile crack extension dW_p/da were measured experimentally by means of the recrystallization–etch technique. The conclusions are as follows:

1. The critical energy dissipation W_p^c remains constant when the specimen thickness is larger than 10 mm.
2. The plastic energy dissipation rate with crack growth dW_p/da in the mid-section has a constant value irrespective of specimen geometry and size during stable crack extension, which can be used as a fracture parameter on crack propagation resistance property.
3. The experimentally obtained relation between energy dissipation at specimen mid-section and the J integral is dependent on specimen thickness.

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