Evaluation of Fracture Toughness of Ductile Thin Metal Sheet

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(Received July 15, 1981)

Abstract

To characterize the stable crack extension, it is commonly used a J-integral R-curve instead of a linear elastic R-curve.

This paper presents the formula obtained by modifying Liebowitz's, so that this formula may be applied to the investigation of crack extension force using a J-integral R-curve for the ductile metal sheets. The effects of specimen geometry, size and initial crack length on J_{R_0} at the onset of stable crack extension are discussed by using this method for the stainless steel sheets, SUS 430, with a thickness of 1.2mm. The stable crack extension phenomena of the same specimens are analyzed by considering the tearing modulus obtained by this method.

1. Introduction

For ductile metals, the fracture toughness characterization by J_{IC} or critical COD has an engineering significance as an applicable design criterion, but the stable crack extension phenomenon is also the object of important consideration, especially for thin metal sheet structures such as piping, vessels etc.

The R-curve method proposed by Irwin[1] is one of the useful methods to determine fracture resistance of metals. Since this method is based on linear elastic fracture mechanics, it seems that this method is not applicable to the evaluation of fracture resistance of low strength metal sheets, the ductile crack extension of which is accompanied by large plastic deformation ahead of the crack tip. Recently, Paris[2] and Hutchinson[3] proposed a new nondimensional material parameter, T, tearing modulus, and tried to analyze the crack instability phenomenon by using a J-integral R-curve. It is necessary to get the accurate J-integral values to find the validity of the tearing modulus for the various specimen geometries. Rice, Paris and Merkle[4], and Merkle and Corten[5] proposed practical formulas for calculation of J-values on the three point bend specimen and the compact tension one. In those formulas, the work done by external force is evaluated by assuming that rotations occur about the point of stress reversal which is defined by stress distribution in a specimen at plastic collapse. Since, at the onset of crack extension, the plastic zone in the vicinity of crack tip is commonly very small as compared with the ligament in the case of a large size specimen, it appears to be difficult to find the rotational point at the elastic-plastic zone. On the other hand, Liebowitz and Eftis[6], and Jones, Poulose, Eftis and Liebowitz[7] showed the modified energy release rate under the consideration of the subcritical crack growth and the inelastic deformation. It is the ad-

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vantage of their method that both fracture toughness at crack initiation and the unstable crack extension are obtained from the R-curve which is evaluated by replacing the load P displacement δ curve by the form of parabola of the n-th degrees. But it appears difficult to obtain the R-curve exactly in the case of very large crack extension, because the approximate P-δ curve is determined by the elastic compliance of the specimen and only one point on the experimental P-δ curve.

In this study, the authors propose the modified Liebowitz's method which selects several points on the P-δ curve corresponding to the elastic compliance of the specimen at the crack extension. Then, the fracture toughness of thin stainless steel sheet, SUS 430, with a thickness of 1.2mm is investigated by using this method. First, a J-integral R-curve for the deep notch compact tension specimen by using this method is in fair agreement with the R-curve by using the Merkle's method[5].

Then, the effects of specimen geometry, size and initial crack length on the J_{R0} at crack initiation are discussed by using the proposed method. Finally, the stable crack extension phenomenon is analyzed by considering the tearing modulus, T, obtained by this method.

2. Evaluation of J-Integral using the proposed method

The load P versus load point displacement δ in Fig. 1 is approximated in the form of a polynomial of the n-th degrees as follows:

$$\delta = \sum_{i=1}^{n} ki \{P \cdot C(a)\}^{i} \tag{1}$$

Where, k_is are the unknown coefficients which are determined from the experimental results. And C(a) is the elastic compliance of the specimen with the crack length a as shown in Fig. 1.

For the crack length a_j, the work done U in loading body is

$$\begin{aligned} \{U\} a=a_j &= \int P d\delta \\ &= \sum_{i=1}^{n} \frac{i}{i+1} k_i \ C^i \ P^{i+1} \end{aligned} \tag{2}$$

J-integral is expressed in the from as follows: (reference Fig. 1)

Therefore J becomes $\Delta U = J \cdot \Delta a_j$

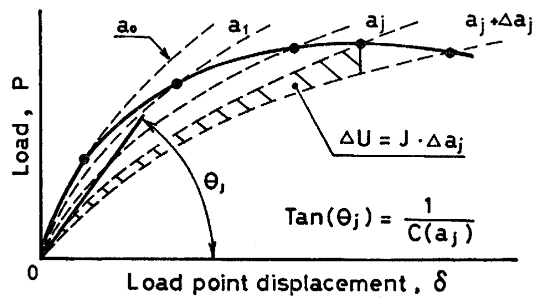


Fig. 1 Typical load versus load point displacement.

$$J=\left(-\frac{\partial U}{B\partial a}\right)_{a=a_j}$$

$$=\left[\left\{\sum_{i=1}^{n}\frac{2i^2}{i+1}k_i(P\cdot C)^{i-1}\right\}\frac{P^2}{2B}\frac{\partial c}{\partial a}+\left\{\sum_{i=1}^{n}i\cdot k_i(P\cdot C)^i\right\}\frac{1}{B}\frac{\partial P}{\partial a}\right] \tag{3}$$

where B is the thickness of specimen. It is assumed that the test machine and fixtures are rigid. Taking $\partial\delta/\partial a$ as zero, from Eq. (1)

$$\frac{\partial\delta}{\partial a}=0=\left\{\sum_{i=1}^{n}i\cdot k_i\cdot(P\cdot C)^i\right\}\frac{1}{P}\frac{\partial P}{\partial a}+\left\{\sum_{i=1}^{n}2i\cdot k_i\cdot(P\cdot C)^{i-1}\right\}\frac{P}{2}\frac{\partial C}{\partial a},$$

$$\frac{1}{B}\frac{\partial P}{\partial a}=-\left\{\sum_{i=1}^{n}2ik_i\cdot(P\cdot C)^{i-1}\right\}\frac{P^2}{2B}\frac{\partial C}{\partial a}\Big/\sum_{i=1}^{n}i\cdot k_i\cdot(P\cdot C)^i \tag{4}$$

Substituting from Eq. (4) into Eq. (3) and rearranging

$$J=\alpha\,G$$

$$\alpha=\sum_{i=1}^{n}\frac{2i}{i+1}k_i(P\cdot C)^{i-1},\quad G=\frac{P^2}{2B}\frac{\partial C}{\partial a} \tag{5}$$

It notes that G is the strain energy release rate for linear elastic fracture mechanics, and α is the coefficient of plastic deformation effect. Thus α will tend to 1 when the plastic zone ahead of crack tip is very small. Tearing modulus, T, proposed by Paris[2] and co-workers becomes

$$T=\frac{E}{\sigma_0^2}\frac{\partial J}{\partial a}=\alpha\frac{E}{\sigma_0^2}\frac{\partial G}{\partial a} \tag{6}$$

where σ_0 is the yield strength 0.2% offset and E is Young's modulus.

3. Experimental procedure

Material used in this study is a 1.2mm thick SUS 430 stainless steel sheet which was annealed at 800°c after the cold-rolling. The chemical compositions and the mechanical properties are given in Table 1 and 2.

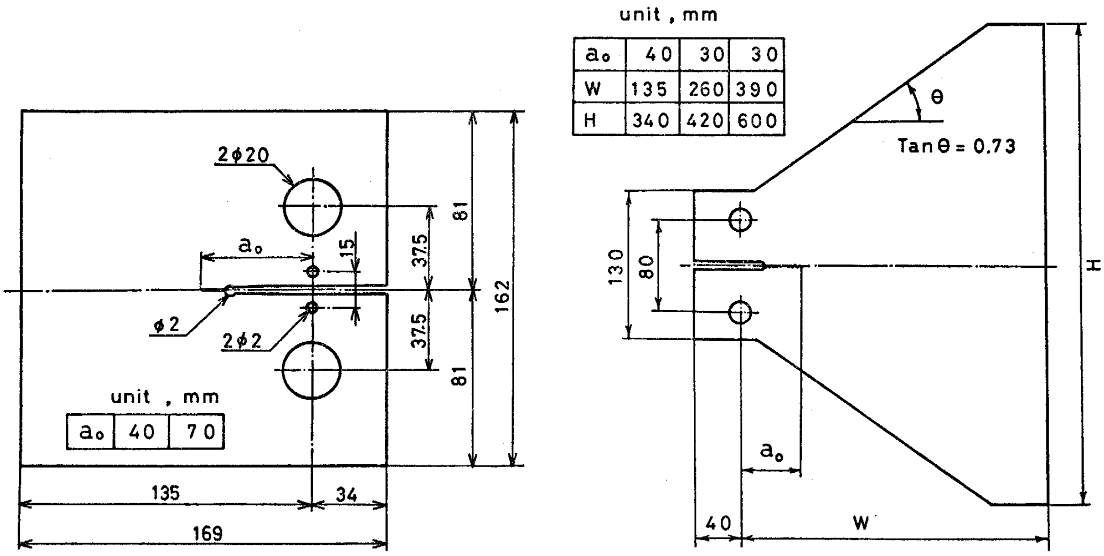
The two specimen types are as shown in Fig. 2. These are the compact specimens (CTS) with initial crack length a_0=70mm and 40mm, and the tapered double cantilever beam specimens (TDCB) with a_0=40mm and 30mm. The specimen width, W, of TDCB was selected as 135, 260 and 390mm in order to investigate the size effects on J_{R0} and

Table 1 Chemical compositions of SUS 430, (%)

C	Si	Mn	P	S	Ni	Cr	Al	N
0.052	0.51	0.36	0.023	0.006	0.09	16.45	0.066	0.0097

Table 2 Mechanical properties of SUS 430

0.2% Yield strength	Ultimate strength	Elongation
307 MPa	463 MPa	40.4 %



(a) Compact tension specimen (b) Tapered double cantilever beam specimen

Fig. 2 Specimen geometries.

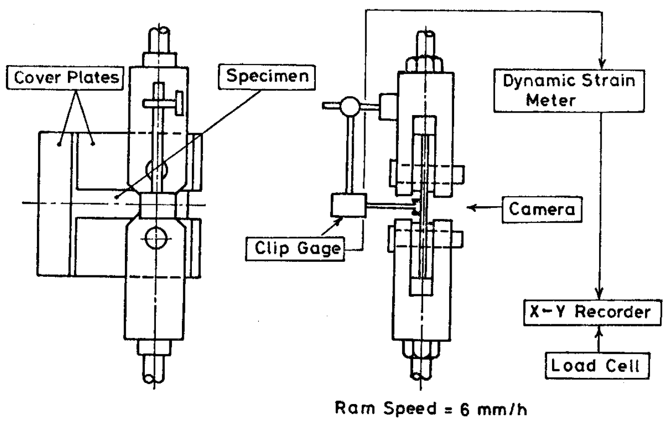


Fig. 3 Schematic illustration of test apparatus.

J-integral R-curves. All specimens were notched and fatigue precracked with the crack running in the rolling direction. Ripling[8] proposed the method that used a specimen, which was made up as an adhered sandwich in which heavy members were glued onto the test material, in order to prevent upsetting of the holes and buckling of the sheet. But the same method can not be applied in this study, because the ductile crack extension is accompanied by large plastic deformation and glued-on cover plates constrain the in-plane deformation of the test material, so that the effect of the cover plates on the load-displacement curve is not of a negligible order. To avoid this trouble, the test material is sandwiched with 20mm thick steel plates of which both outside surfaces are clamped by hand-vises.

The effect of the cover plates on the stiffness of the specimen is of a negligible order as shown in next section. The schematic illustration of test procedure is shown in Fig. 3.

The ram opened the load point of the specimen at about 6mm/h, and the load line displacement versus load was recordde on an X-Y recorder. The crack extension Δa was measured by the travelling microscope and the photomicrograph.

4. Results and discussion

4.1. Comparison between the proposed formula and Merkle's

Rices's J-line integral values were calculated by FEM in order to evaluate the accuracy of J-integral values obtained by proposed method.

Fig. 4 show the mesh division for a half soecimen and the fatted lines are contours

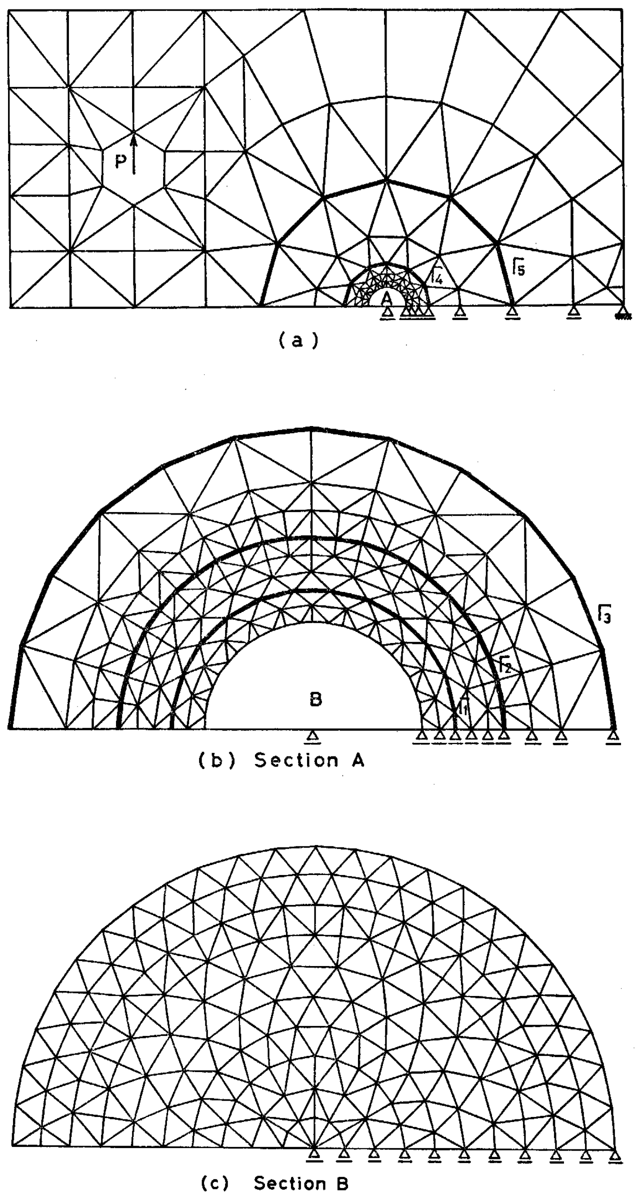


Fig. 4 Finite-element idealization for crack configuration.

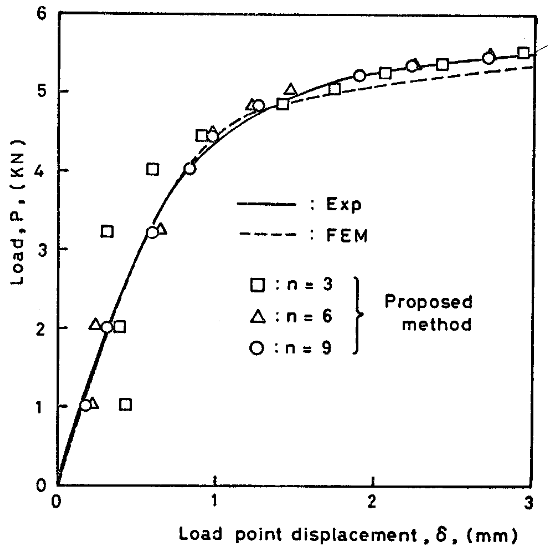


Fig. 5 Comparison between experimental and calculated P versus δ curve diagram.

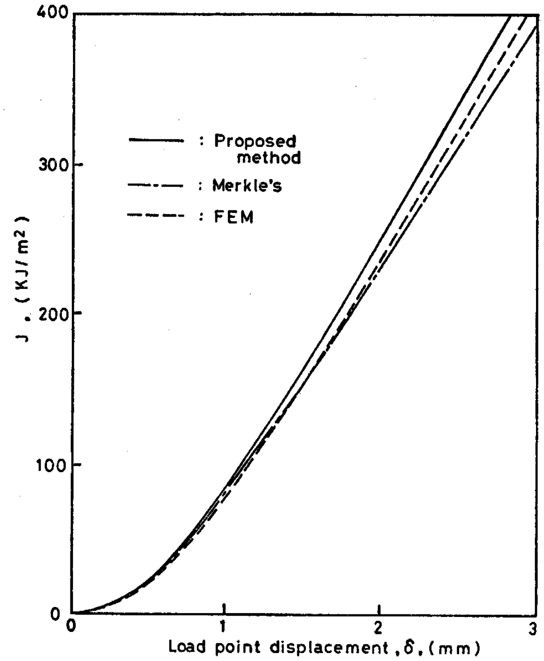


Fig. 6 Results obtained by using proposed method, Merkle's FEM analysis for J-δ relationship.

of J-line integral. To get a good approximation for the P-δ curve obtained by experiment, after a number of trials, it was sufficient to take nine terms for n in Eq. (1), as shown in Fig. 5. On the other hand, the P versus δ using Finite Element computations, a dotted line show in Fig. 5, was in good agreement with the experimental results. Hence, it seems that the effect of cover plates on the specimen stiffness can be neglected. The elastic compliance C(a) of specimen is given by using the FEM analysis.

Fig. 6 shows the relationship between J-integral and δ for CTS (a_0=70mm), which were evaluated by using the proposed formula, Merkle's and the EFM computations. The FEM computations were the line integral along a contour remote from the crack tip and their calculations were carried out for both stationary and growing cracks. The results obtained by the proposed method and Merkle's were in fair agreement with the J-integral values using FEM computations, though the material used in this study had high ductility such as SUS 430 stainless steel sheet. Merkle's formula is very excellent if applied to deep notch compact specimen, because it is very simple and is derivatived from a single P versus δ relationship. On the other hand, the proposed method is a slightly complicated in determining the elastic compliance and measuring the crack extension Δa, but this proposed method may apply to specimens with various geometries and in the elastic-plastic condition prior to the general yielding.

4.2. Discussion for J-integral R-curve

A J-integral R-curve of the thin ductile metal sheet has the distinctive feature as shown in Fig. 7. Namely,

(A) the region of crack tip blunting,

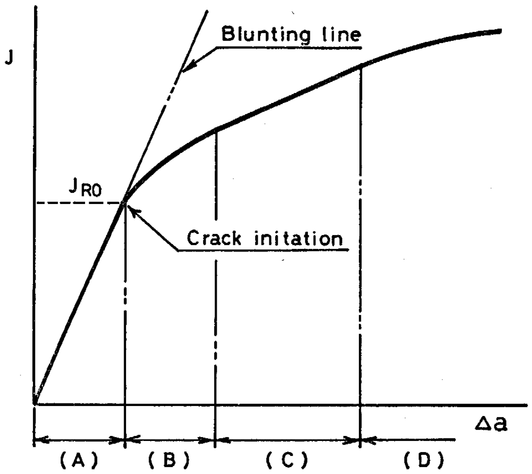


Fig. 7 Schematic illustration of J-Δa curve.

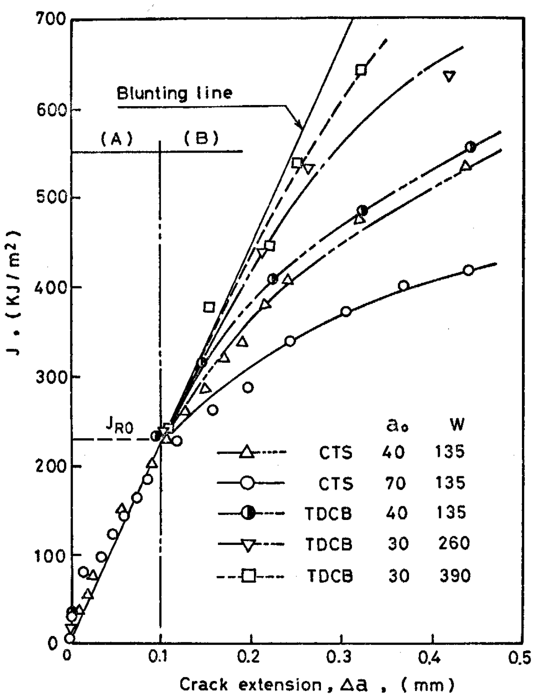


Fig. 8 J-Δa curves in the region (A) and (B).

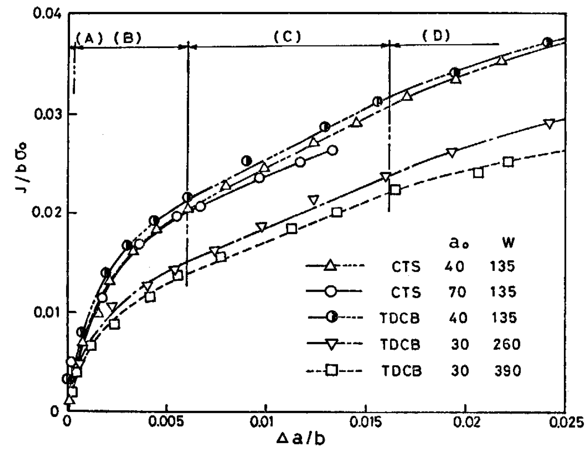


Fig. 9 Effects of specimen size on J/bσ_0-Δa/b.

(B) the region of the transition from flat fracture to slant fracture,

(C) tearing modulus, T=constant region,

(D) T value tends to zero.

First, the experimental results in regions (A) and (B) are detailed as shown in Fig. 8. The figure gives evidence that J_{Ro} at the onset of crack extension is independent of the crack length, specimen type and size, and the values were about 230 KJ/m^2. But the initial tearing slope, $\delta J/\delta a$, depended on the ligament width. Especially, for some of the TDCB ($a_0/w=0.12$, 0.08), the magnitude of $\delta J/\delta a$ is almost equal to the slope of blunting line, therefore, it is difficult to determine distinctly J_{Ro} by using J-integral R-curve only. In this study, the onset of crack extension is estimated by a combination of the CTOD (Crack Tip Opening Displacement) approach and the J-integral R-curve.

Finally, $J/b\sigma_0$ versus $\Delta a/b$ is given in Fig. 9, where b denotes the ligament width of specimen and σ_0 is the yield strength 0.2% offset. For the specimens with same initial crack length (a_0=40mm) and ligament width, these curves are almost equal without regard to the difference of specimen type. J valuse increases in proportion to the ligament width. On the other hand, the tearing modulus, T, is independent of the initial crack length and specimen size in region (C). In this investigation by using the proposed method for SUS 430 stainless steel sheet, the T value is about 600.

5. Conculusions

In this paper, the authors proposed a method obtained by modifing Liebowitz's, approach and applied this method to the evaluation of J-integral R-curve for the compact specimen and the tapered double cantilever beam specimen in order to investigate the phenomenon of stable crack growth of the thin ductile metal sheet, such as a 1.2mm thick stainless steel sheet (SUS 430), we obtained the following results.

1. For a compact specimen with the deep notch, J-values evaluated by this method displayed good agreement with the results obtained using Merkle's and FEM computations.

2. The J values at the onset of stable crack extension were independent of specimen size and initial crack length a. But the initial tearing slope of J, $\partial J/\partial a$, depended on specimen size and increased in proportion to a_0/w values.

3. The tearing modulus, T, decreased with the crack extension at the first stage of stable crack extension, region (B). This phenomenon would be caused by the transition of fracture surface from flat to slant. On the other hand, T values were constant under the slant fracture condition, (region (C)), without regard to the difference of specimen size.

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