ELASTIC-PLASTIC FRACTURE TOUGHNESS J_{IC} TEST METHOD RECOMMENDED IN JAPAN

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INTRODUCTION

In Japan, the Japan Society of Mechanical Engineers (JSME) Commitee S781 on "Standard Method of Test for Elastic-Plastic Fracture Toughness J_{IC}" (Chairman: H. Miyamoto, Vice-chairman: H. Kobayashi) had made an effort towards standardization of the J_{IC} test method. The JSME Standard was published in October 1981 under the designation of JSME S001-1981 [1].

The objective of the J_{IC} test method recommended by JSME is to determine J_{IC}, the value of J at the onset of actual ductile tearing (dimpling) for metallic materials under the mode I, plane-strain condition. The recommended test specimens are compact tension or three-point bend type that contain deep initial cracks. The JSME Standard includes two multiple specimen techniques and three single specimen techniques. In the former, the J_{IC} value is determined by the stretched zone width (SZW) technique or the R-curve technique. In the latter, the electrical potential, ultrasonic or acoustic emission technique is utilized.

On the other hand, the American Society for Testing and Materials (ASTM) Standard for the J_{IC} test method was published in August 1981 under the designation of ASTM E813-1981 [2]. There are several differenes between the JSME and ASTM methods.

The purpose of this paper is to give a brief description of the J_{IC} test method recommended by JSME and to discuss its applicability and usefulness with special attention to a comparison between the two methods recommended by JSME and ASTM.

STRECTCHED ZONE WIDTH (SZW) TECHNIQUE

Two or more specimens are loaded to selected different displacement levels which are lower than that at the initiation of slow stable crack growth. The J-integral of each specimen is calculated by a modified Merkle-Corten equation [3] in terms of an area under load versus load-line displacement record. The specimen is unloaded and crack extension, Δa, that occurred during loading is marked by such an appropriate way as subsequent fatigue cycling. After breaking the specimen open, microscopic observation of the fatigue precrack tip is made on the fracture surface. The sub-critical stretched zone width, SZW, is determined as the average of three or more measurements of apparent crack growth at evenly spaced locations from 3/8 to 5/8 of the thickness of the specimen as shown in Fig.1. To establish a crack tip plastic blunting line, J values are plotted against the corresponding measured SZW values and a best fit line between the relations is determined as illustrated in Fig.2.

Three or more specimens are pulled apart by overload and the critical stretched zone width, SZW_C, of each specimen is determined. SZW_C is defined as a critical value of SZW at the initiation of ductile tearing and is not affected by any following stable crack growth. So, it is possible to measure SZW_C on the overload fracture surface by the same procedure as the measurement of SZW. Using a method of least squares, a parallel best fit line of J upon SZW_C to the J-axis is determined as shown in Fig.2.

The intersection of the line $SZW=SZW_C$ with the blunting line marks J_{in} as illustrated in Fig.4. The J_{in} value defines J_{IC}, provided the requirements on fatigue precracking and the following validity requirements are satisfied.

$$b_o = W - a_o \geq 25J_{in}/\sigma_{fs} \quad (1)$$

$$B \geq 25J_{in}/\sigma_{fs} \quad (2)$$

where b_o = initial uncracked ligament, W = specimen width, a_o = original crack size, B = specimen thickness, and σ_{fs} = effective yield strength which is the average of tensile-yield strength (σ_{ys}) and the ultimate-tensile strength (σ_B). Eq.(2) is not necessarily required, provided J_{in} is confirmed to be constant irrespective of the thickness by an additional test for specimens which have a different thickness from the original one (desirably, changing the thickness more than twice as large or less than half as small as the original one).

R-CURVE TECHNIQUE

A plastic blunting line is determined experimentally in the same way as the SZW technique.

Four or more specimens are loaded up to displacement levels so as to cause ductile tearing. Following to the procedure described in the SZW technique, the physical crack growth, Δa, is determined as the average of the measurements which are made at three or more locations spaced evenly between 3/8 and 5/8 of the thickness of the specimen as shown in Fig.3. A best fit straight line of J upon Δa that are less than 1 mm is determined as the materials resistance (R-curve) to crack growth.

The intersection point between the regression line (R-curve) and the blunting line defines J_{in}. J_{in} equals to J_{IC} if the following equation is satisfied in addition to Eq.(1) and Eq.(2).

$$(dJ/da)_R \leq (1/2)(dJ/da)_B \qquad (3)$$

where $(dJ/da)_R$ = the slope of the R-curve, and $(dJ/da)_B$ = the slope of the blunting line.

SINGLE SPECIMEN TECHNIQUES

The electrical potential, ultrasonic or acoustic emission technique can be used to make the following measurement non-destructively during loading of specimens; (1) the difference of electrical potential, (2) the difference of ultrasonic echo, or (3) the variation of acoustic-emission event count, accumulated energy count or amplitude distribution of the event.

The single specimen techniques require actually three specimens, namely A, B and C, to complement the uncertainty of the techniques. A load-line displacement, $\delta_{in}(A)$, of the first specimen A at the initiation of ductile tearing is determined by one of the non-destructive techniques. The second specimen B is loaded up to a displacement level which is larger than $\delta_{in}(A)$ but smaller than $1.1\delta_{in}(A)$. The third specimen C is loaded up to a displacement level which is larger than $0.9\delta_{in}(A)$ but is smaller than $\delta_{in}(A)$. During the loading, the specimen B and C are monitored by one of the non-destructive techniques so as to confirm the initiation of ductile tearing on the specimen B but no initiation on the specimen C. $\delta_{in}(B)$ is determined as a value of displacement of the specimen B at the initiation of ductile tearing.

After unloading, fractographic examination of the three specimens is made on the fracture surface. When the initiation of ductile tearing is observed on the specimen A and B but not on the specimen C, the J_{in} value is determined as an average of the two J values corresponding to $\delta_{in}(A)$ and $\delta_{in}(B)$. J_{in} equals to J_{IC}, provided Eq.(1) and Eq.(2) are satisfied.

COMPARISON OF TWO STANDARDS ON J_{IC} TEST METHOD

Comparison of the J_{IC} test methods recommended by JSME and ASTM was made according to actual test results. As summarized in Table 1, the results obtained are as follows:

(1) If we assume a J versus SZW (=Δa) blunting line to be of the form

$$J = \lambda \, \sigma_{fs} \, SZW \qquad (4)$$

where σ_{fs} is the effective yield strength, the experimentally determined values of the constant λ for alloy steels and aluminum alloys show a tendency to become smaller as σ_{fs} becomes larger. For intermediate-strength materials, however, Eq.(4) can stand and the value of λ is 4. This experimentally determined blunting line [4,5] does not coincide with the specified equation in the ASTM Standard (i.e., λ=2). In the case of some low- and intermediate-strength materials, the intersection of the assumed blunting line in the ASTM Standard and the R-curve can not be obtained. Therefore, the JSME Standard recommends that the blunting line should be determined experimentally for each material.

(2) In some materials, the J_{IC} value determined by the single specimen techniques of JSME method have wide variation due to material inhomogeneity. For this kind of materials, difficulty arises in determining one R-curve by the R-curve technique (both JSME and ASTM methods). It is possible, however, to determine accurately J_{IC} for each specimen as the intersection of the J-SZW blunting line and the line of SZW=SZWc according to the JSME method.

(3) The JSME Standard defines crack extension as the mid-thickness average, Δa_{max}, of inner three or more measurements instead of the through-the-thickness average, Δa_p, at nine or more locations as defined in the ASTM Standard. If we define the crack extension as Δa_p (ASTM method), the slope of the R-curve shows a tendency to become smaller as the specimen size becomes larger. On the other hand, use of Δa_{max} (JSME method) at the mid-thickness of the specimen where the plane-strain flat type fracture precedes can give a unique and lowest slope of the R-curve regardless of specimen thickness. This is the reason why Eq.(2) on thickness requirement is not always necessary in the JSME Standard. According to the ASTM method, the valid plane-strain R-curve can not be evaluated as a material property.

(4) Qualification of Δa data is different between the two standards. In the JSME Standard, 0.15 mm lower limit offset line is eliminated and the maximum crack extension is limited to 1.0 mm instead of the 1.5 mm offset line in the ASTM Standard. The R-curve being nonlinear, the slope decreases with increasing Δa and tends to show a plateau. A linear fit of R-curve for large values of Δa (such as the data between the two offset lines in the ASTM method) can overestimate J_{IC}. The JSME method recommends to approximate the R-curve as a straight line using the Δa data just after the initiation of ductile tearing. So, according to the JSME method, the J_{IC} value can be evaluated more accurately using smaller specimen size compared with the ASTM method.

(5) The JSME Standard accepts the three single specimen techniques. The electrical potentil and ultrasonic techniques yield fairly good results in some intermediate- and high-strength materials.
The accoustic emission technique is affected strongly by micro-structure of materials, so that the applicability of the technique to J_{IC} test method depends on the type of materials. The unloading compliancle technique in the ASTM Standard is not particularly recommended in the JSME Standard due to the inaccuracy of the technique for small values of Δa.

CONCLUSION

The J_{IC} test method recommended by the Japan Society of Mechanical Engineers, JSME S001-1981, was outlined and its applicability and availability compared with the ASTM Standard, ASTM E813-81, were described in this paper.

REFERENCES

[1] Standard Method of Test for Elastic-Plastic Fracture Toughness J_{IC}, JSME Standard, S001-1981, (1981).

[2] Standard Test for J_{IC}, A Measure of Fracture Toughness, ASTM Standard, E813-81, (1981).

[3] Clarke, G.A. and Landes, J.D., Journal of Testing and Evaluation, Vol.7, No.5 (1979), 264/269.

[4] Kobayashi, H., Hirano, K. Nakamura, H. and Nakazawa, H., Proc. ICF 4, Vol. 3, Pergamon Press (1977), 683/592.

[5] Kobayashi, H., Nakamura, H. and Nakazawa, H., ASTM STP 803 (1983), in Press.

Table 1 Comparison of two standards on J_{IC} test method.

Item	JSME S001-1981	ASTM E813-81
Thickness of specimen, B	$(B \geq 25\ J_{in} / \sigma_{fs})^{*1}$	$B > 25\ J_Q / \sigma_Y$
Location for measurement of Δa	Mid-thickness average at 3 or more locations in (3/8-5/8)B	Through-the-thickness average at 9 or more locations
Limit of Δa	≤1.0 mm	Between the 0.15mm and 1.5mm offset lines
Blunting line	To be determined experimentally*2	$\Delta a_B = J / 2\sigma_Y$
Applicable multiple-specimen techniques	SZW technique or R-curve technique	R-curve technique
Applicable single-specimen techniques	Electrical potential, ultrasonic, or acoustic emission technique	Unloading compliance technique

(Note) *1 : Not necessarily required, provided J_{in} is confirmed to be constant regardless of thickness B.

*2 : Recommended equations on blunting line can be used for some specified materials.

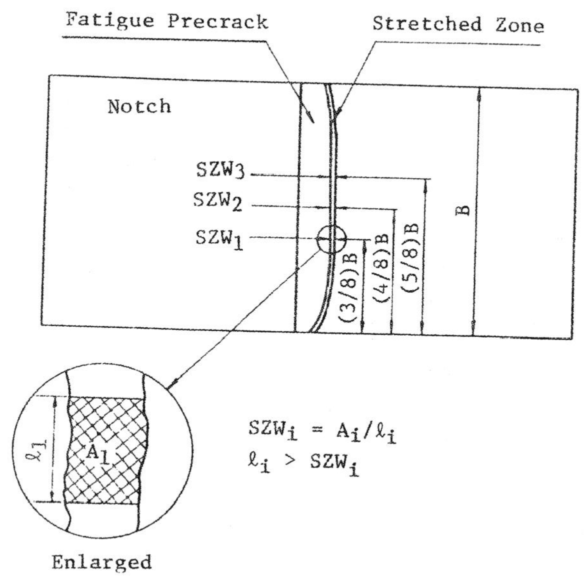

Fig.1 Schematic fracture appearance of J_{IC} specimen and measurement of SZW in the JSME Standard.

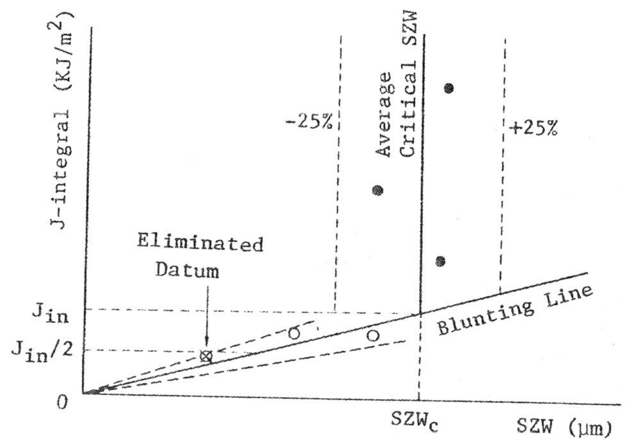

Fig.2 Schematic illustration of the SZW technique in the JSME J_{IC} test method.

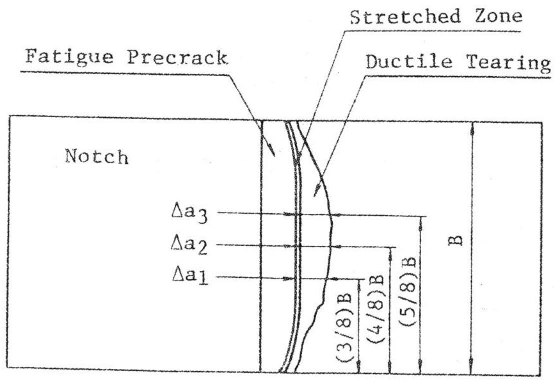

Fig.3 Schematic fracture appearance of J_{IC} specimen and measurement of Δa in the JSME Standard.

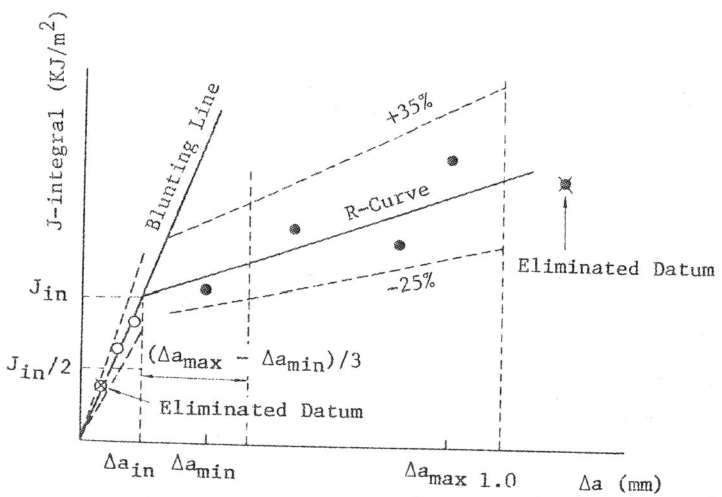

Fig.4 Schematic illustration of the R-curve technique in the JSME J_{IC} test method.