ELASTIC-PLASTIC FRACTURE TEST METHODS: THE USER'S EXPERIENCE

Library of Congress Cataloging in Publication Data

Elastic-plastic fracture test methods.

(ASTM special technical publication; 856)
Papers presented at the Symposium on User's Experience with Elastic-Plastic Fracture Toughness Test Methods.
Includes bibliographies and index.
"ASTM publication code number (PCN) 04-856000-30."
1. Fracture mechanics—Congresses. 2. Materials—Testing—Congresses. 3. Elasticity—Congresses. 4. Plasticity—Congresses. I. Wessel, E. T. II. Loss, F. J. III. ASTM Committee E-24 on Fracture Testing. IV. Symposium on User's Experience with Elastic-Plastic Fracture Toughness Test Methods (1983: Louisville, KY) V. Series.
TA409.E423 1985 620.1'126 84-70607
ISBN 0-8031-0419-7

Library of Congress Catalog Card Number: 84-70607

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Printed in Ann Arbor, MI
April 1985

Foreword

The symposium on User's Experience with Elastic-Plastic Fracture Toughness Test Methods was presented at Louisville, KY, 20–24 April 1983. The symposium was sponsored by ASTM Committee E-24 on Fracture Testing. E. T. Wessel, Westinghouse R&D, and F. J. Loss, Materials Engineering Associates, presided as chairmen of the symposium and are editors of the publication.

Related ASTM Publications

Fracture Mechanics: Fifteenth Symposium, STP 833 (1984), 04-833000-30

Elastic-Plastic Fracture: Second Symposium—Volume I: Inelastic Crack Analysis and Volume II: Fracture Curves and Engineering Applications, STP 803 (1983), 04-803000-30

Crack Arrest Methodology and Applications, STP 711 (1980), 04-711000-30

Elastic-Plastic Fracture, STP 668 (1979), 04-668000-30

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

ASTM Committee on Publications

ASTM Editorial Staff

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Introduction

Interest in elastic-plastic fracture has increased significantly over the past decade. New approaches to analyze structural performance under elastic-plastic conditions have been accompanied by the development of test methods to characterize material behavior in a manner compatible with the analysis. Key issues that must be addressed in test method development are characterization of geometry factors in the structure with respect to crack-tip constraint, specimen size effects, crack initiation, stable crack extension, and fracture mode. A rational test method should provide information from a laboratory specimen, which lends itself to a standard approach with due regard to these key issues such that useful information can be developed for the assessment of structural integrity.

Several test methods have been developed as a result of advances in elastic-plastic fracture mechanics, for example, J-integral R-curve, tearing instability, and crack-tip opening displacement (CTOD) approaches. A few of these methods have been standardized in the United States and other countries, and other methods are under development. A critical review of these procedures was considered necessary for others to benefit from the experience gained to date. This information will lead to improvements in existing standards and provide the basis for new test methods. The Symposium on User's Experience with Elastic-Plastic Fracture Toughness Test Methods was held in Louisville in April 1983 to provide a forum for an exchange of ideas among scientists and engineers who are actively engaged in test method development and application. This symposium provided a unique opportunity for representatives from several countries to present and discuss their views relating to experimental characterization of elastic-plastic fracture behavior in terms of laboratory specimens. Primary objectives were to define the problems and limitations associated with current test methods as a means to assess the state of the art, to describe new experimental techniques, and to highlight areas requiring further investigation.

The content of this publication will be particularly useful to experimentalists working in the field of elastic-plastic fracture. This should include researchers involved in material property studies, test laboratories, and organizations involved with structural safety and licensing. The contents of this book represent the current status of the elastic-plastic test methods that are in widespread use. Emphasis is placed on techniques used by different laboratories in measuring the parameters required by the various test methods. Since many of these techniques are new, it is expected that some will be refined and perhaps incorporated in appropriate test methods. This symposium was meant to provide a report of progress aimed at focusing investigations in this field worldwide.

Four major areas were addressed by the symposium: comparison of standards in various countries; problems encountered with test methods; improvements in techniques and methods; and problems associated with material characterization in the brittle-to-ductile transition region. The symposium concluded with a workshop that provided the participants with an opportunity to critique the papers. Emphasis in the presentations was on application of the methods to characterize material behavior in terms of the *J* integral, *R* curve, and CTOD approaches. Methods to measure stable crack initiation and growth were also discussed with emphasis on the compliance and electric potential drop techniques.

The collection of papers from this symposium represents the first of its kind in the United States and provides an assessment of the state of the art in many of the elastic-plastic test procedures in current use or under development. Reviews of developments on this topic in Europe and Japan are provided. It is hoped that this volume will encourage further progress in the field and provide the basis for future symposia on this topic.

The editors would like to acknowledge the assistance of J. D. Landes, J. P. Gudas, W. R. Andrews, and M. E. Lieff in planning and organizing the symposium. We also express our appreciation to all of the attendees for their open and fruitful presentations and discussion at the symposium, and for their subsequent suggestions and recommendations pertinent to improvement of the test methods; to the authors for submitting the formal papers that comprise this publication; and to the many reviewers whose high degree of professionalism ensured the quality of the publication. The editors also wish to express their appreciation to the ASTM Publications staff for their contributions in preparing the STP.

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Comparison of J_{Ic} Test Methods Recommended by ASTM and JSME

REFERENCE: Kobayashi, H., Nakamura, H., and Nakazawa, H., "**Comparison of J_{Ic} Test Methods Recommended by ASTM and JSME,**" *Elastic-Plastic Fracture Test Methods: User's Experience, ASTM STP 856,* E. T. Wessel and F. J. Loss, Eds., American Society for Testing and Materials, 1985, pp. 3–22.

ABSTRACT: The elastic-plastic fracture toughness J_{Ic} test method recommended by the Japan Society of Mechanical Engineers (JSME) Standard Method of Test for Elastic-Plastic Fracture Toughness J_{Ic} S001-1981 is outlined. Its applicability and utility compared with the ASTM Test for J_{Ic}, a Measure of Fracture Toughness (E 813) are discussed in this paper. It appears that JSME Standard S 001-1981 offers a superior approach to ASTM J_{Ic} determination in some aspects.

KEY WORDS: ductility, tearing, fracture tests, elastic-plastic fracture toughness, J integral, J_{Ic} test, blunting line, *R* curve, stretch zone, ductile tearing, tearing modulus, plane strain, metallic materials

In Japan, the Japan Society of Mechanical Engineers (JSME) Committee S781 on Standard Method of Test for Elastic-Plastic Fracture Toughness J_{Ic} (Chairman: H. Miyamoto, Vice-chairman: H. Kobayashi) standardized a J_{Ic} test method, which was published in October 1981 under the designation JSME S 001-1981.

The objective of the J_{Ic} test method recommended by JSME is to determine J_{Ic}, the value of J integral at the onset of Mode I, plane-strain, ductile tearing for metallic materials. The recommended test specimens are compact (CT) or three-point bend types that contain deep fatigue 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 stretch zone width *SZW* technique or the *R*-curve technique. In the latter, the electrical potential, ultrasonic, or acoustic emission techniques can be applied. This method is not recommended in cases where unstable cleavage fracture occurs before the determination of the *R* curve. Under small scale yielding conditions, however, the JSME standard includes the modified ASTM Test for Plane-Strain Fracture Toughness of Metallic Materials (E 399) as a special case.

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On the other hand, ASTM Test for J_{Ic}, a Measure of Fracture Toughness (E 813) was published in August 1981. A J_{Ic} criterion and its test method were developed by Begley and Landes [1] and ASTM Task Group E24.01.09 [2]. Their test method was adopted into ASTM E 813. In ASTM E 813, attention is directed mainly to processes of ductile tearing, and the following J versus Δa blunting line is assumed

$$\Delta a = \delta/2 = J/2\sigma_{fs} \tag{1}$$

where δ is the crack-tip opening displacement, and σ_{fs} is the average of the yield stress σ_{ys} in uniaxial tension (offset = 0.2%) and the tensile strength σ_B. The R curve is determined by the multiple-specimen technique or the single-specimen technique (unloading compliance). The J_{Ic} value is defined as a J value at the intersection of the blunting line and the R curve. There are several differences between the two methods recommended by ASTM and JSME.

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 given to a comparison of this method with that recommended by ASTM.

Stretched Zone Width Technique

The stretched zone width *SZW* technique has been proposed by the present authors [3]. This technique is the most important one recommended in the JSME Standard. The procedure is summarized as follows.

1. Statically load two or more specimens to selected different displacement levels that are lower than those at the onset of ductile tearing. Calculate the J integral of each specimen by a modified Merkle-Corten equation [4] in terms of an area under load versus load-line displacement record.
2. Unload each specimen and mark the crack extension caused by plastic blunting that occurred during loading by an appropriate method such as subsequent fatigue cycling. Then, break each specimen open to reveal the fracture surface.
3. Measure microscopically the subcritical *SZW* from the fatigue precrack tip to the tip of the marked crack at three or more locations spaced evenly from ⅜ to ⅝ of the specimen thickness as shown in Fig. 1. Determine the average SZW.
4. Plot all *J*-SZW data points, and determine a best-fit blunting line through an original point as shown in Fig. 2.
5. Pull three or more identical specimens apart by overload.
6. Measure microscopically the critical stretched zone widths (SZW_c) by the same method as the measurement of *SZW*. Determine the average SZW_c.
7. Mark J_{in} as a J value at the intersection of the line $SZW = SZW_c$ and the blunting line as shown in Fig. 2.

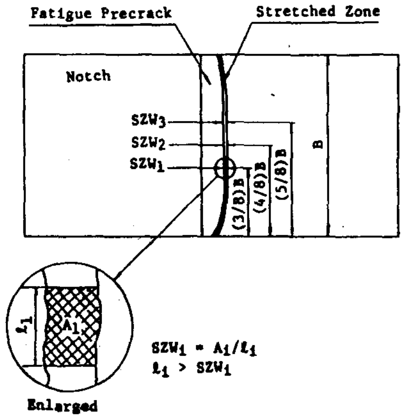

FIG. 1—*Schematic illustration of SZW measurements in the JSME standard.*

8. $J_{in} = J_{Ic}$ if the requirements on fatigue precracking, and the following validity requirements are satisfied

$$b_0 = W - a_0 \geq 25(J_{in}/\sigma_{fs}) \tag{2}$$

$$B \geq 25(J_{in}/\sigma_{fs}) \tag{3}$$

where b_0 is the initial uncracked ligament, W is the specimen thickness, and a_0 is the original crack size. Equation 2 is not necessarily required if J_{In} is confirmed to be constant irrespective of B by an additional test for specimens that have a different B from the original B. It is desired to change B to more than twice as large or less than half as small as the original B.

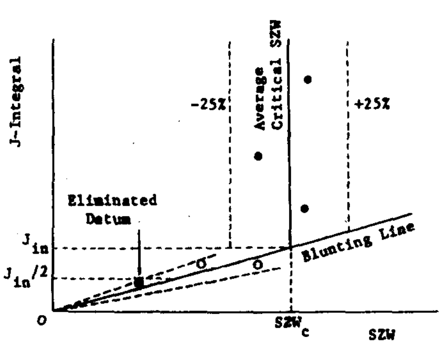

FIG. 2—*Schematic illustration of SZW technique in the JSME standard.*

R-Curve Technique

The *R*-curve technique recommended by JSME is almost identical to that recommended by ASTM except for the following four points.

1. The blunting line is determined experimentally in the same method as the *SZW* technique.
2. Four or more specimens are loaded up to displacement levels so as to cause ductile tearing. By following the procedure described in the *SZW* technique, the physical crack extension Δa is determined as the average of the measurements that are made at three or more locations spaced evenly from ⅜ to ⅝ of the specimen thickness as shown in Fig. 3.
3. Using a method of least squares, a linear regression line of J upon Δa is determined as shown in Fig. 4. All data points that do not fall within $\Delta a < 1$ mm are eliminated, and at least four data points must remain. This linear regression line represents the beginning stage of material resistance to ductile tearing (*R* curve). The intersection of the *R* curve with the blunting line marks J_{in} as shown in Fig. 4.
4. $J_{in} = J_{Ic}$ if the following validity requirement is satisfied in addition to the requirements of Item 8 in the *SZW* technique.

$$(dJ/da)_R \leq (1/2)\,(dJ/da)_B \qquad (4)$$

where $(dJ/da)_R$ is the slope of the regression line and $(dJ/da)_B$ is the slope of the blunting line.

Single Specimen Techniques

The JSME standard includes three single-specimen techniques. The electrical potential, ultrasonic, or acoustic emission techniques can be used to make the following measurement nondestructively and continuously during loading: (1) the difference of electrical potential, (2) the variation of ultrasonic signal amplitude, or (3) the variation of acoustic-emission event count, accumulated energy

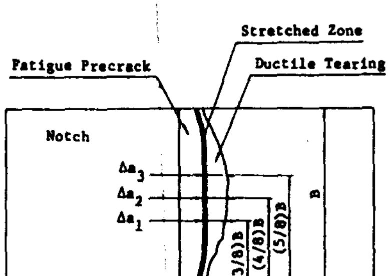

FIG. 3—*Schematic illustration of* Δa *measurements in the JSME standard.*

count, or amplitude distribution of event. The procedure is summarized as follows.

1. Each single-specimen technique actually requires three specimens, namely, A, B, and C, to compensate for the uncertainty of the technique.
2. Determine a load-line displacement, $\delta_{in}(A)$, of the first specimen A at the onset of ductile tearing by one of the single-specimen techniques.
3. Load the second specimen B up to a displacement level that is larger than $\delta_{in}(A)$ but is smaller than $1.1\delta_{in}(A)$.
4. Load the third specimen C up to a displacement level that is larger than $0.9\delta_{in}(A)$ but is smaller than $\delta_{in}(A)$.
5. Monitor the specimens B and C during loading by one of the single-specimen techniques so as to confirm the onset of ductile tearing on the specimen B but no onset on the specimen C.
6. Determine a load-line displacement $\delta_{in}(B)$ of the specimen B at the onset of ductile tearing.
7. Unload, mark, and break each specimen by following the procedure described in Item 2 of the *SZW* technique. Examine fractographically the fracture surface of the three specimens and confirm the onset of ductile tearing on the specimens A and B but not on the specimen C.
8. Determine J_{in} as an average of two J values corresponding to $\delta_{in}(A)$ and $\delta_{in}(B)$.
9. $J_{in} = J_{Ic}$ if the requirements of Item 8 in the *SZW* technique are satisfied.

The comparison of the J_{Ic} test methods recommended by ASTM and JSME is summarized in Table 1.

Evaluation of Blunting Line

For an "ideal crack" (a saw-cut crack or a fatigue precrack where the previous fatigue loading effect can be considered negligible compared with the following

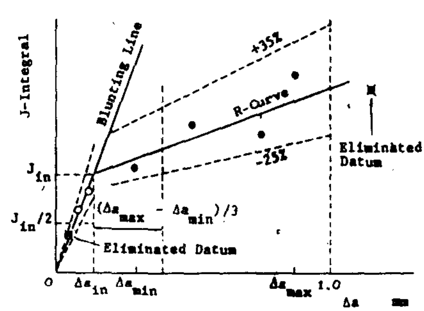

FIG. 4—*Schematic illustration,of* R-*curve technique in the JSME standard.*

TABLE 1—*Comparison of J_{Ic} test methods recommended by JSME and ASTM.*

Item	JSME Standard S001-1981	ASTM E 813
Specimen thickness B	$B \geq 25\ J_{in}/\sigma_{fs}$[a]	$B \geq 25\ J_Q/\sigma_{fs}$
Applicable multiple-specimen techniques	SZW technique or R-curve technique	R-curve technique
Blunting line	to be determined experimentally[b]	$\Delta a = J/2\sigma_{fs}$
Location for measurement of Δa	midthickness average at 3 or more locations	through-thickness average at 9 or more locations
Limit of Δa	$\Delta a \leq 1.0$ mm	between 0.15 and 1.5 mm offset lines
Applicable single-specimen techniques	electrical potential, ultrasonic, or acoustic emission technique	unloading compliance technique

[a]Not necessarily required if J_{in} is confirmed to be constant irrespective of B.
[b]Recommended equations on blunting line can be used without experimental determination for some specified materials.

monotonic load), a relation between the crack-tip opening displacement δ and the stress intensity factor K, or the J-integral of the form

$$\delta = (1 - \nu^2)\ K^2/\lambda E\sigma_{fs} \tag{5}$$

in the linear elastic fracture mechanics case or

$$\delta = J/\lambda\sigma_{fs} \tag{6}$$

in the elastic-plastic fracture mechanics case under the plane-strain conditions has been found, where ν is Poisson's ratio, E is Young's modulus, and λ is about 2. A schematic section profile of the subcritical stretch zone is shown in Fig. 5. The geometric relation between Δa or SZW and δ is given by

$$\Delta a = SZW = \delta/2\tan\beta = J/2\lambda\sigma_{fs}\tan\beta \tag{7}$$

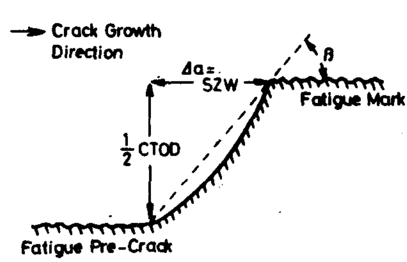

FIG. 5—*Schematic section profile of subcritical stretch zone.*

where 2β is the crack-tip blunting angle, and the quantity 2tanβ has a value between 1.4 and 2.

In recent years, many experimental data of *SZW* have been accumulated in the results of the J_{Ic} tests carried out by the present authors [*5*] and other researchers [*6*] in Japan. Figures 6 and 7 present all the results on a double-logarithmic plot of *SZW* for various materials as functions of J/σ_{fs} and J/E. If we assume relationships of two types of form

$$SZW = C_1\ (J/\sigma_{fs}) \tag{8}$$

$$SZW = D_1\ (J/E) \tag{9}$$

the values of C_1 and D_1 are as shown in Table 2. As the present authors [*5,6*] have shown, the *J-SZW* blunting line of the ideal crack depends not on σ_{ys} or on σ_{fs} but on *E*.

A specific examination in Fig. 6 shows that the values of C_1 for alloy steels ($0.23 < C_1 < 0.57$) and aluminum alloys ($0.23 < C_1 < 0.44$) have a tendency to become larger as σ_{fs} becomes larger [*7*]. It should be noted that if J/σ_{ys} instead of J/σ_{fs} is taken as a parameter, dependence on σ_{ys} becomes more remarkable. Therefore, it is evident that the relation between δ or Δa and *J* does not obey Eqs 5 or 6. For intermediate-strength materials (σ_{fs} = from 500 to 800 MPa for

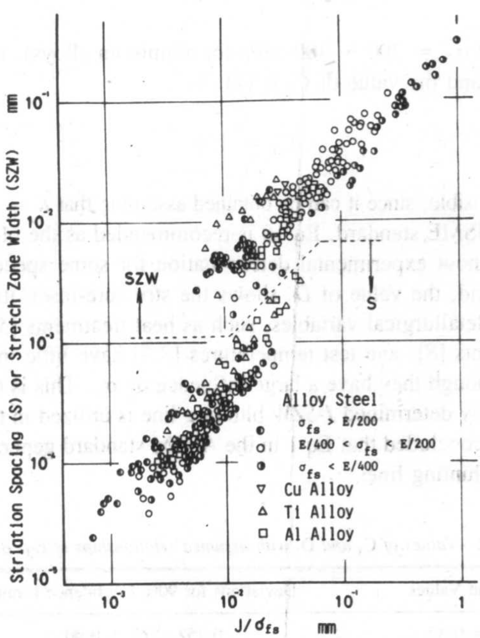

FIG. 6—*Comparison of* SZW *and* S *as functions of* J/σ_{fs} *and* $\Delta J/\sigma_{fs}$.