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◉ 論 文

Load-Ratio법에 의한 SA508C-3와 알루미늄 합금의 탄소성 파괴저항 곡선평가

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Evaluation on Elastic-Plastic Fracture Resistance Curve of SA508C-3 and Aluminum Alloy Steels by Load-Ratio Method

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Key Words : Load-ratio method, Unloading compliance method, Elastic-plastic fracture resistance curve, Normalized load displacement curve, Rotation hinge model

Abstract

A method is proposed to evaluate the elastic-plastic fracture resistance curve only with load displacement records without the crack length measurement in CT specimen. This method is based on the idea that the effect of plastic deformation and the crack growth can be measured only by using a load-displacement record. If we know the reference-load curve representing the hardening of specimen, then the crack extension can be calculated by the elastic compliance determined from the load ratio.

The results of this proposed method were compared to those of the elastic-plastic fracture resistance curve for the ASTM standard unloading compliance method. The experimental results for two kinds of ductile materials showed that the proposed method well simulates the material J-R curves. This method is currently applied for CT specimens, but it can be extended to the other specimen geometries.

1. INTRODUCTION

As a parameter characterizing the fracture behavior of the ductile materials, J-integral is most widely applied to the structural design on the basis of the J_{IC} and J-R curve test method, which becomes the standardized test method of ASTM E813[1], E1152[2] for the measurement

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of fracture toughness. Usually, the multiple specimen method to measure J_{IC} is applied. But, owing to the economic effectiveness and the errors of data, single specimen methods tend to be principally applied. To obtain the characteristic of J-R curve with a single specimen test, we need a method to evaluate the crack growth length in fracture test. There are two methods: the method of unloading compliance and the DC and AC potential drop. Thus two methods are recommended ASTM standardized ones. The precise instrument equipment and a lot of experiences for the actual experiment are needed.

When we, at the industrial sector with the principal objective of present material development, apply the those test methods against the frequently made trial products, it causes a lot of problems in terms of an economic effectiveness and time. In addition, it is necessary for us to simplify the test procedure because of the difficulty of treating the radioactive specimen that becomes the basis of the safety evaluation for the nuclear power plant. For ten years or so, many researchers have been interested in developing and simplifying the method for the test and also analysis procedure has become much interested in for the researchers, and key-curve analysis method by Ernst[3] presented the possibility of load displacement curve which did not require precision. But, this method is lacking in the background of physical meaning and at the same time has many difficult problems of realistic application procedure.

This research is to present a method of deciding the J-R curve characteristic only by utilizing the load-displacement curve without any particular precision instrument equipment. This research is based on the physical meaning that indicates the effect of work hardening of both the crack growth and the plastic deformation of material by load variation at the fracture toughness test. This research compares the test results of the proposed method with those of ASTM, the unloading compliance method by using SA508C-3 and Al 6061-T3 specimens to evaluate the reliablility of the fracture resistance curve.

2. THEORETICAL BACKGROUND

Typical load-displacement curve, obtained at the test of the fracture toughness of ductile material, is shown in Fig. 1. The crack propagation of the material with the ordinary work hardening originates at a certain point before the maximum load point A or one between this point and the elastic area. It is expected that the load on the specimen continually increases owing to the decrease of sectional load area that results from the crack propagation crossing the maximum load point P_{max}. In the case of the fracture toughness specimen mainly receiving the bending load, the supporting load of uncracked ligament supports the load variation along with the crack length and, therefore, can be normalized into the following limit load formula. In the case of CT specimen under the condition of plane strain, the limit load P_0 is expressed as follows[1].

$$P_0 = 1.455\sigma_{ys} \cdot B \cdot \beta \cdot b \qquad (1)$$

$$\beta = \sqrt{4\left(\frac{a}{b}\right)^2 + 4\left(\frac{a}{b}\right) + 2} - \left(\frac{2a}{b} + 1\right)$$

Where B is thickness of specimen, a is crack length, and b is ligament length.

P_0 of the equation (1) shows the degree of work hardening arising only from the load support area. Fig. 2 is the normalized load displacement curve that is obtained by substituting the initial crack length for the growing crack length measured by using the unloading compliance method. As shown in equation (1), load-displacement curve propagates the crack; and in spite of the decrease of the total load on the specimen, the ligament relatively indicates the continuous work hardening. Here, we can consider the effect of work hardening of the material, which varies with the geometry of the given specimen, and the softening effect along with the crack propagation.

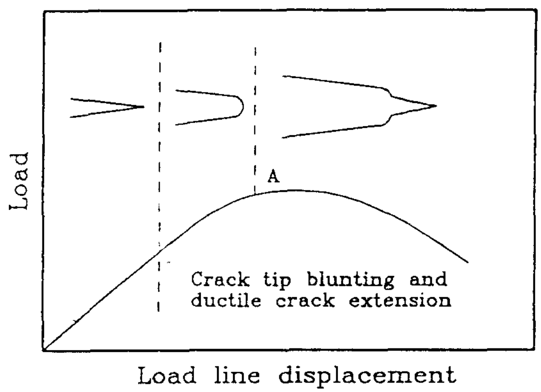

Fig. 1 Schematic representation of load-dispacement record during a fracture toughness test

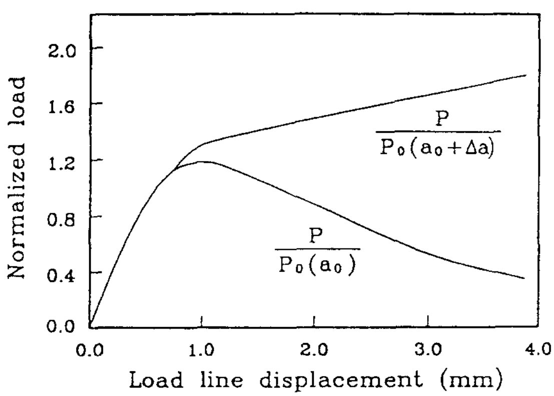

Fig. 2 Normalized load-displacement curve by the equation (1) with the initial and the growing crack

In the hardening effect, the relationship between load-displacement and crack length can be observed in Fig. 3. Working on the fictitious material that does not permit crack propagation, the load of work hardening increases with OA line along with the displacement. As for the actual material that propagates the crack in the test, initially the load goes along OS line and then separates at point S into SA and SA′ on load-displacement curve, and at the points initial crack propagation begins.

We can explain the physical process up to point P′ as follows. At first, it stops the crack and increases the displacement we can reach point P. Then, if we fix the displacement and increase the crack as far as Δa, and elastic load can occur and the load on the specimen decreases into P′. But the quantity of plastic deformation between P and P′ is same. Accordingly, the elastic compliance of P′ in Fig. 3 can be obtained as follows:

$$C(a_0+\Delta a) = C_0 \times \frac{P}{P'} \tag{2}$$

In the case of CT specimen, the elastic compliance under the unloading compliance method retains the direct relationship with the crack length and by Saxena and Hudak[5] as follows:

$$\frac{a}{W} = 1.000196 - 4.06319U + 11.242U^2 - 106.043U^3 + 464.335U^4 - 650.677U^5 \tag{3}$$

$$U = \frac{1}{\sqrt{B \cdot E \cdot C} + 1}$$

Therefore, if we know the load line displacement curve OA, we easily determine the elastic compliance by equation (2) at the location S of monotonic load displacement OA′. This values substitutes with the equation (3), and then the actual crack length is measured.

There are some methods to seek the reference curve OA. One is to use the analysis of elastic-plastic compliance by FEM that was developed by the researchers like Kumar[1].

$$\Delta_L = \alpha \cdot \varepsilon_0 \cdot a \cdot h_3(a/W, n) \cdot \left(\frac{P}{P_0}\right)^n \qquad (4)$$

Here Δ_L is load line displacement, ε_0 is yield strain, h_3 is the function of α and n which are Ramberg-Osgood tensile constants, as shown $\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n$. But to utilize equation (4), we should know the relationship between material and true stress-strain which makes it difficult for as to use the rotation of specimen in accordance with the plastic deformation in precise and practical test of the equation (4).

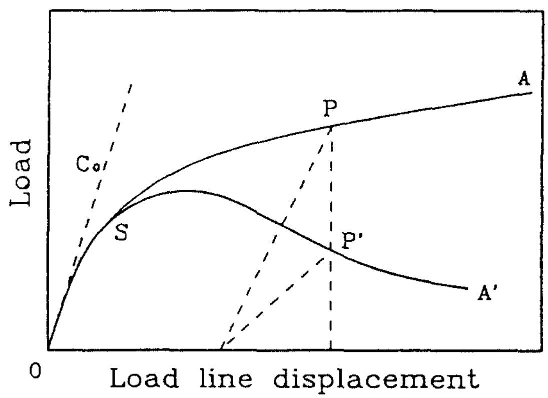

Fig. 3 The basic idea of load-ratio method for direct determination of the elastic compliance

Accordingly, in this study, I attempted to perform the following simple method:

Fig. 4 shows the normalized load displacement curves for various crack lengths. Initial crack length is a_0. As the crack length gradually increases from a_0 to a_f in the test, the normalized load displacement curve for the increased crack length appears as a real line in Fig. 4. When we finish the test, we can measure the length of final crack on the specimen surface. Point F of Fig. 4 is real measurement value. At the initial stage, in which specimen is loaded and the crack does not greatly propagates, this measured load displacement curve nearly corresponds to the reference curve. We suppose that we can make the normalized load displacement curve close to the approximate direct line the gradual crack propagation.

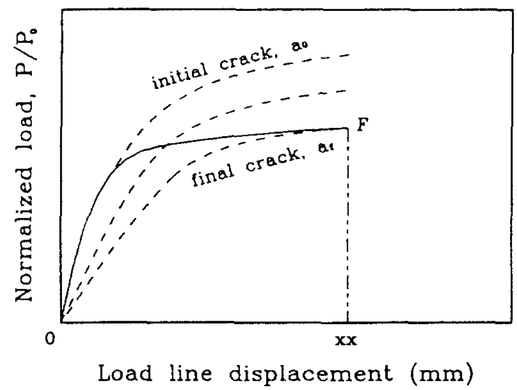

Fig. 4 Normalized load-displacement curves for various crack lengths(The solid line is for growing crack and the differences are exaggerated)

We can obtain the reference load curve by drawing the tangential line, which begins at the last point of F as in Fig. 5, on the measured load displacement curve. Equation (2) is the necessary compliance relation formula based on the length of the initially fixed crack which is the initial length to utilize the approximate curve for the following incremental formation of transformation curve in Fig. 5.

$$C_i = C_{i-1} \times \frac{\left(\frac{P_i}{P_{0,i}}\right)}{\left(\frac{P_i}{P_{0,i-1}}\right)} \qquad (5)$$

Here $P_{0,i}$ is the calculated limit load by the equation (1) in i term.

The variation of the gradual compliance can be calculated by selecting the basic points on the line of load displacement, which is the variation of utilizing the theoretical compliance and the equation (5).

In addition, what we should consider is that, as shown in Fig. 5, the approximate reference curve is not directly related with the efficiency of the growth of crack arising from the crack blunting. Here the crack blunting and physical crack growth may happen. But this study focuses on the efficiency of crack blunting by using the following theoretical method. Despite its differences in accordance with the material, the angle of blunting becomes nearly 45° . The effect of crack growth resulting from blunting becomes about half of CTOD. In the case of the fracture toughness specimen under the dominant bending load, the theoretical CTOD which can be considered as rotation hinge is based on the analysis by the researchers like Saxena[5] and Others[6] is calculated in Fig. 6.

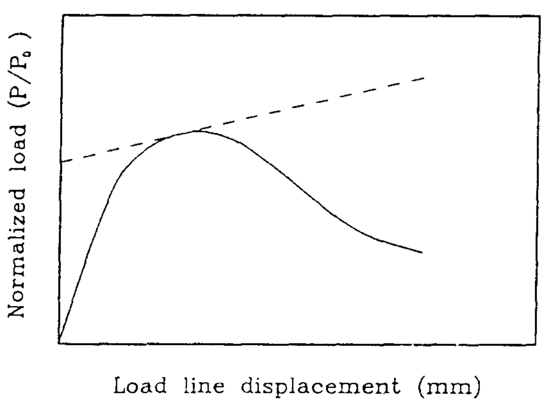

Fig. 5 Approximation of the reference curve by a tangent line

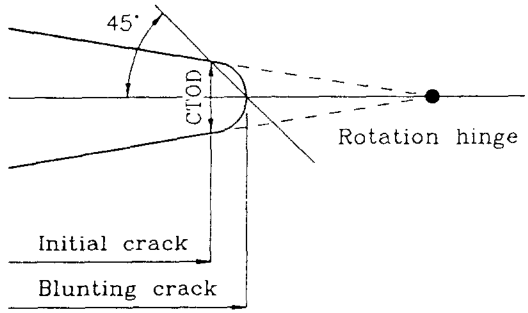

Fig. 6 A rotation hinge model for calculation of blunting crack length

All the calculation procedures could be treated by graphics on the PC to be easily applied to a series of procedures for the purpose of determining crack propagation, and other uncommented interpretation procedures were calculated by the standardized test method of ASTM.

3. RESULTS AND DISCUSSION

To examine the applicability of the load ratio method, the final crack length could be calculated by employing both of the final load-displacement and the initial crack length on the test specimens. As shown in Fig. 7, the calculated crack length has an error less than 1%, compared with the real measured crack length at SA508C-3 and Al 6061-T3 specimens. Because the last point F of Fig. 4 corresponds to the point appeared in the experiment. This result supports the theoretical applicability.

For the sake of estimating the experimental applicability of J-R curve analysis method developed in this study, the results of unloading compliance method of ASTM were compared with by using two kinds of materials and specimens as those in Table 1.

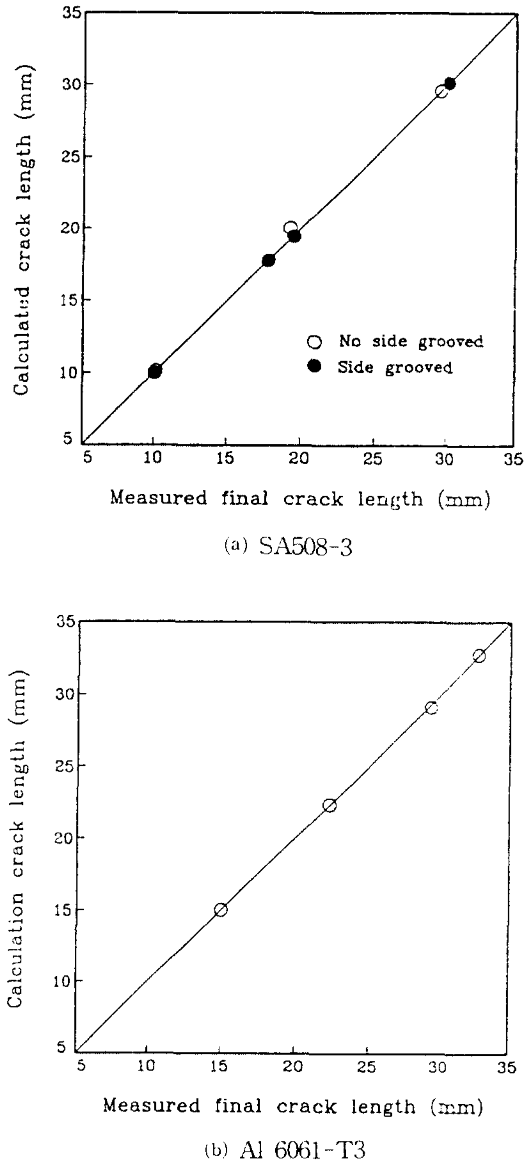

Fig. 7 Comparisons of calculated crack lengths with measured ones for final crack after fracture toughness tests

In Fig. 8, the results of the proposed load ratio method and those of the unloading compliance method are compared with each method using ½ CT SA508C-3 no side grooved specimens. Fig. 9 shows the result obtained by using ½CT SA 508-3 side grooved specimen. Fig. 10 indicates the result for Al6061-T3 specimen. Because ½ CT SA508C-3 is high ductile material, it is difficult for me to evaluate the J_Q and J-R curve by ASTM unloading compliance method[7]. Considering on the result of testing with side grooved specimens as in Fig. 9, it was realized that the possibility of evaluating J_Q and J-R curve by ASTM unloading compliance[8),9)]. In order to evaluate J_Q and J-R curve for ductile materials, we should not use no side grooved specimen but side grooved specimen. In Fig. 8 and Fig. 9, the result of the proposed load ratio method shows that the J_Q and J-R curves on the side grooved specimens are same as those on the no side grooved specimen. In the case of Al 6061-T3 specimen, the J-R curve slope estimated by the load ratio method is slightly smaller than that by the ASTM U.C. method.

The J-R characteristic curve obtained by the proposed method, compared with the result of U.C.M. represents the satisfactory precision. What is emphasized in this study is that the proposed approximate method requires no special equipment or no much experience for application of ASTM method.

The test results of the J_Q and J-R curve by the ASTM unloading compliance method and those of the proposed load ratio method are compared with in Table 2. The value of no side

Table 1 List of the specimen to be analyzed

No.	Materials	Y.S (MPa)	U.T.S (MPa)	Test temp.	Specimen	
					size	code
1	SA508C-3	319	504	R.T	½CT	no side grooved
						side grooved
2	Al 6061-T3	320	410	R.T	1CT	no side grooved

grooved ½CT SA508C-3 specimen does not appear. But the value error of J_Q by load ratio method is about 11.4% and 11.5% respectively for E813 and E1152 less than that by ASTM U.C. method. In the case of Al 6061-T3, the value error of J_Q by load ratio method shows 9.5% and 6.5% respectively for E813 and E1152 less than that by ASTM U.C. method.

The recent method [10], which explains recent large scale structure's elastic-plastic fracture mechanics, tends to utilize the value of J-R curve rather than the value of J_Q. The presented method in Fig. 8, Fig. 9, and Fig. 10

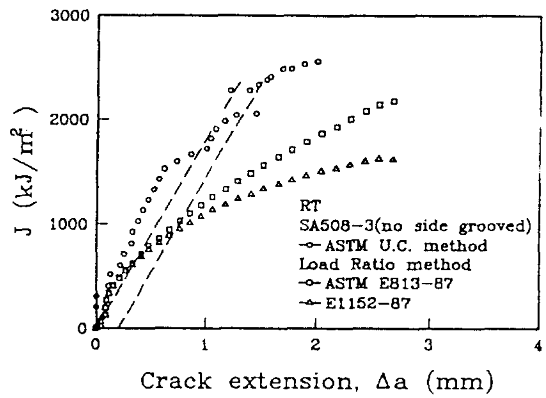

Fig. 8 J-R curves as determined the proposed method in SA508C-3 no side grooved specimen

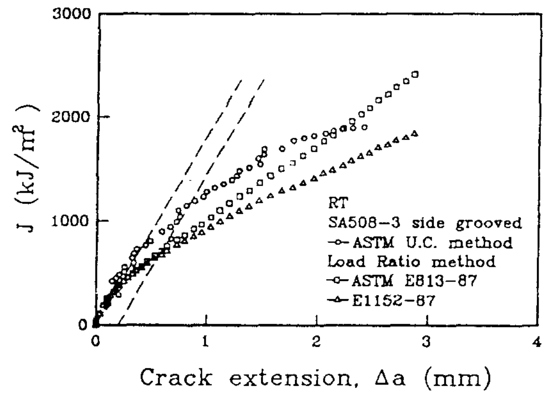

Fig. 9 J-R curves as determined the propose method in SA508-3 side grooved specimen

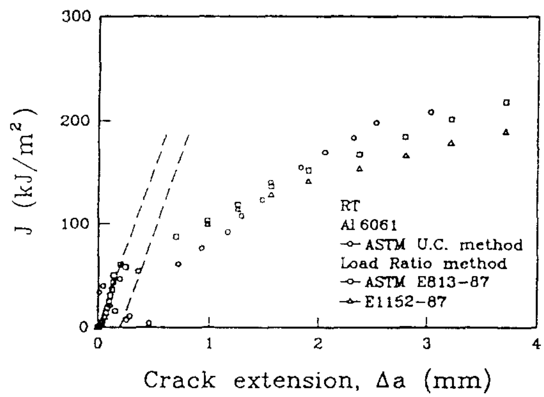

Fig. 10 J-R curves as determined the propose method in Al6061-T3 specimen

Table 2 Comparison of the J-R test results analyzed by the ASTM unloading compliance method and the proposed load-ratio method

Specimen	Analysis method		$J = C \times (\Delta a)^m$		J_Q(kJ/m²)	Error(%) of J_Q
			C(kJ/m²)	m		
SA508C-3 (No S.G.)	ASTM(U.C.)		1574.5	0.423	-	
	Load ratio	E813	1203.2	0.799	624.2	-
		E1152	1046.3	0.741	624.8	-
SA508C-3 (S.G.)	ASTM(U.C.)		964.6	0.498	605.2	
	Load ratio	E813	1079.1	0.624	536.3	-11.4
		E1152	946.8	0.573	535.0	-11.5
Al 6061-T3	ASTM(U.C.)		108.2	0.345	52.6	
	Load ratio	E813	107.7	0.769	56.9	-9.5
		E1152	100.8	0.743	56.0	-6.5

can be applied approximately to describe the behavior of the whole ductile fracture. In this study, the slope of blunting line calculated at the assumed rotation hinge in the specimen is almost similar to, or sightly larger than, the slope of blunting line of ASTM as in Fig. 8, Fig. 9, and Fig. 10. This result has been proved by researchers[11] and so indirectly supports the applicability of the proposed analysis method.

4. CONCLUSION

1) This study proposes to evaluate the elastic-plastic fracture resistance curve, by using the load-displacement curve of CT specimen in tensile test without both the repeat unloading/reloading and the precision measurement equipment.

2) The results of this method are compared with the results of the elastic-plastic fracture resistance, which are obtained by the ASTM standard unloading compliance method. The experimental results for three kinds of materials show that the proposed method is well appropriate for the analysis of the ductile material J-R curves.

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