ASTM MANUAL ON

ELASTIC–PLASTIC FRACTURE

Laboratory Test Procedures

JAMES A. JOYCE

Manual on Elastic-Plastic Fracture: Laboratory Test Procedures

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NOTE: This manual does not purport to address (all of) the safety problems associated with its use. It is the responsibility of the user of this manual to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

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Foreword

THIS PUBLICATION, *Manual on Elastic-Plastic Fracture: Laboratory Test Procedures,* was approved by ASTM Committee E-8 on Fatigue and Fracture. This is Manual 27 in ASTM's manual series. The author, James A. Joyce, is employed at the U.S. Naval Academy, Mechanical Engineering Department, Annapolis, MD.

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1

Introduction

THIS MANUAL IS INTENDED TO provide a background for developing elastic-plastic fracture toughness data in accordance with ASTM Test Method for J-Integral Characterization of Fracture Toughness (E 1737) and ASTM Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement (E 1290). These standards provide the requirements for obtaining J-integral and CTOD quantities from laboratory tests; however, they provide little information on why certain requirements are imposed and how to carry out various aspects of the tests.

This manual provides specific guidance and instruction on equipment, apparatus, test fixtures, transducers, test setup, test procedure, and analysis of the data. Although nothing compares with hands on training as offered by the ASTM Technical and Professional Training Course on Elastic-Plastic Fracture,[1] this manual attempts to provide the next best thing through the use of test examples, example calculations, photographs of test apparatus and fracture samples, as well as expert advice and reference to papers in the literature describing various test techniques.

The sections that follow are organized sequentially as one would proceed in developing a laboratory capability to accomplish these fracture mechanics tests. Fixtures and apparatus are described first, then electronics, transducers, and recording equipment. Then an example test is set up, run, and analyzed according to the elastic-plastic fracture toughness standards, i.e., E 1737 and E 1290. The data are then qualified according to these standards. The terminology used throughout this manual is that of E 1737 and E 1290, and the reader is referred to these two standards, included here in Appendix B, for definitions of the terminology.

Two different types of tests are described, the basic test procedure leading to a single measurement quantity, i.e. the J-integral at the onset of cleavage fracture, and the advanced or resistance curve procedure that requires an unloading compliance or electric potential apparatus to estimate the crack extension at several locations on the load displacement record. The basic procedure requires a relatively simple apparatus and a test procedure similar to that required for a standard tension test, while the advanced procedure requires a more sophisticated arrangement to obtain the estimates of crack length, as well as crack extension from which the fracture toughness resistance curve (J-R curve) can be developed.

The apparatus is then described in detail for both procedures, including a discussion of the test machine and the displacement transducer requirements. Considerable time is spent on specimen and test fixture preparation. Specimen precracking is then discussed at length because this is an important aspect of fracture toughness testing often difficult and frustrating to the new practitioner. The test procedures are described, including the test setup, running the test, recording the data, crack length marking, and post test crack length measurements.

Finally, and certainly the most important part, there is a discussion of the data analysis. Examples are presented showing the evaluation of all fracture toughness quantities presently included in ASTM standards E 1737 and E 1290. All examples are taken from tests described fully in this manual. Sample software listings written in Microsoft QuickBASIC are included to do these analyses and to check the standard requirements as far as possible. Examples are presented demonstrating qualification of the measured toughness quantities in accordance with applicable ASTM test standard procedure requirements.

The final section presents a "heads up" on what the new developments are likely to be in elastic-plastic fracture testing since the ASTM standards are continually being changed, extended, and improved.

I would like to acknowledge the assistance of J. D. Landes, Edwin Hackett, Rick Link, and T. L. Anderson, who aided in the development of the original course notes on which this manual is based or helped to edit its final form.

[1]ASTM Technical and Professional Training, held at ASTM's previous address: 1916 Race Street, Philadelphia, PA.

2

Overview of Elastic-Plastic Fracture

ELASTIC-PLASTIC FRACTURE MECHANICS (EPFM) has developed from linear elastic fracture mechanics (LEFM) and attempts to eliminate the highly restrictive limits of that discipline so that a scientific method can be applied to structural applications for which low-strength, high-toughness materials are used. Early work by Wells (1961) was directed toward structural steels that were too tough to be characterized by LEFM. He proposed that the crack tip opening displacement (CTOD) of a blunted crack was a characteristic of the material's toughness and that it could be used as a crack-tip-characterizing parameter for materials for which LEFM was not valid. A more complete discussion of the analytical background of the CTOD method can be found in Anderson (1991). Standard methods of CTOD testing were developed in Britain (Wells 1961), and improvement has continued, leading to the recent British Standard BS 5762 (1979) and ASTM standards E 1290-89 and E 1290-93.

The J-integral was first proposed by Rice (1968) as a path-independent integral for measuring the intensity of the stress and strain field ahead of cracks and notches. The form of the crack-opening mode, deformation plasticity, and crack tip stress and strain fields were developed by different approaches by Hutchinson (1968) and Rice and Rosengren (1968), and the J-integral was the natural measure for quantifying the intensity of the dominant term. In this way, the J-integral is to a nonlinear elastic crack exactly what the stress intensity is to an elastic crack tip, and elastic-plastic fracture mechanics had a parallel to the widely understood linear elastic case.

Experimental work was done by Begley and Landes (1972) and Landes and Begley (1972) to measure J experimentally for standard laboratory test geometries. Early results showed that the J-integral could relate the conditions for crack initiation from one geometry to another, and a dramatic interest in J-integral fracture mechanics developed. A good discussion of the technical aspects of this development is presented in Anderson (1991).

A major step in the development of a practical experimental test method for the J-integral was the development by Rice et al. (1973) of a simple relationship between J and the specimen load displacement record for the deeply notched bend bar geometry, namely that:

$$J = \frac{2\int P d\delta}{Bb} \tag{1}$$

where

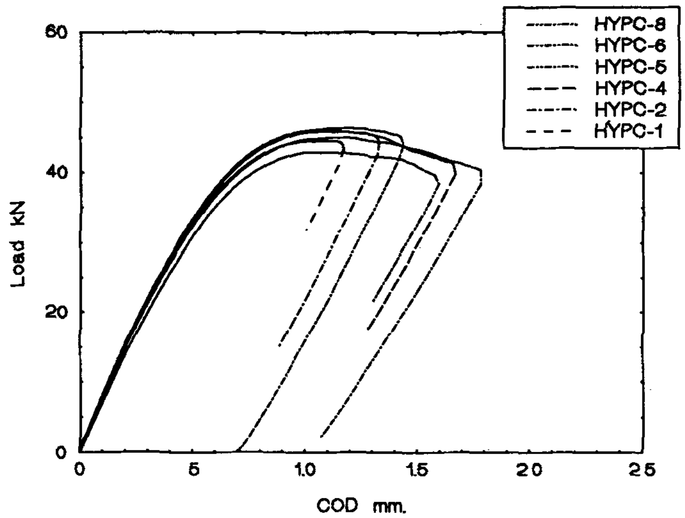


FIG. 1—Multi-specimen load displacement records for an HY80 steel.

W = specimen width[2],
B = the specimen thickness,
b = $(W - a)$ is the uncracked ligament,
a = the crack length, and
$\int P d\delta$ = the area under the load versus load line displacement record for the specimen or work done on the specimen.

With this equation, J could be evaluated for three-point bend specimens at any point on the load displacement record if the crack length, a, and hence the remaining ligament, b, was known.

The first practical method for laboratory evaluation of the J-integral near the onset of crack initiation, called J_{Ic}, was presented by Landes and Begley (1974). This method, called the multi-specimen method, used several identical specimens precracked to the same crack length and tested to different points on what should be similar load displacement curves, as shown for a structural steel in Fig. 1.

From each specimen, a single data pair was obtained with the J-integral obtained at the end of test for each specimen from Eq 1, while the crack extension was obtained by heat tinting or otherwise marking the extent of the crack extension, then breaking open the specimen using a low temperature to cause cleavage or fatigue cycling as applicable for the material, and finally measuring the average crack exten-

[2]The terminology used in this manual corresponds to that of the ASTM standards E 1290 and E 1737. These documents can be found at the back of this manual, and the reader is directed there for clear definitions of the terminology used.

sion using an optical traveling stage microscope. The results from a series of specimens is shown in Fig. 2. The J-integral at crack initiation, J_{Ic}, was evaluated from the intersection of a linear best fit line and an initial blunting line as shown in Fig. 2. This method became the basis for the first ASTM J_{Ic} standard, E 813-81 (ASTM Test Method for J_{Ic}, a Measure of Fracture Toughness).

Quantifying the elastic-plastic fracture toughness at crack initiation was not satisfactory for many applications, especially those in the nuclear industry where some degree of crack extension was acceptable as long as it occurred in a stable manner and its extent could be conservatively predicted. A crack growth resistance curve methodology was developed directly from the J-resistance (J-R curve) used in ASTM E 813-81 to evaluate J_{Ic}.

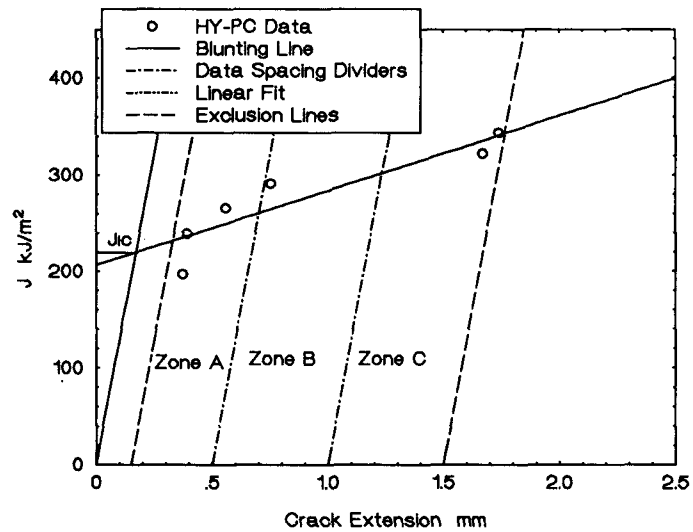


FIG. 2—J_{Ic} obtained from J-R data for HY80 steel using E 813-81.

Important applications also existed, especially in nuclear reactor surveillance, where six or so identical specimens were not available for the evaluation of a single J_{Ic} data point. For both of these reasons, single specimen methods were developed, first the unloading compliance method and then the electric potential method, to obtain a full J-R curve from a single specimen test—an R curve with enough definition to evaluate material variability, and for stability analyses, the resistance curve slope.

The first unloading compliance method was presented by Andrews et al. (1976) using a complex system of laboratory-built apparatus. A computer-enhanced, interactive system was developed by Joyce and Gudas (1979) that used a digital system to develop the J-R curve using what was at that time an exotic system, but one that has since become the laboratory standard for state-of-the-art fracture testing. This method became the basis for the first ASTM J-R curve standard, ASTM Test Method for Determining J-R Curves (E 1152-87), and was incorporated as well into an updated version of E 813, E 813-87.

More recent work has continued to improve these two basic standards. A major step was the recent combination of the two standards into the combined J_{Ic}, J-R curve standard E 1737. This standard also allows for the evaluation of J-integral values at the onset of fracture instability. For this purpose, two new quantities, J_c and J_u, have been introduced representing the onset of fracture instability without and with significant ductile crack extension, respectively. Additionally, one is now allowed to use the measured J_{Ic} from a test that terminates unstably if approximately 1 mm of stable crack extension is present. Also, the J-R curve is acceptable up to the onset of instability if it meets the standard's requirements.

Also new in the E 1737 standard is an Annex describing an electric potential procedure, and a new specimen—the disk-shaped DC(T) specimen—is included.

Analysis

3.1 *J*-INTEGRAL AND δ EQUATIONS

WHILE THE PRINCIPAL OBJECTIVE of this manual is to describe experimental aspects of elastic-plastic fracture testing, it is still necessary to define the quantities that we are measuring by presenting the ASTM standard equations that are currently used. The J-integral of Rice (1968) is defined in terms of a path integral not easily measured experimentally. For simple bend-type specimens, however, a straightforward analysis has been developed to relate J to the area under the load versus load point displacement record. Two different equations are used to evaluate J in ASTM fracture standards, the first applicable when the amount of crack extension is small, while the second includes a correction for crack extension. The multi-specimen J equation of ASTM E 1737 is:

$$J = J_{el} + J_{pl} \tag{2}$$

where

J_{el} = elastic component of J, and
J_{pl} = plastic component of J.

For the single edge-notched bend specimen (SE(B)) at a point corresponding to V_i and P_i on the specimen load versus load line displacement record,

$$J = \frac{K^2(1 - \nu^2)}{E} + J_{pl} \tag{3}$$

where:

$$K = \left[\frac{PS}{(BB_N)^{1/2}W^{3/2}}\right] f(a_o/W) \tag{4}$$

with:

$$f(a_o/W) = \frac{3(a_o/W)^{1/2}[1.99 - (a_o/W)(1 - a_o/W)[2.15 - 3.93(a_o/W) + 2.7(a_o/W)^2]]}{2(1 + 2\,a_o/W)(1 - a_o/W)^{3/2}} \tag{5}$$

and

$$J_{pl} = \frac{2\,A_{pl}}{B_N b_o} \tag{6}$$

where

a_o = the crack length,
W = specimen width,
B = the specimen thickness,
B_N = the net specimen thickness measured between the side groove roots,
b_o = $(W - a_o)$ is the uncracked ligament at the start of the test,
A_{pl} = Area A under the load versus load point displacement as shown in Fig. 3.

For the compact specimen (C(T)) and the disk compact specimen (DC(T)), at a point corresponding to V_i, P_i on the specimen load versus load line displacement record:

$$J = \frac{K^2\,(1 - \nu^2)}{E} + J_{pl} \tag{7}$$

where:

$$K = \left[\frac{P}{(BB_NW)^{1/2}}\right] f(a_o/W) \tag{8}$$

for the C(T) specimen:

$$f(a_o/W) = \frac{(2 + a_o/W)[0.886 + 4.64(a_o/W) - 13.32(a_o/W)^2 + 14.72(a_o/W)^3 - 5.6(a_o/W)^4]}{(1 - a_o/W)^{3/2}} \tag{9}$$

and for the DC(T) specimen:

$$f(a_o/W) = \frac{(2 + a_o/W)[0.76 + 4.8(a_o/W) - 11.58(a_o/W)^2 + 11.43(a_o/W)^3 - 4.08(a_o/W)^4]}{(1 - a_o/W)^{3/2}} \tag{10}$$

The plastic component of J is given by:

$$J_{pl} = \frac{\eta A_{pl}}{B_N b_o} \tag{11}$$

where $\eta = 2 + 0.522\, b_o/W$. The η factor has been introduced by Sumpter and Turner (1976) and Paris et al. (1980) as a

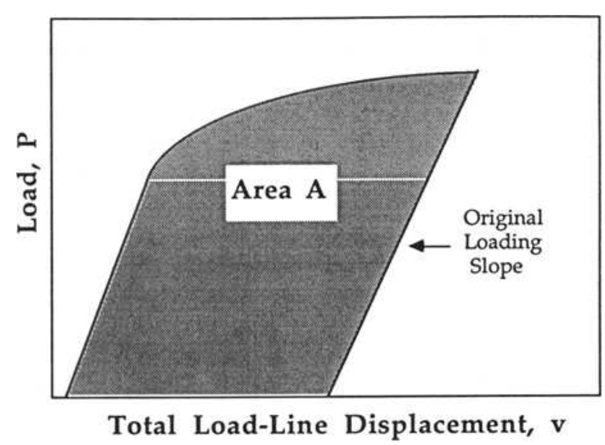


FIG. 3—Definition of the plastic area for *J* calculation.

convenient terminology for the factor relating the J-integral to the area under the specimen load versus load line displacement relationship. For the case of the deeply cracked bend specimen of Eq 6, $\eta = 2$ and the same form as that of Eq 11 could be used. Various η factors have been introduced for other fracture specimen geometries (Joyce et al. 1992) and even for the evaluation of CTOD (Kirk and Dodds 1992).

The quantities a_o and b_o used in all of the above expressions are the initial values obtained from a nine-point average measurement of the fatigue precrack length after completion of the test.

These J equations do not include a correction for crack growth, depending only on the crack length a_o at the beginning of test as measured optically after the test. This simple relationship should only be used to obtain J_{Ic} since the J-R curve resulting from this analysis will be elevated and nonconservative due to the lack of a crack growth correction term.

The J-integral quantities of Eq 6 and Eq 11 are deformation plasticity quantities giving the J-integral for a specific crack length as if the specimen was loaded from the start of the test with that crack length. If crack extension occurs, the measured load displacement record must be corrected if the measured data are to be used to obtain a correct J-integral corresponding to the crack length that exists at a particular point of interest on the load displacement record.

A comparison is made in Fig. 4 of load displacement records for a particular specimen, the upper one being the experimentally measured result for the real test in which the specimen is undergoing crack extension. At a point like that labeled "A" on Fig. 4, the crack length has grown to magnitude a_1, which is different than the initial crack length a_o.

The deformation plasticity J-integral at this point would correctly be evaluated from the load displacement curve of a specimen that started with the crack length a_1 and for which the crack did not grow as the specimen was loaded to Point A, a load displacement curve that would have the appearance of the lower curve on Fig. 4. The lower curve is, of

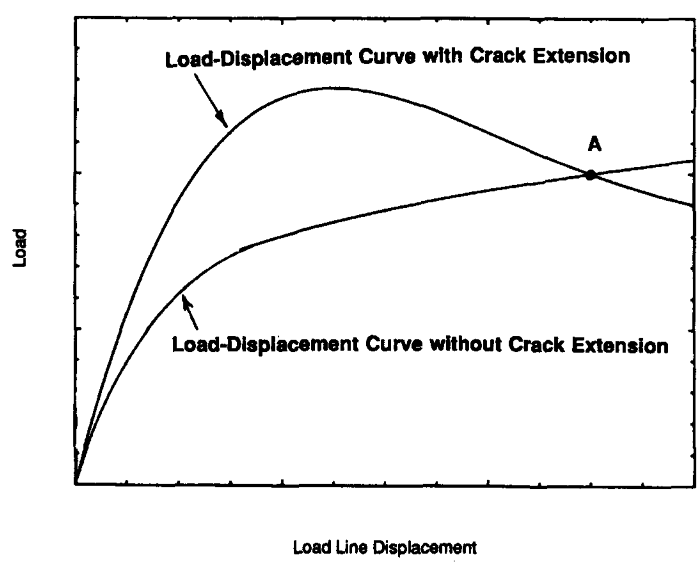


FIG. 4—Comparison of load displacement curves with and without crack extension.

course, not available, but work by Ernst (1981) has shown how to correct the measured data to obtain an accurate estimate of the J-integral as if this lower curve were known.

The more accurate methodology for evaluating J, as used in the advanced test procedure of E 1737, is:

$$J = J_{el} + J_{pl} \tag{12}$$

where J_{el} = elastic component of J, and J_{pl} = plastic component of J.

The elastic component of J can be calculated at each point V_i, P_i, from the LEFM stress intensity as:

$$J_{el} = \frac{(K_{(i)})^2(1 - \nu^2)}{E} \tag{13}$$

where K for the SE(B) specimen is given by:

$$K_{(i)} = \left[\frac{PS}{(BB_N)^{1/2}W^{3/2}}\right] f(a_i/W) \tag{14}$$

and K for the C(T) and DC(T) specimens is given by:

$$K_{(i)} = \left[\frac{P_i}{(BB_N W)^{1/2}}\right] f(a_i/W) \tag{15}$$

with $f(a_i/W)$ a function of specimen type, given by:

SE(B) specimen:

$$f(a_i/W) = \frac{3(a_i/W)^{1/2}[1.99 - (a_i/W)(1 - a_i/W)[2.15 - 3.93(a_i/W) + 2.7(a_i/W)^2]]}{2(1 + 2\,a_i/W)(1 - a_i/W)^{3/2}} \tag{16}$$

C(T) specimen:

$$f(a_i/W) = \frac{[(2 + a_i/W)[0.886 + 4.64(a_i/W) - 13.32(a_i/W)^2 + 14.72(a_i/W)^3 - 5.6(a_i/W)^4]]}{(1 - a_i/W)^{3/2}} \tag{17}$$

DC(T) specimen:

$$f(a_i/W) = \frac{[(2 + a_i/W)[0.76 + 4.8(a_i/W) - 11.58(a_i/W)^2 + 11.43(a_i/W)^3 - 4.08(a_i/W)^4]]}{(1 - a_i/W)^{3/2}} \tag{18}$$

The subscript on a_i is present to emphasize that the crack length is changing here, and that the most recent value is used at each instant.

The plastic component of J can be calculated at each point V_i, P_i from the incremental equation:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{(i-1)}}{b_{(i-1)}}\,\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right)\right] \times \left[1 - \gamma_{(i-1)}\,\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right] \tag{19}$$

where for the SE(B):

$$\eta_{(i-1)} = 2.0, \text{ and}$$

$$\gamma_{(i-1)} = 1.0,$$

and for the C(T)and DC(T)specimens:

$$\eta_{(i-1)} = 2.0 + 0.522\, b_{(i-1)}/W, \text{ and}$$

$$\gamma_{(i-1)} = 1.0 + 0.76\, b_{(i-1)}/W.$$

The separation of J into elastic and plastic parts was introduced in the 1987 versions of ASTM E 813 and ASTM E 1152 basically to improve the accuracy and consistency of J when near LEFM conditions applied. The analysis of E 813-81 used the total area under the load versus load line displacement curve and a plastic η factor, which can be considerably different than the correct elastic η factor. This result could be considerably in error when the elastic component of J was large compared to the plastic component. Instead of using elastic and plastic areas, and the corresponding elastic and plastic η factors, it was decided to obtain the elastic component from the stress intensity and only the plastic component from the η factor method. This separation also improved the comparability of the results of E 813-87 and those of ASTM Test Method for Plane-Strain Fracture Toughness of Metallic Materials (E 399) for the linear elastic case.

Justification for use of the J-integral in the presence of crack growth has been provided by Hutchinson and Paris (1979), who showed that J remained applicable as long as a region of proportional plastic deformation surrounds the crack tip and dominates any small region of nonproportional straining at the crack tip.

Justification for the use of the J-integral when the overall load capacity of the specimen is falling is based on finite element results (Shih et al. 1979; Dodds et al. 1994) that show that the stress and strain fields in front of the crack are not diminishing and the falling overall load is resulting from reductions in the size of the remaining uncracked ligament.

In the ASTM crack tip opening displacement (CTOD) standard, E 1290, the CTOD is estimated from crack opening displacement (COD) measurements at the specimen surface (SE(B)) or load line (C(T)). The CTOD is separated into two components and calculated from:

$$\delta = \delta_{el} + \delta_{pl} \tag{20}$$

where the δ_{el} is calculated from:

$$\delta_{el} = \frac{J_{el}}{2\sigma_Y} = \frac{K^2}{2\sigma_Y E'} \tag{21}$$

with:

$$K = \frac{YP}{B\sqrt{W}} \tag{22}$$

and for the SE(B) specimen:

$$Y = \frac{6(a_o/W)^{1/2}[1.99 - (a_o/W)(1 - a_o/W)[2.15 - 3.93(a_o/W) + 2.7(a_o/W)^2]]}{2(1 + 2a_o/W)(1 - a_o/W)^{3/2}} \tag{23}$$

and for the C(T) specimen with:

$$Y = \frac{(2 + a_o/W)[0.886 + 4.64(a_o/W) - 13.32(a_o/W)^2 + 14.72(a_o/W)^3 - 5.6(a_o/W)^4]}{(1 - a_o/W)^{3/2}} \tag{24}$$

$$E' = \frac{E}{(1 - \nu^2)} \tag{25}$$

The plastic component is obtained from an analysis that assumes a rotation point near the center of the ligament, defined by r_p, as shown in Fig. 5. A simple similar triangles analysis can now be used to obtain the plastic component of the CTOD as:

$$\delta_{pl} = \frac{r_p(W - a)V_p}{r_p(W - a) + a_o + z} \tag{26}$$

in which V_p is the plastic component of the crack mouth opening displacement at the measurement point. The r_p coefficient depends slightly on the crack length and specimen type and is given by:

$$r_p = 0.4(1 + \alpha) \tag{27}$$

where for the SE(B) specimen $\alpha = 0.1$ and $r_p = 0.44$, and for the C(T) specimen:

$$\alpha = 2\sqrt{[(a_o/b_o)^2 + a_o/b_o + 1/2]} - 2(a_o/b_o + 1/2) \tag{28}$$

giving r_p between 0.46 and 0.47 for $0.45 \le a_o/W \le 0.55$.

3.2 LIMITS OF APPLICABILITY

The magnitudes of fracture toughness that can be measured by fracture mechanics tests are limited by the sizes of the test specimens available. Tougher, lower-strength materials require larger specimens for the results to be acceptable. Other requirements are present to assure that the data are of acceptable quality, the specimen precracking adequate, and that a distinctly measurable point is present. The qualification requirements are covered in detail in Section 8, and examples are provided.

Generally, a test is run on a standard specimen and, if a sudden instability does not occur, a tentative J-integral value near the onset of ductile crack growth, J_Q, is evaluated. For J_Q to be qualified as a J_{Ic} according to E 1737, the following requirements are established:

1. $B, b_o > 25\, J_Q/\sigma_Y$.
2. dJ/da evaluated at Δa_Q is less than σ_Y.

The first condition requires that the specimen is large enough that the J-integral controls the stress and strain fields in an annular region surrounding the crack tip. This requirement was proposed by Paris (1972) and is basically a requirement that the CTOD is small in comparison with all specimen dimensions. This requirement has been a part of the J-integral fracture standards from the beginning.

The second condition requires that a distinct change in slope occurs between the initial blunting behavior and the subsequent J-R curve and is only violated for high-toughness materials like austenitic stainless steels. A serious shortcoming of J_{Ic} is that it is evaluated from the intersection of two curves with similar slopes, resulting in large measurement variability in higher-toughness materials.

If fracture instability occurs, a J at fracture instability, J_{Qc}, is measured and can be qualified as J_c if it meets the following conditions:

1. $B, a_o, b_o > 200\, J_{Qc}/\sigma_Y$.
2. Measured ductile crack extension at J_{Qc} is less than $0.2 + J_{Qc}/M\sigma_Y$ mm.

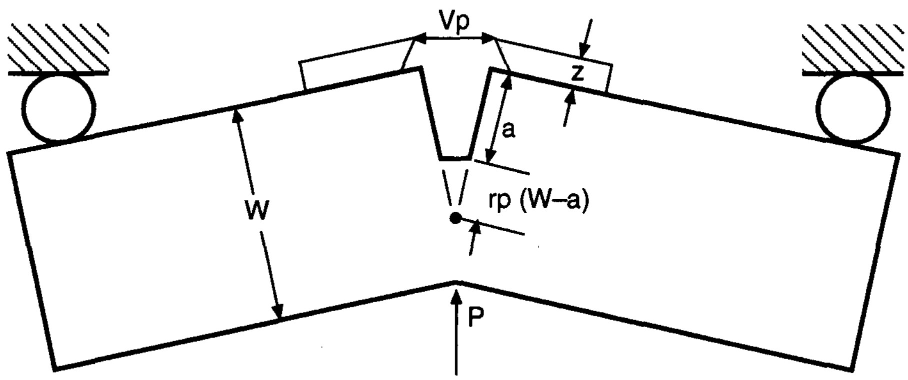


FIG. 5—Schematic for CTOD evaluation from COD.

3. K_{max} during the final 0.64 mm of precracking shall be less than 0.6 $(J_{Qc}E)^{1/2}$.

The first condition requires that the specimen be large enough so that small-scale yielding conditions (SSY) exist at the crack tip (Anderson and Dodds 1991). If this condition is violated, extensive plasticity develops at the crack tip, constraint is lost, and the J-integral at fracture instability becomes very dependent on the specimen in-plane dimensions.

The second condition disallows extensive ductile crack extension before instability, which can raise or lower the crack tip constraint. This requirement was added for conservatism, and methods to correct for the effects of ductile crack extension before instability are presently the subject of intensive research (Dodds and Tang 1993; Dodds et al. 1994). M is the slope of the construction line used to evaluate J_{Ic}. The usual value for M is 2.0. The ASTM E 1737 standard allows a higher value to be used based on six or more measured J versus Δa data pairs in the early part of the J-R curve. A value of M greater than 2 leads to a lower value of J_{Ic} and is generally used only for some austenitic stainless steels.

The final condition assures that the precracking load did not interfere with the result of the test, a requirement adapted from a similar requirement in E 399.

A J_c value that meets these requirements would be expected to exhibit a weak dependence on specimen thickness, i.e., crack length, since the volume of material subjected to intense stresses depends on crack length. This dependence is discussed more fully in Wallin (1989).

The part of the measured J-R curve qualified by E 1737 is restricted to the region established by:

1. The smaller of $J_{max} = b_o\sigma_Y/20$ or $J_{max} = B\sigma_Y/20$.
2. $\Delta a_{max} = 0.1\ b_o$.

The first of these requirements is a slightly less stringent version of the J_{Ic} requirement, which is intended to assure that the specimen is large enough for J to control the stress and strain fields surrounding the crack tip.

The second requirement restricts the extent of ductile crack extension allowed. The original requirement on crack extension was $\Delta a_{max} = 0.06\ b_o$, resulting from finite element work by Shih et al. (1979). More recent work by Newman et al. (1985) has been used to extend this requirement to $0.1b_o$ in E 1152-87. Work by Joyce and Hackett (1991b), based on experimental measurements, supports extending this limit to $0.25b_o$, arguing that it is the finite element analyses, not the J-R curve, that is failing in the previously cited work. ASTM E 1737 at present suggests taking data to crack extensions in excess of $0.1b_o$, but does not yet accept data beyond this limit as "valid."

The CTOD standard, E 1290, requires that the laboratory test be done on section thicknesses at least as large as the thickness of interest in the structural application. If this is so, and standard test samples are used, there are no size requirements like those of E 1737. If instability occurs before the maximum load is reached, a δ_Q can be measured that is called δ_c if less than 0.2 mm of ductile crack extension has occurred and δ_u if more than 0.2 mm of ductile crack extension has occurred. If maximum load is reached without instability, a δ_m is measured and reported. Transfer of the results to applications with larger section sizes is disallowed.

3.3 COMPLIANCE EQUATIONS

Unloading compliance techniques are used to obtain estimates of the crack length from accurate and precise measurements of the specimen compliance made from periodic unloadings during the fracture test. Crack lengths are determined based on the measured specimen compliance. Relationships between the measured compliance and the specimen crack length are therefore very important and are provided in E 1737.

For SE(B) specimens, where the span-to-width ratio is 4 with crack mouth opening displacements measured at the notched edge, the crack length is:

$$a_i/W = [0.999748 - 3.9504\ U_x + 2.9821\ U_x^2 - 3.21408\ U_x^3 + 51.51564\ U_x^4 - 113.031\ U_x^5] \quad (29)$$

where:

$$U_x = \frac{1}{\left[\frac{B_eWE'C_i}{S/4}\right]^{1/2} + 1} \quad (30)$$

and:

$$B_e = B - \frac{(B - B_N)^2}{B} \quad (31)$$

where

C_i = specimen crack mouth opening elastic compliance $(\Delta V_m/\Delta P)_i$ on an unloading/reloading sequence,
ΔP = increment of load, and
ΔV_m = increment of crack mouth opening displacement measured at the specimen surface.

For C(T)and DC(T) specimens, the crack length is given by:

$$a_i/W = [1.000196 - 4.06319\ U_x + 11.242\ U_x^2 - 106.043\ U_x^3 + 464.335\ U_x^4 - 650.677\ U_x^5] \quad (32)$$

and

$$a_i/W = [0.998193 - 3.88087\ U_x + 0.187106\ U_x^2 + 20.3714\ U_x^3 - 45.2125\ U_x^4 + 44.527\ U_x^5] \quad (33)$$

respectively, where:

$$U_x = \frac{1}{[B_e E' C_{ci}]^{1/2} + 1} \quad (34)$$

C_{ci} = rotation-corrected specimen crack opening compliance on an unloading/reloading sequence, given in E 1737 as:

$$C_{ci} = \frac{C_i}{\left[\frac{H^*}{R}\sin\theta - \cos\theta\right]\left[\frac{D}{R}\sin\theta - \cos\theta\right]} \quad (35)$$

These compliance equations are obtained using elastic, small displacement finite element analysis (Hudak and Saxena 1978). For high-toughness materials, the specimen geometry can change during the test and a rotation correction is necessary to accurately predict crack length from compliance for these materials. E 1737 requires the use of this correction for all C(T) and DC(T) specimens since in the limit of small specimen half rotation, $C_{ci} = C_i$.

For the C(T) and DC(T) specimens, this correction is obtained using the geometry shown in Fig. 6, giving:

C_i = measured specimen elastic compliance (at the load line),
H^* = initial half span of the load points (center of pin holes),
R = radius of rotation of the crack centerline, $(W + a)/2$, where a is the updated crack length,
D = one half of the initial distance between the displacement measurement points,
θ = angle of rotation of a rigid body element about the unbroken midsection line, or
$\theta = \sin^{-1}[(d_m/2 + D)/(D^2 + R^2)^{1/2}] - \tan^{-1}(D/R)$, and
d_m = total measured load-line displacement.

For cases where an elastic compliance is not measured but is needed to separate the area under the load versus displacement record into elastic and plastic parts, the required compliance can be calculated from a/W using the following formulas.

For the SE(B) specimen load line compliance:

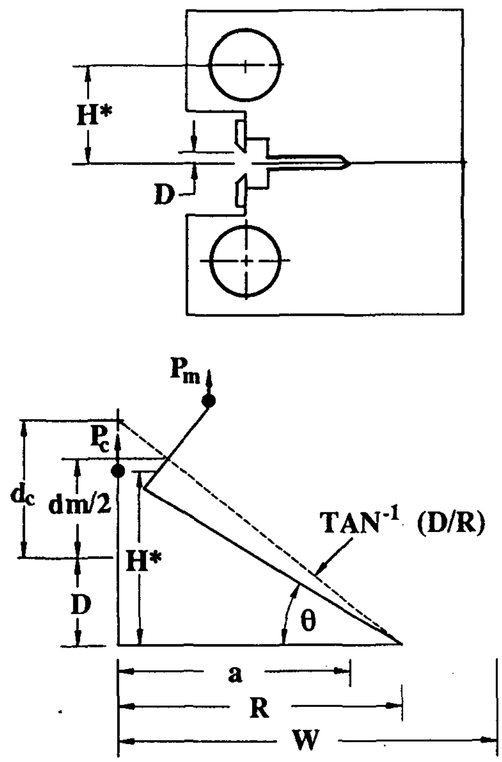


FIG. 6—Elastic compliance correction for specimen rotation.

$$C_{LLi} = \frac{1}{E'B_e}\left(\frac{S}{W - a_i}\right)^2 [1.193 - 1.98(a_i/W) + 4.478(a_i/W)^2 - 4.443(a_i/W)^3 + 1.739(a_i/W)^4] \quad (36)$$

For the SE(B) specimen crack opening displacement compliance,

$$C_{COD} = \frac{6S}{E'WB_e}\left(\frac{a_i}{W}\right)\left[0.76 - 2.28(a_i/W) + 3.87(a_i/W)^2 - 2.04(a_i/W)^3 + \frac{0.66}{(1 - a_i/W)^2}\right] \quad (37)$$

For the C(T) specimen, with the crack opening displacement measured at the load line,

$$C_i = \frac{1}{E'B_e}\left(\frac{W + a_i}{W - a_i}\right)^2 [2.1630 + 12.219(a_i/W) - 20.065(a_i/W)^2 - 0.9925(a_i/W)^3 + 20.609(a_i/W)^4 - 9.9314(a_i/W)^5] \quad (38)$$

For the DC(T), with the crack opening displacement measured at the load line,

$$C_i = \frac{1}{E'B_e[1 - (a_i/W)]^2} [1.62 + 17.80(a_i/W) - 4.88(a_i/W)^2 + 1.27(a_i/W)^3] \quad (39)$$

4

Apparatus

4.1 FIXTURES

FIXTURES FOR LOADING STANDARD fracture toughness specimens are described carefully in all ASTM fracture standards. Requirements are also included for the alignment of the specimen in or on the loading fixtures for proper testing.

For bend testing, the standard fixture is identical for E 1737 and E 1290 and is shown in Fig. 7. The critical dimensions in this case are the parallelism of the roller surfaces, base, and loading ram, the initial span, and the size of the rollers used. All of these requirements are addressed in Fig. 7.

The requirement that the material of the fixture and rollers be steel with a Rockwell hardness in excess of 40 RC is essential to avoid plastic indentation of the loading surfaces or rollers so that the rollers move freely during the course of the test. Low-stiffness springs or rubber bands should be used to assure that the support rollers are initially against the inner stops so that the proper bend span is present. Fine alignment marks on the specimen and rollers can be very useful in the alignment of the specimen and to center the roller, as shown in Fig. 8.

If the center of the loading roller is located in the plane of the crack, the moment in the crack plane will be very close to the proper value, that is, $M = PS/4$, even if the crack plane is not centered exactly between the support rollers. This occurs because the closer support then carries a greater share of the applied load and the error in applied moment is proportional to the square of the error in the misalignment. For example, a 1% error in alignment results in a 0.01% error in moment. If the loading roller is not located in the crack plane, a lower moment will be applied to the crack plane, resulting in a nonconservative fracture toughness measurement.

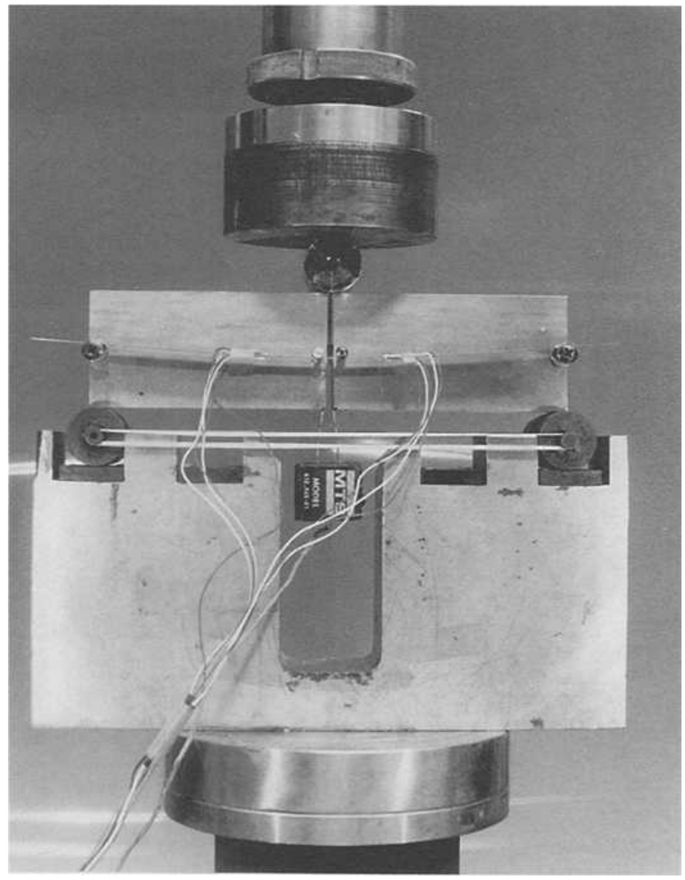


FIG. 8—SE(B) fixtures with rollers aligned for test.

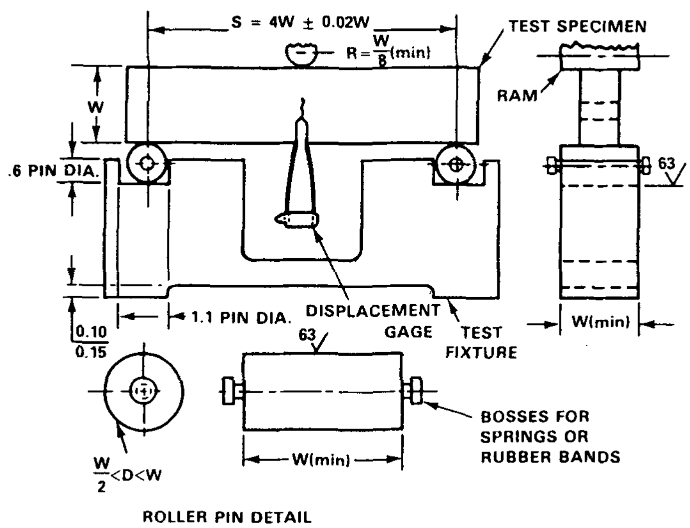


FIG. 7—The standard fixture for bend testing.

When side-grooved specimens are tested, the side groove acts as an aid in aligning the loading roller. When side grooves are not present, the use of scribe marks or other markings on the specimen is highly recommended.

For precracking single edge notched bend (SE(B)) specimens, it is often convenient to use fixed roller bend fixtures as shown in Fig. 9. The fixtures have been inverted to take the mass off the actuator so that higher fatigue precracking frequencies can be achieved. The rollers are also constrained so that they cannot "walk" during fatigue cycling. While these fixtures are suitable for fatigue precracking, they are not acceptable for the main fracture toughness test because the support rollers are not free to roll as the elastic-plastic fracture test proceeds.

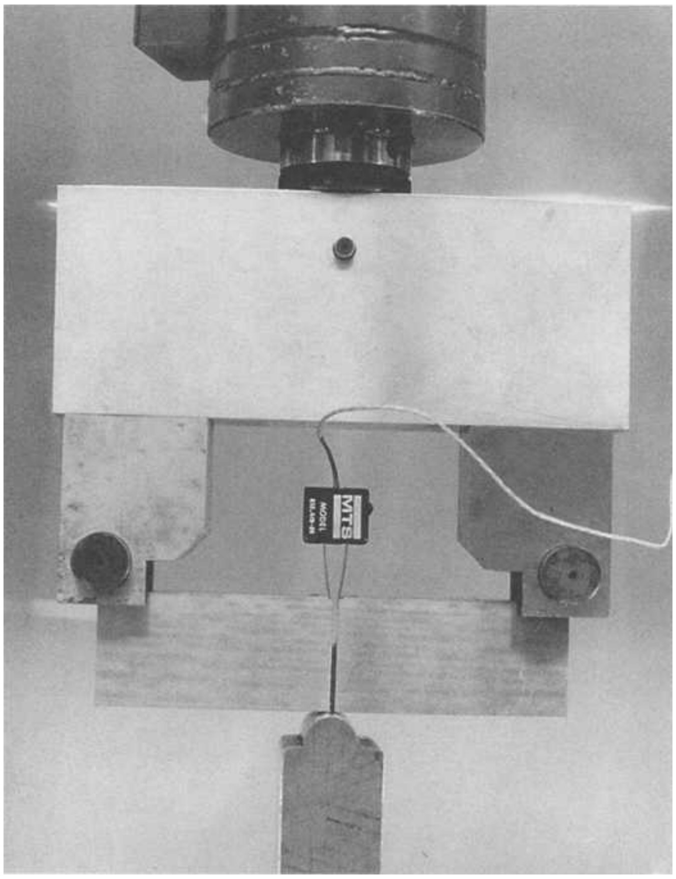


FIG. 9—Inverted precracking fixtures for SE(B) specimen.

Clevis drawings are provided in all ASTM fracture test standards for compact tensile (C(T)) specimens. In general, the test of a C(T) specimen requires two sets of test clevises. Fatigue precracking should be done in clevises with round holes [see ASTM Test Method for Measurements of Fatigue Crack Growth Rates (E 647)], while the fracture test must be done using clevises that have loading flats.

The standard clevises of ASTM E 1737 are shown in Fig. 10. The flat-sided holes in these clevises are required to apply the correct "two-point" loading to the specimen as it opens under load. Fatigue precracking can be done with these clevises, but this will lead to chipping or indenting of the loading surface, which will make the clevises unsuitable for further fracture toughness testing.

It is also important that the C(T) loading pin be free to roll on the flat clevis surface without contacting the edges of the clevis. In ASTM E 813-89, two C(T) specimen geometries are recommended, as shown in Fig. 11, with the loading pin diameter and position being the major differences. The first geometry, with the larger loading holes, was the original geometry, being the only specimen recommended by E 813-81, and this geometry is essentially that of the C(T) specimen of E 399 with a cutout added to allow the load line crack opening displacement to be measured.

If a pin of $0.25W$ diameter is used with this specimen, only $\pm 0.0025W$ of clearance is available when this specimen is installed in the recommended clevises of E 813-89. This leaves almost no room for the pin to roll as the specimen deforms during loading. This is an intolerable situation for unloading compliance testing and should be avoided. An example showing the effect of this specimen/pin/clevis interference is shown in Fig. 12. This *J-R* curve was obtained by testing a 1T[3] C(T) specimen having the $0.25W$ hole diameter, as is generally used at a large national laboratory where this specimen was machined, using clevises of the E 813-89 geometry as used at the U.S. Naval Academy, where this specimen was tested. This problem is addressed if the new clevis geometry of E 1737 and Fig. 10 is used since the hole geometry has been changed to accommodate the $0.25W$ pin diameter and to still leave adequate room for the pin to roll during the test.

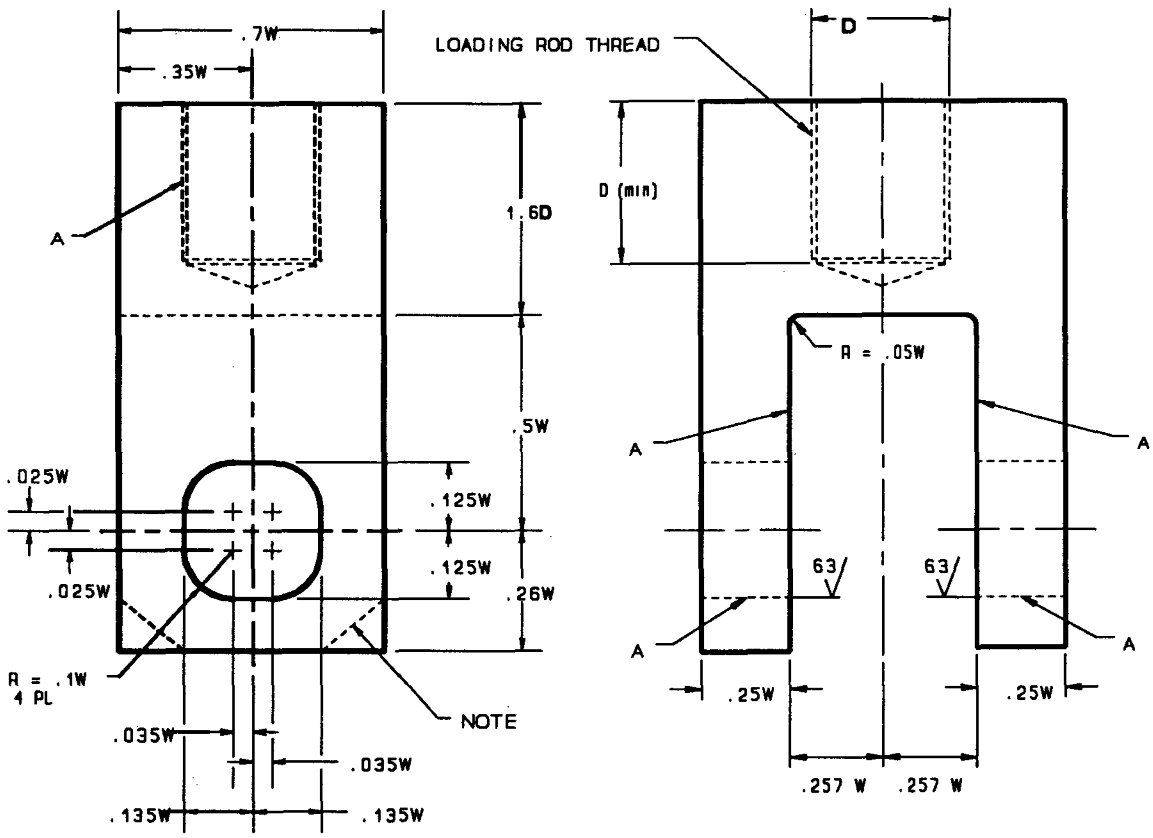
The second C(T) specimen geometry was developed to assure that the loading pins were free to roll on the clevis flats even if a very tough alloy was tested. This specimen geometry can be much less expensive to machine, and the cutout is scaled to allow the use of store-bought injector-style razor blades, which can be spot welded or otherwise attached to the load line surfaces provided. This procedure provides excellent knife edges at a low cost.

The principal drawback of the second specimen geometry is the reduced load capacity of the smaller loading pins, which will not support loads greater than about 75 kN (for a 1T specimen) unless an exotic alloy is used for the pins. Even this load will not be reached unless the specimens are fit rather tightly widthwise to the clevises so that the pins are loaded in double shear and not in three- or four-point bending, and problems can still arise if the specimen deforms near the pin hole, plastically expanding widthwise and locking itself into the clevis. For these materials, deeper initial cracks are recommended to avoid pin failures or specimen deformations.

As in the case of the SE(B) specimen tests, careful alignment of the loading fixtures, clevises, and the specimen itself is essential for accurate testing of C(T) specimens. This alignment should begin with an accurately centered load cell and straight-loading rods between the load cell, actuator, and clevises. This alignment should be verified and not assumed. An accidental single compression loading of a compact specimen in originally straight fixtures can leave the fixtures bent and worthless for further fracture testing. Certainly one of the advantages of the SE(B) specimens is that once straight and parallel fixtures are prepared, they are likely to remain straight and parallel and are not as easily damaged as are the more fragile C(T) fixtures.

The use of an environmental chamber greatly enhances the chances for trouble in aligning the load train. Interference between the environmental chamber and the load train at any point can greatly degrade the quality of the unloading compliance results.

[3]It is common practice to designate specimen sizes as 1T, 2T, 4T, etc., where the 1, 2, 4, etc., designates the specimen thickness in inches, and $W/B = 2$. Thus, a 1T specimen has $W = 2.0$ in. (50.8 mm) and B = 1.0 in. (25.4 mm). European researchers often use the 1T designation for a specimen with $W = 50.0$ mm and $B = 25.0$ mm, and similarly for larger or smaller sizes. If the ratio W/B is not 2.0, specimens are usually designated as, for example, a 1T plan size 1/2 in. thick.



A - SURFACES MUST BE FLAT, IN-LINE AND PERPENDICULAR,
AS APPLICABLE, TO WITHIN 0.002 In. T.I.R. (0.05 mm)

NOTE - Corners may be removed as necessary to accomodate the clip gage.

FIG. 10—Clevis for C(T) specimen testing.

4.2 TRANSDUCERS AND ELECTRONICS

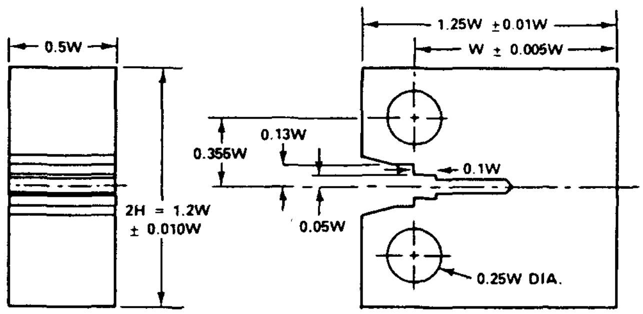
A key element in successful fracture toughness testing is the transducers that are used. All ASTM fracture testing standards require that the load transducer meet the requirements of ASTM E 4 (Practices for Force Verification of Testing Machines), which refers the user to ASTM E 74 (Practice for Calibration of Force Measuring Instruments for Verifying the Load Indication of Testing Machines). Calibration of the load-measuring system is best left to the machine manufacturer or to other qualified vendors. The test engineer has only to keep the calibration up to date.

The other measurement required in a fracture toughness test is a crack mouth opening displacement, a load line displacement, or both. Each of these measurements requires a displacement transducer, a transducer conditioner, and a readout device. Recording equipment is discussed more fully in the next section. Information is given in ASTM E 1737 on the calibration of extensometers and displacement transducers. Requirements for these transducers are specified in the ASTM fracture standards.

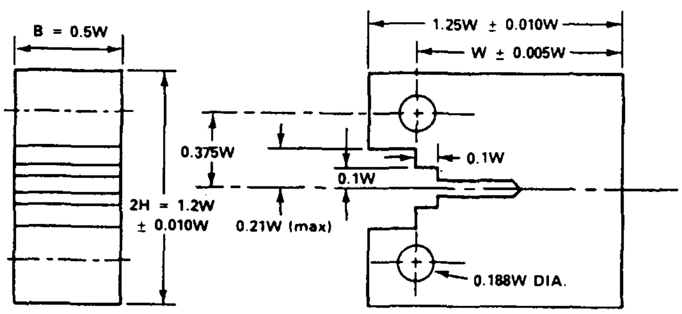
The original crack mouth opening displacement transducer was developed by Fisher et al. (1966) at the National Aeronautics and Space Administration and is shown schematically in Fig. 13 and in hardware in Fig. 14. A commercially available version of this gage is shown in Fig. 15, and several vendors supply a range of crack opening displacement gages that can be used at temperatures from liquid helium immersion to greater than 300°C. For high-toughness materials, a larger crack opening displacement range is required than is provided by the gage in Fig. 13, and larger displacement range gages have been developed. An example from E 1737 is shown in Fig. 16.

Load line transducers required for SE(B) specimens are less universal and much less available. A strain gage bridge "flex bar" was developed at NSWC, Annapolis (Joyce and Hackett 1986), as shown in Fig. 17. This gage is typically made from high-strength steel, but can be made from nickel superalloys if higher temperatures are required. An alternative system using a commercial LVDT (see Fig. 18) has been presented by Dawes (1979) and works fine for 1/2T or larger specimen configurations. It is also possible to obtain the load line displacement directly from a remote transducer built into the test machine, but care must be taken to remove machine compliance and displacements due to indentation of the specimen and fixtures so that an accurate specimen deflection is obtained (see KarisAllen and Matthews 1994).

Two categories of fracture toughness test will be discussed in this manual. The first type is used for evaluating a single point fracture toughness quantity—like a δ_c according to



C(T) Specimen for pin of 0.24*W* (+0.000 *W*/−0.005*W*) diameter



C(T) Specimen for pin of 0.1875*W* (+0.000*W*/−0.001*W*) diameter

FIG. 11—Two compact specimen designs recommended by E 1737.

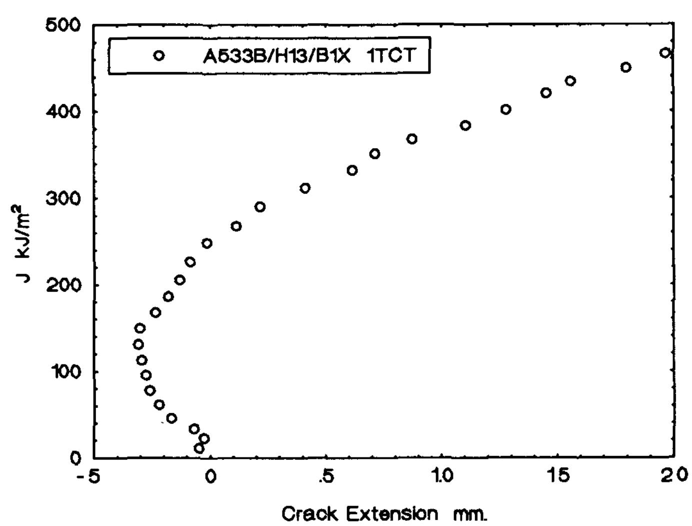


FIG. 12—Example *J-R* curve showing apparent crack backup due to pin/clevis interference.

ASTM E 1290, or one point of a multi-specimen J_{Ic} evaluation according to ASTM E 813. This procedure will be called the *basic test procedure*. A more advanced procedure is required for an unloading compliance test as, for example, is utilized in ASTM E 1152. This second procedure requires more stringent tolerances on the crack tip opening displacement gage and on the data acquisition system. For the basic procedure, a schematic of a fracture toughness test system is shown in Fig. 19.

Most modern test machines include transducer amplifier/conditioners that can be used for the crack mouth opening displacement and load line displacement transducers, but in some cases separate amplifier/conditioners are required. Care must be taken that the crack opening displacement transducer and amplifier produce an output signal that is quiet and stable, as well as accurate. For the basic procedure, all transducer amplifiers should have noise less than ±5 mV on a standard ±10-V range and should be stable to ±10 mV over a 10-min period.

Standard equipment will generally provide these requirements easily, but some equipment, like older MTS Model 442 controllers, can be noisy, on the order of ±30 mV on a 10-V range, and these amplifiers should be avoided—except for specimen precracking. The above requirements are generally consistent with 3 1/2-digit digital voltmeters or 12-bit analog to digital (A/D) recorders that have resolutions of 1 part in 4096 and generally ±1 bit of noise.

The calibration accuracy and repeatability of all displacement transducers should be checked before each series of tests. The fracture test standards require that, for the basic procedure, the crack opening displacement and, if used, the load line gage demonstrate a maximum deviation of the individual data points from a fit to the data to be less than ±1% over the full working range of the gage. This information is often provided by the vendor, but since gages can change over time, it should be checked. A calibration fixture made by mounting a commercial micrometer head in a laboratory-built stand is shown in Fig. 20, and a typical calibration data set is plotted in Fig. 21, showing both the measured data and the calibration curve. The tabulated data for this case is shown in Table 1, and a least squares best fit linear regression analysis gives the calibration equation:

$$COD = 0.4064V - 2.984 \times 10^{-3} \text{ mm} \tag{40}$$

In this case, a linear calibration is used, but this is not required by the fracture test standards. Column 3 in Table 1 shows the crack opening displacement values calculated from Eq 34, while Column 4 shows the deviation between Columns 1 and 3, and Column 5 shows the percentage difference as a function of the full-scale range. These data are quite typical, showing a double crossover between the transducer output and the equation results. The maximum deviation of Column 5 is −0.08%, which is well within the ±1% required by the basic test method.

For the basic procedure, analog X-Y recorders can be used, but digital data acquisition is highly recommended. Plug-in analog to digital cards are available for PCs at a nominal cost that will take 12-bit resolution data that are fully adequate for the basic test procedure. Digital data facilitates calculating areas under the load displacement record, provides compact and permanent storage and ease of display, and is used throughout the examples in this manual. Recording equipment is discussed more fully in the following section.

The advanced test procedure requires that the crack opening displacement gage demonstrate a maximum deviation of the individual data points from a fit to the data to be less

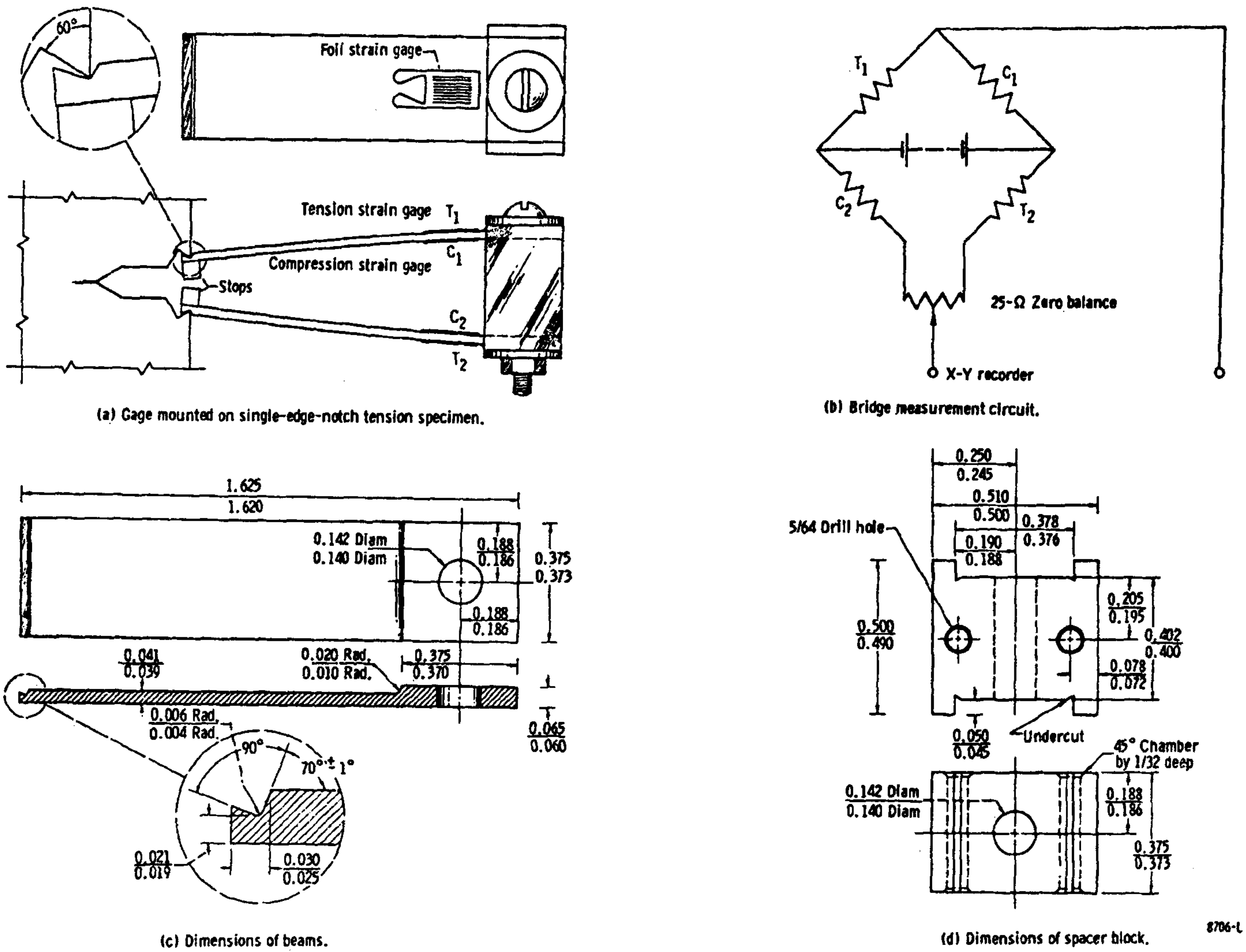


FIG. 13—Double cantilever displacement gage for fracture testing.

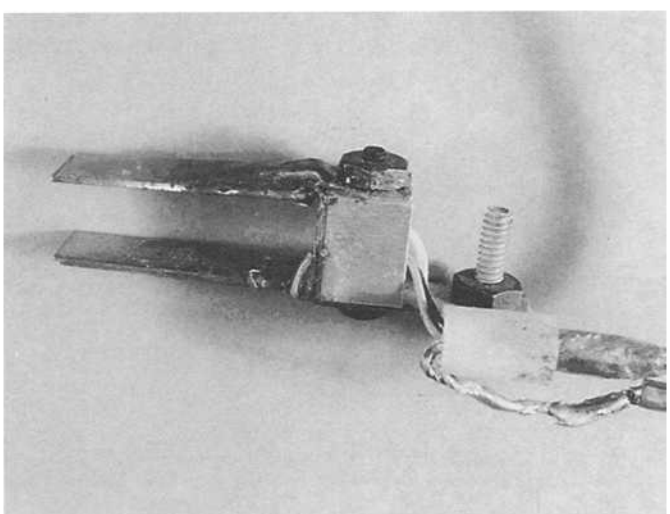


FIG. 14—The original-style laboratory-built crack mouth opening gage.

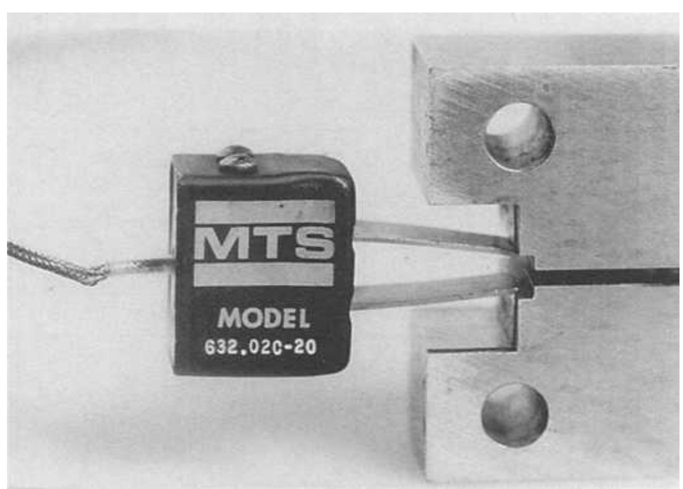


FIG. 15—Commercial version of a COD gage.

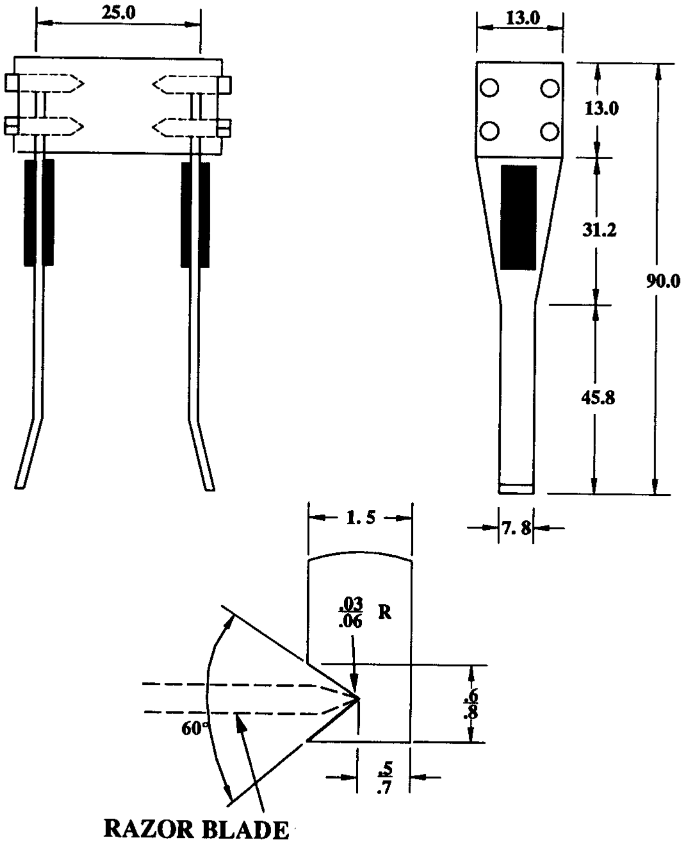


FIG. 16—Clip gage design for 8.0-mm working range (Note: all dimensions are in millimetres).

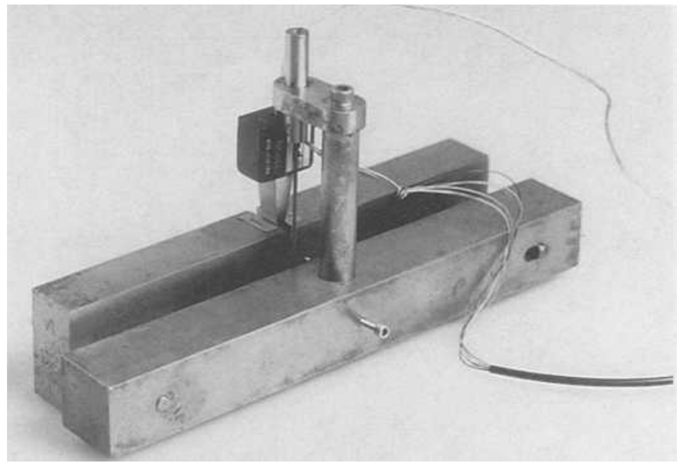


FIG. 18—Backing bar and LVDT load line displacement system.

than ±0.2% over the full working range of the gage. This requirement is easily exceeded by the calibration data shown in Table 1. This requirement is generally met by commercial gages using a linear fit, but not always, and this requirement should be checked relatively often.

Notice that a linear fit is not required and that the ±0.2% requirement can be obtained if necessary by using higher-order terms in the calibration equation—a straightforward modification if a digital system is being used. A digital system is a requirement of the advanced test procedure. Requirements for the load transducer and the load line transducer, if used, are not tightened for the advanced procedure.

The digital resolution used for the crack opening displacement measurement needs to be higher for the advanced system as well. For steel specimens with cracks near the short limit allowed by E 1737, $a/W = 0.5$ for example, the total crack opening displacement change on a 15% unloading can be as little as 1% of the full transducer range. A 12-bit A/D will see only three or four distinct readings on such an unloading, and the slope resolution will be totally inadequate.

The test standards "suggest" a resolution of 1 part in 32 000 (16 bit) and a signal stability of 4 parts in 32 000 over a 10-min interval. These requirements are difficult to meet and are not required for flexible materials like aluminum or for moderately to deeply cracked specimens. In most cases, a standard instrumentation amplifier like that in an Instron machine, in an MTS Model 458 controller, or bought separately from Vishay, etc., when combined with a good clip gage and calibrated at 0.5 mm/V and used with a 5 1/2-digit digital voltmeter or 16-bit A/D, will give satisfactory results.

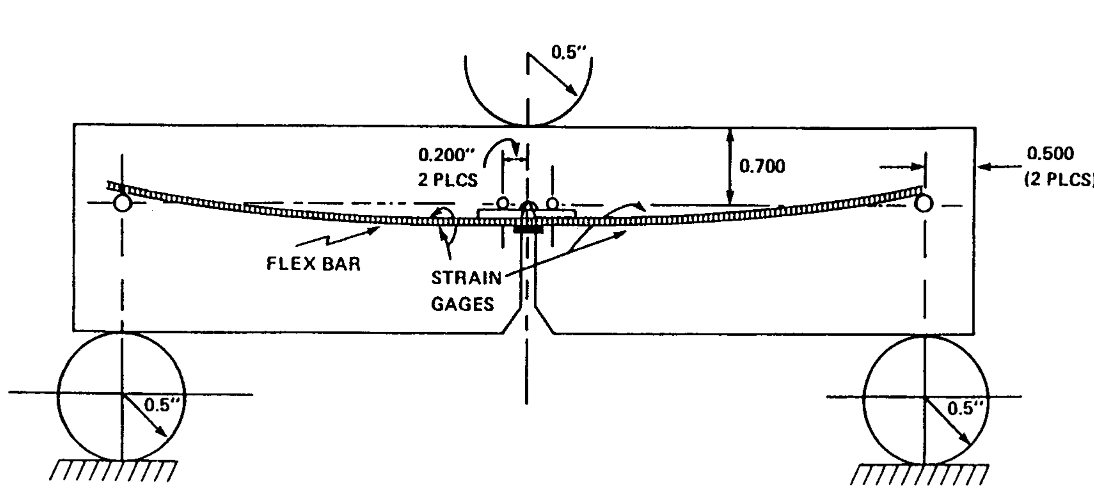


FIG. 17—A strain gage bridge flex bar.

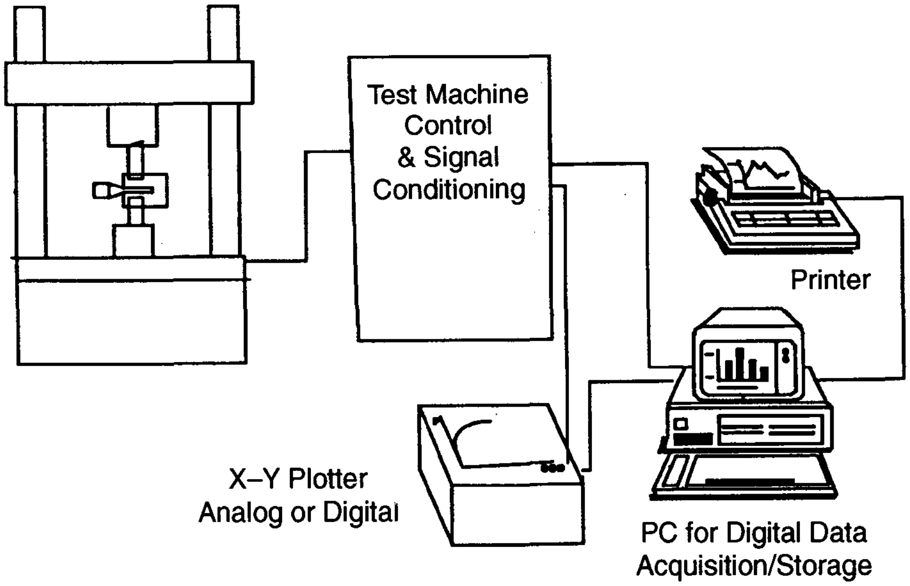


FIG. 19—Basic test apparatus.

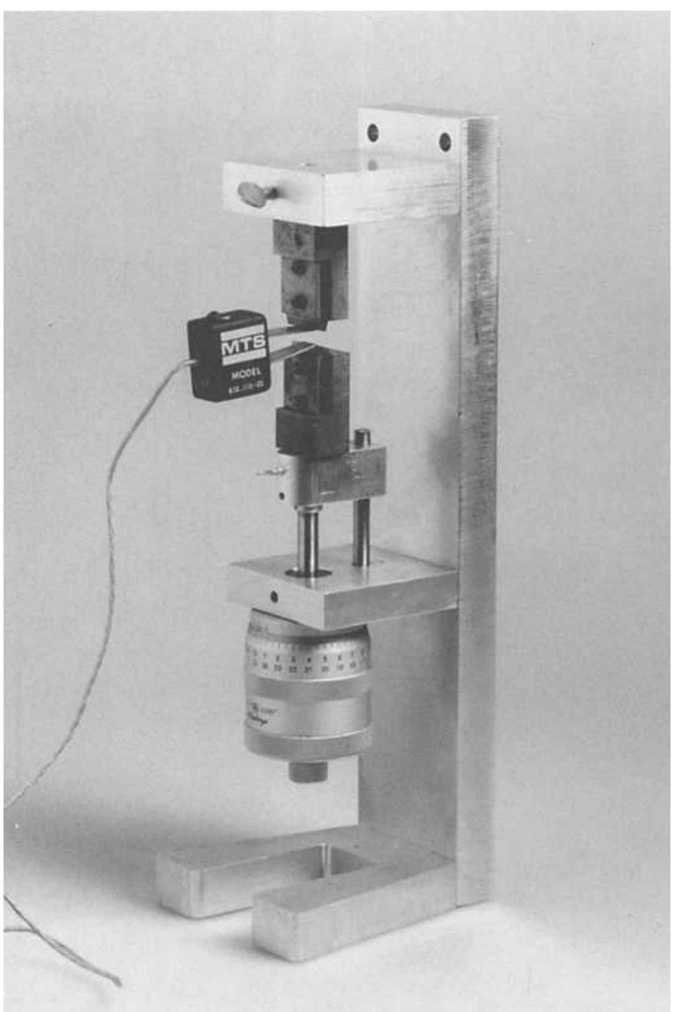


FIG. 20—Calibration fixture for crack opening displacement gages.

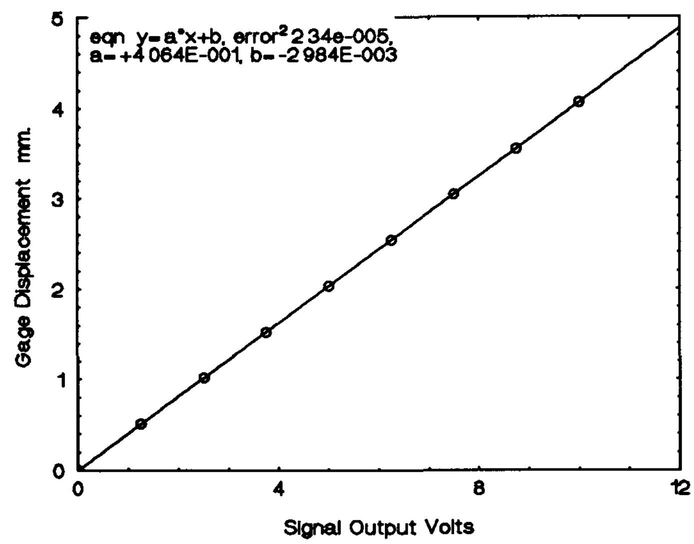


FIG. 21—Calibration results for Transducer SN-153.

TABLE 1—Calibration data COD Gage SN153.

Calibration Setting, in.	Calibration Setting, mm	Signal Output Volts	Calculated COD, mm	Deviation, in.	Deviation, % of Range
0.160	4.064	10.0022	4.0612	−0.0028	−0.07
0.140	3.556	8.75348	3.5535	−0.00203	−0.05
0.120	3.048	7.51032	3.0490	0.00102	0.02
0.100	2.540	6.25861	2.5408	0.00015	0.02
0.080	2.032	5.01109	2.0342	0.00215	0.05
0.060	1.524	3.75900	1.5356	0.00165	0.04
0.040	1.016	2.51034	1.0185	0.00249	0.06
0.020	0.508	1.24913	0.50627	−0.00173	−0.04
0.000	0.0	−0.00532	−0.00322	−0.00322	−0.08

4.3 RECORDING EQUIPMENT

Fracture toughness testing requires that the signals from the load and crack opening displacement transducers be measured, calibrated, and stored for analysis to obtain the elastic-plastic fracture toughness quantities. Recording equipment plays an important role in this process. For the basic test procedure, an analog "X-Y" recorder resulting in a pen plot on a graph paper is sometimes satisfactory. Modern digital electronic equipment provides much better recording techniques, and these new techniques will be used in the examples developed in this manual.

In general, to record each of the signals described in the preceding section, a digital voltmeter, interfaced to a PC, can be utilized, or a combined voltmeter/scanner can be used economically if three or more signals are to be measured. A very cost-effective system is the Keithley Model 2000 digital voltmeter/scanner, which can read ten channels of data and communicate with a PC via a IEEE-488 interface or an RS-232 interface. Roughly equivalent instruments are available from Hewlett Packard and Fluke.

An alternate system can include a combined analog to digital (A/D) digital to analog (D/A) card, which is available from Metrabyte/Keithley, Data Translation, or National Instruments. Such a card is generally supplied with software that allows the user to interact with the plug-in card and PC as if he had a powerful digital voltmeter/oscilloscope.

Specimen Preparation

5.1 SPECIMEN MACHINING

SPECIMEN DRAWINGS THAT include machining tolerances are provided for each specimen type in all ASTM fracture test standards. All tolerances are well within what is achievable with good machine shop practice. The most important tolerance in the SE(B) specimens is the parallelism of the loading surfaces, and, in the C(T) specimen, the corresponding pinhole alignment and parallelism. Surface finishes are generally not critical, especially when side grooves are used. The initial machined notch should be perpendicular to the plane of the pinhole center lines in the C(T) and DC(T) specimens. The initial machined notch and precrack combination must lie within an envelope as shown in Fig. 22. These notches can generally be cut with slitting saws that have been ground to a tip of radius on the order of 0.1 mm. Modern wire electric discharge machining (EDM) techniques now allow initial notch openings to be as narrow as 0.2 mm, and EDM slots can be substituted for the conventionally machined notches if desired.

For most materials, side grooves are necessary to produce a straight and even ductile crack extension. Typical side-grooved and nonside-grooved fracture surfaces are shown in Fig. 23. The crack in the nonside-grooved specimen extends only in the center region, while in the side-grooved specimen the crack extends uniformly across the specimen thickness. Three-dimensional finite element analyses by DeLorenzi and Shih (1983) and by Nevalainen and Dodds (1995) have shown that the side grooves tend to make the J-integral at the crack tip more uniform across the specimen, eliminating the low J-value near the specimen surfaces.

The nonuniform crack extension found in nonside-grooved specimens cannot be accurately measured by un-

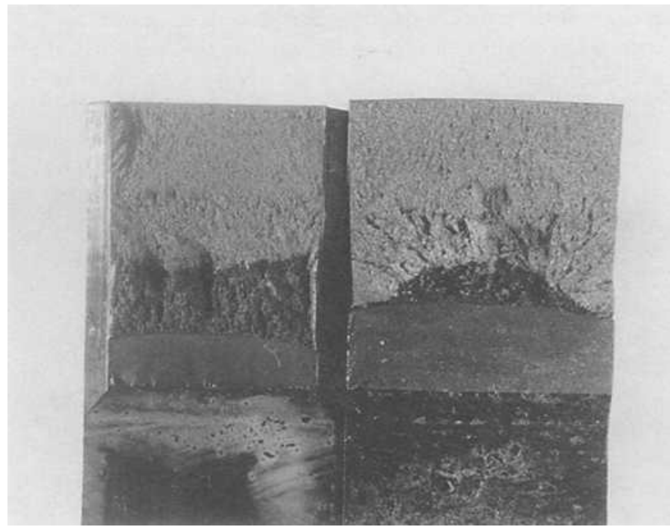


FIG. 23—Photograph showing how ductile crack extension develops in side-grooved and nonside-grooved specimens.

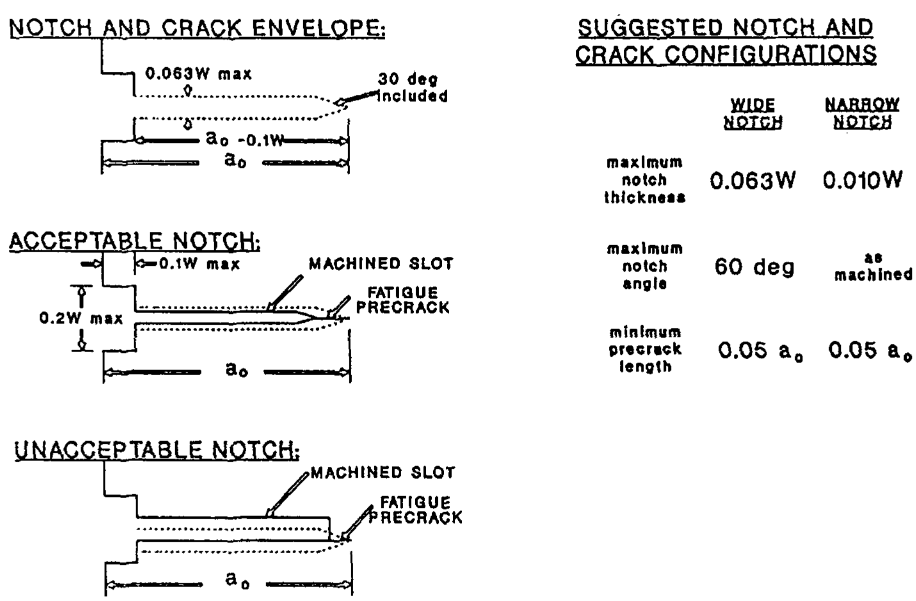


FIG. 22—Definition of an acceptable notch and crack envelope for fracture toughness testing.

loading compliance techniques (Gudas et al. 1979), which generally underestimate the crack length in comparison with an optical nine-point area average crack length. When multi-specimen methods are used, it has been shown (Morland 1990) that the resulting *J-R* curve is elevated in comparison with that resulting from side-grooved specimens and is dependent on the specimen thickness.

The statement is sometimes made that "the structure is not side grooved, so why are side grooves and straight cracks required in ASTM fracture testing standards." If, for example, an engineer has a specific application in mind, for instance a through-wall circumferential crack in a pressure vessel wall, laboratory tests on standard specimens without side grooves might be the correct characterization. If the structural crack is, however, through-wall and long in comparison to its depth, the *J-R* curve measured by high-constraint, side-grooved specimens would more accurately predict the structures behavior.

In any case, the side-grooved, deeply notched ASTM standard result is intended to be the conservative lower bound, resulting in a safe analysis when applied to a structural application. If less of a safety factor is desired, changes to this configuration can be made, but the test results should then not be reported as being according to the ASTM standard requirements.

Side grooves are normally cut with standard Charpy notch cutters that have a 45° included angle and a root radius of between 0.125 and 0.2 mm. Side grooves should not be machined until after precracking to avoid a tendency for the precrack to advance more rapidly along the specimen surface, where the side groove root provides an additional stress concentration. Side grooves are nominally lined up with the root of the initial notch, even when the fatigue precrack appears to deviate from the initial notch plane. In most cases, the fatigue precrack is adequately coplanar with the initial notch plane within 1 mm of the surface, and the side groove will be aligned with the precrack if it is aligned with the machined notch root.

It is good research practice to prepare a data sheet for each specimen as shown in Fig. 24. Part of this sheet is filled in after machining, part after precracking, and part after the test is complete. This form can be kept in a computer spreadsheet, if desired, or it can exist initially as paper and when complete be input to a computer.

5.2 PRECRACKING

Specimen precracking is often one of the most complex, time-consuming, and difficult aspects of fracture toughness testing. This is certainly one aspect of fracture toughness testing that requires an investment of time to develop the tools and the techniques for consistent and efficient precracking, at least if many specimens must be prepared. The most common machine used for this process is a servohydraulic test machine, although a rotating mass machine or a displacement-controlled cam-type machine can be substituted, if necessary. It is required that the loads applied by the fatigue precracking machine be known to $\pm 5\%$.

Both the maximum stress intensity and maximum load are controlled during precracking. The maximum load allowed during the final stage of precracking (see below) is set in terms of P_M, given by:

for SE(B) specimens:

$$P_M = \frac{0.5\sigma_Y B b^2}{S} \tag{41}$$

for C(T) and DC(T) specimens:

$$P_M = \frac{0.4\sigma_Y B b^2}{(2W + a)} \tag{42}$$

Precracking requirements specified by ASTM standards E 1737 and E 1290 are as follows:

1. The length of the fatigue precrack extension from the machined notch shall not be less than 5% of the total crack size, a_o, and not less than 1.3 mm.
2. For the final 50% of fatigue precrack extension or 1.3 mm, whichever is less, the maximum load shall be no larger than P_M, or a load such that the ratio of the maximum stress intensity applied during fatigue precracking to the elastic modulus (K_{max}/E) is equal to or less than 1.6×10^{-4} $\sqrt{m}$.
3. If fracture instability is possible, it should be noted that an extra limitation can affect J_c and that the K_{max} applied during precracking must be less than $0.6(J_{Qc}E)^{1/2}$ since this requirement might be the true limit to the allowed maximum load during precracking.

E 1290 still maintains a requirement that the ratio of the minimum precracking load to maximum precracking load not exceed 0.1. This requirement existed in the 1987 versions of E 813 and E 1152, but has been removed from E 1737. The stress intensity applied can be calculated using the formulas for K used to evaluate the elastic component of J.

These requirements basically place limits on the maximum load that can be applied to the specimen during precracking. These requirements generally allow a specimen to be precracked in less than 100 000 cycles, which can usually be accomplished within an hour. For the special case where a cleavage interruption is possible, the precracking load limits can be lower, and the time to precrack a specimen can be substantially longer. Generally, it is advisable to notch the specimen about 2.0 mm short of the desired final crack length. This allows adequate room to start the crack at a somewhat higher stress intensity and then to lower the stress intensity for the final 1.3 mm (0.05 in.) of crack growth.

Longer precracks are, of course, allowed—they just take longer. It is often standard practice to stop the precracking process and to reverse the specimen in the fixture one or more times to aid in obtaining a straight precrack, but the best technique is to have the system aligned accurately enough so that this is not necessary.

The usual precracking procedure is to start with loads that give a maximum stress intensity of approximately 75% of those allowed by the above limits and then, after cycling for 10 min or so, increase the applied loading, repeating the stepwise increases at 10-min intervals until the crack is observed to be growing. If load increases were required above the P_M level, the load can be shed smoothly as the crack grows so that the conditions above are satisfied over the last 1.3 mm, as required.

Clearly, the precracking process requires some means to measure the crack length. A straightforward method re-

Specimen Data Sheet

Specimen I.D.: ____________ **Material:** ____________ **Date:**____________

Material Properties:

E ________________ σ_{YS} ________________

v ________ σ_{TS} ________________

σ_{Y} ________________

Specimen Dimensions:

W _________ B _________ B_N _________

H ________ (C(T)) L ________ (SE(B)) D _________ (DC(T))

Notch Depth #1 ________________ Notch Depth #2 ________________

Average Notch Depth ________________

Crack Length Surface Measurements:

Position	Notch (mm/in)	Fatigue Crack (mm/in)	Fatigue Length (mm/in)	Ductile Tear (mm/in)	Ductile Length (mm/in)
1					
2					
3					
4					
5					
6					
7					
8					
9					

Average Fatigue Precrack Length ___________

Average Ductile Extension = ____________

Initial Crack Length = Notch Depth + Average Precrack Length = ____________

Final Crack Length = Initial Crack Depth + Ductile Extension = ____________

FIG. 24—Example data sheet with measurement data for a fracture toughness test.

quires only a calibrated traveling stage microscope mounted so that the test mechanic can observe the crack as the specimen is cycled. This method is enhanced if the specimen is polished near the notch tip and not side grooved. Scribe lines on the specimen surfaces can be used to mark increments of precrack growth and the final crack length. This process requires continual human monitoring and is impractical (outside of the university, at least) if 20 or 100 or more specimens are to be precracked.

Several other techniques have been developed to monitor the crack length and to control the applied cyclic loading. The first system used in Annapolis involved inserting a crack

FIG. 25—Automated precracking system.

opening displacement gage into the system and connecting it to a laboratory-built peak detector/comparator/relay "black box" that could be used to shut off the servohydraulic loading when a desired maximum crack opening displacement was achieved with the test machine cycling in load control.

Use of the standard handbook (Tada et al. 1985) compliance equations—and a little trial and error—resulted in a system that required only minor oversight and resulted in repeatable precracks in standard specimens. This was improved by developing a "smart" box which included an early microprocessor that calculated slopes and evaluated maximum and minimum load and crack opening displacement values and returned them to a PC. The PC then was capable of shutting down the servohydraulic machine when the final desired crack size was achieved or if stress intensity limit conditions were exceeded.

A later version replaced the "smart" box with a plug-in A/D and D/A card that could be installed in the PC. This system could measure the load and crack opening displacement data including the maximum values, calculate the compliance and crack length, and do the necessary calculations and report the present crack length and maximum stress intensity to the test operator. It could also shut down the test system when the final crack length was reached or a maximum stress intensity condition was encountered. It did not have control of the loading directly, however, and could not shed the load mean and amplitude as the crack grew.

The most recent system used in Annapolis adds a second D/A card to generate the command signal, eliminating completely the servohydraulic test machine function generator. With the PC in control of the test machine, load shedding is now possible and constant K_{max}, constant ΔK, or even ΔK

shedding conditions can be used during specimen precracking. This system is shown precracking a SE(B) specimen in Fig. 25, although of course most of the system is internal to the PC and most of the development effort is in the QuickBASIC program that controls the operation.

Several vendors have developed fatigue crack growth analysis programs that can be used for precracking since they provide stress intensity control and will stop the test at a set crack length. These software packages invariably require the specific hardware of the vendor involved, but if many specimens are to be precracked, these software packages can, nonetheless, provide economical systems for precracking, as well as supplying a capability for fatigue crack growth rate testing and even for fatigue crack growth rate threshold testing.

In general, for elastic-plastic fracture testing, Chevron notches are not needed, and, since they add considerable machining expense, they should be avoided. If the fatigue fixtures are well aligned, high-toughness materials will fatigue in a straight and controlled fashion. Careful fixture alignment is always the principal method to obtain straight fatigue precracks. Sharp-machined notches are essential, as well, and fine wire EDM notches have proven to be very effective as starters for straight fatigue precracks.

6

Basic Test Procedure

6.1 RUNNING THE TEST

A SCHEMATIC OF THE APPARATUS needed for a basic test is shown in Fig. 19 (see Section 4). For the test used as an example here, the specimen is an HY80 structural steel alloy tested at room temperature as part of an E 813 multi-specimen J_{Ic} investigation. In Fig. 26, the specimen is shown mounted in test clevises with the clip gage installed. In this case, the small-hole specimen (see Fig. 11, design for pin 0.188W, in Section 4) is used with spot-welded razor blade knife edges.

Care must be taken to align the loading pins at the centers of the clevis flats after a slight load has been applied to the specimen. If this load is lost, i.e. by heating the specimen and loading fixtures, care must be taken to visually assure that the load pins remain aligned at the start of testing. Several slow unloading/loading cycles below the P_M value can be applied to assure that the crack opening displacement gage is properly seated and the specimen sits freely in the clevises.

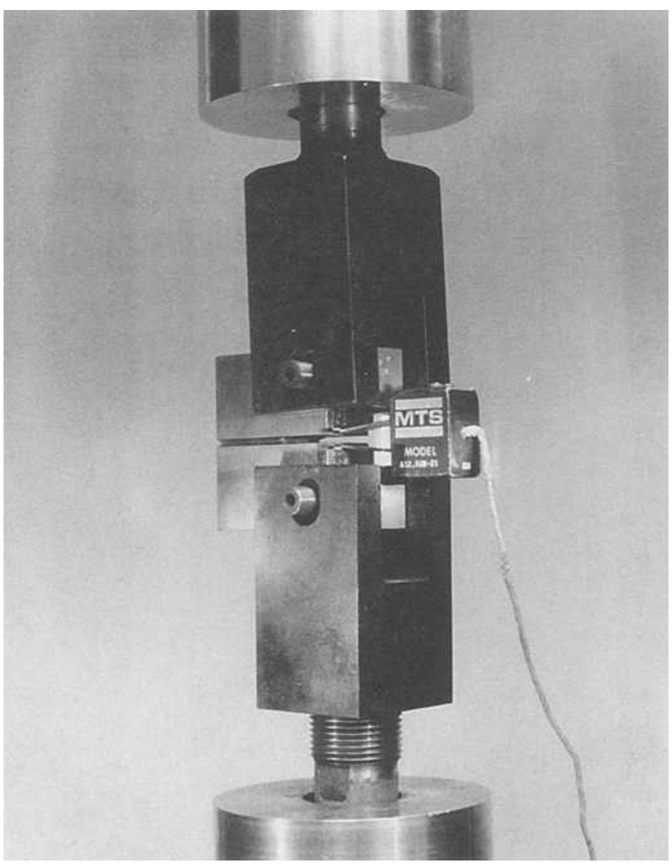


FIG. 26—C(T) specimen mounted in test clevises.

The test machine rate should be set to satisfy the requirements of the applicable fracture standard, i.e. for E 1737, the time from the initial load to the P_M load should be between 0.1 and 10 min for E 1290 so that $0.55 \le dK/dt \le 2.75$ MPa$\sqrt{m}$ to P_M. A typical rate is generally on the order of 0.5 mm/min so that P_M is reached in approximately 1 min and the test duration is between 10 and 40 min. An example load versus load line displacement record is shown in Fig. 27.

After stopping the test at the desired crack opening displacement, stopping the data acquisition, and returning the load to zero, the specimen can be removed from the test fixtures. If the specimen is cold, it should be heated to room temperature as soon as possible to avoid condensation and oxidation. It is generally convenient to proceed directly to heat tinting at this time so the ductile crack growth can be measured and recorded.

The E 1737 standard suggests that heat tinting of steels can be accomplished at a temperature of 300°C for 10 min. This might be somewhat conservative, and higher temperatures or longer times may be used. Only a slight burnishment of the specimen surface is generally required to result in a distinct tinting of the ductile fracture surface. Overtinting can cause damage to the features of the fracture surface and should be avoided when possible. Some materials, like aluminum, copper-nickel alloys, and some stainless steels, do not heat tint well. For these specimens, fatigue cycling is often the only way to mark the extent of ductile crack growth during a basic fracture toughness test.

Reinitiating a fatigue crack from a ductilely torn, high-toughness material can, however, be challenging. The best method is to start the cycling with R no larger than 0.1 and

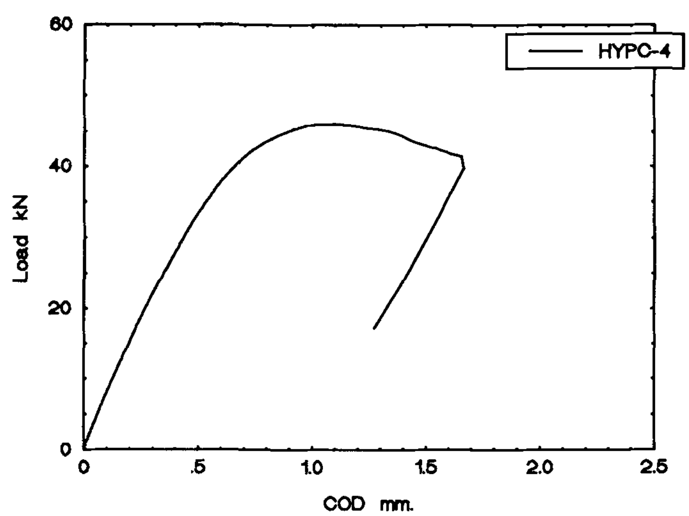


FIG. 27—Load versus COD for basic specimen HYPC4.

a P_{max} approximately three quarters of the load held by the specimen at the end of the ductile tearing step. If necessary, this maximum load can be increased in small steps after a block of 20 000 fatigue cycles has been applied. Caution is advised here. The maximum fatigue load must be kept as low as possible so that hole growth processes do not occur during the fatigue crack reinitiation process, which will make it impossible to measure the ductile tearing crack extension.

After marking the extent of ductile crack growth by heat tinting or fatigue cycling, the specimen must be broken open to expose the crack surface for measurement. Typically for ferritic steels this is done by chilling the specimen using immersion in liquid nitrogen to produce a cleavage of the remaining specimen ligament. For some steels, dry ice and methanol can be used; in some cases, materials will cleave adequately at room temperature. Even austenitic stainless steel, which does not demonstrate a ductile to brittle transition, should be broken open at as cold a temperature as is practical to reduce the amount of deformation the specimen undergoes.

The combination of heat tinting and cleavage produces a clearly measurable area of ductile crack extension, as shown in Fig. 28.

6.2 MEASURING THE CRACK

The elastic plastic fracture test standards require that a nine-point average measurement be made of the original fatigue precrack and the final ductile crack extension. A schematic to aid visualizing this measurement is shown in Fig. 29. The standard language is: "Along the front of the fatigue crack and the front of the marked region of slow stable crack extension, measure the crack size at nine equally spaced points centered about the specimen centerline and extending to 0.005W from the root of the side groove or surfaces of plane-sided specimens."

For the example specimen of Fig. 28, the net thickness is 20 mm, so the spacing between the measurement lines is 2.5

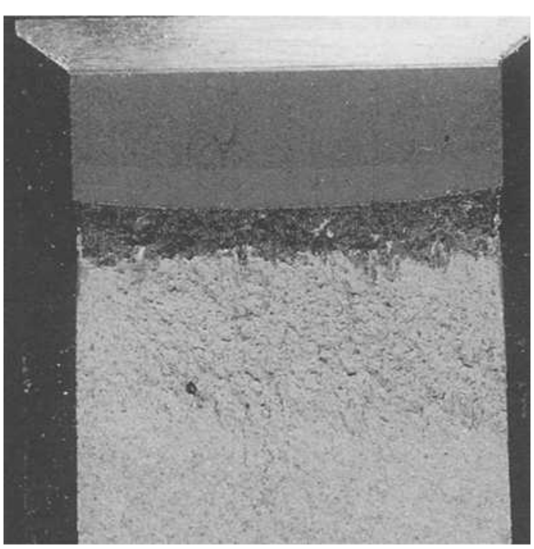


FIG. 28—Fracture surface showing fatigue precrack and ductile tear.

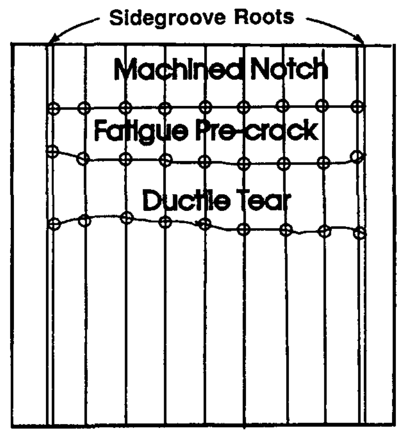


FIG. 29—Measurement grid for nine-point average crack length and crack extension measurement.

mm (0.1 in.) and the surface adjustment is 0.25 mm (0.01 in.). A set of measurements taken from this specimen is shown in a spreadsheet format in Table 2. Please note that the specimen HYPC7 was tested as a single-specimen unloading compliance test and is discussed more completely in Section 7. The spreadsheet is useful since a template can be set up to do the average calculations and to act as a record of the measurement. Both the original crack size, a_o, and the final physical crack size, a_p, are obtained by first averaging the two near-surface measurements and then using this value and the remaining seven points to obtain an eight-point average crack length.

Since it is difficult to move a traveling microscope large distances, all measurements taken here are relative to the machined notch root. The depth of the notch root is obtained before the test by taking an average of two surface measurements of the notch depth and recording it on the specimen data sheet. Optical measurements were input into Columns 2, 3, and 5 of the spreadsheet, allowing calculation of Columns 4 and 6 to 8. The average fatigue crack extension, the average ductile crack extension, the average initial crack length, and the final measured crack length can then be calculated from the measured data and the initial notch length. The columns giving the percent difference between the average crack length and the individual measurements are used in the data qualification section below.

6.3 ANALYSIS FOR J_{Ic} USING BASIC TEST DATA

The result of a basic fracture test is a single value, generally the J-integral corresponding to a measured amount of ductile crack growth for partial construction of a multi-specimen data set from which a J_{Ic} value is to be determined. The objective of this section is to take the data obtained from a series of multi-specimen basic tests and to develop J_{Ic} according to ASTM E 1737.

6.4 THE MULTI-SPECIMEN METHOD

In the multi-specimen method, at least five nominally identical specimens are tested using the basic test method.

TABLE 2—Spreadsheet for Specimen HV-PC7 crack length measurements (Material HY-80).

Crack Measurement Position (see Fig. 29)	Notch Measurement Position, mm	Fatigue Crack Measurement Position, mm	Fatigue[1] Crack Extension, mm	Ductile Crack Position, mm	Ductile Crack[2] Extension, mm	a_o[3] Difference, %	a_f[4] Difference, %	Ductile[5] Crack Extension Difference, %
1	18.161	12.548	5.613	10.262	2.286	1.73	−4.68	8.79
2	18.161	12.217	5.944	9.5	2.717	0.68	−2.45	−8.40
3	18.161	11.963	6.198	8.915	3.048	−0.12	−0.73	−21.61
4	18.186	11.862	6.324	9.576	2.286	−0.52	−2.67	8.79
5	18.161	11.836	6.325	9.347	2.489	−0.52	−2.00	0.69
6	18.186	11.811	6.375	9.779	2.032	−0.68	−3.26	18.93
7	18.186	11.938	6.248	9.627	2.311	−0.28	−2.82	7.80
8	18.212	12.09	6.122	9.449	2.641	0.12	−2.30	−5.37
9	18.263	12.395	5.868	9.627	2.768	0.92	−2.82	−10.44

NOTE: An average of the two surface measurements of the initial notch length before test gives $a_N = 25.42$ mm.
An 8-point average of Column 4, see Section 6.2, added to a_N gives $a_0 = 31.58$ mm.
An 8-point average of Column 6, see Section 6.2, added to a_0 gives $a_f = 34.09$.
An 8-point average ductile crack extension measured for this specimen = 2.51 mm.
[1]Column 2 minus Column 3.
[2]Column 3 minus Column 5.
[3]Percent difference between the individual a_0 measurement and the average a_0.
[4]Percent difference between the individual a_f measurement and the average a_f.
[5]Percent difference between the individual ductile crack extension measurement and the average ductile crack extension measurement.

Each specimen is tested to a different total displacement so that each specimen should have a slightly different amount of ductile crack extension in the range 0.2 to 1.8 mm. Each specimen is loaded in turn, the crack extension is marked by heat tinting or fatigue cracking, the specimen is broken open to expose the crack surface, and the extent of crack extension is measured using an optical eight-point average technique and recorded. Subsequent tests are adjusted to obtain a range of crack extension results so that a clearly defined J-resistance curve is developed.

The data that should be available after each basic test are a load versus load line displacement record, preferably digital but possibly analog, and two specimen halves from which the original precrack length and crack extension can be measured. Crack length and shape measurement techniques were discussed previously. A set of load versus load point displacement records from six HY80 1T C(T) specimens is shown in Fig. 1 (see Section 2). The tests were run to different final crack opening displacements to obtain a range of crack extension values. Measured crack length data were obtained for each specimen and recorded in Table 3.

To compute the J-Δa data pairs, each digital load displacement record was imported into a spreadsheet, as shown for specimen MULTI-4 in Table 4. The experimentally measured data are in Columns 2 and 3 in this spreadsheet. Information is also input giving the specimen dimensions, material properties, and measured initial and final crack lengths. The spreadsheet is then programmed to calculate for each load displacement data pair: the total area under the load displacement curve, the elastic and plastic areas using the specimen compliance calculated from the specimen dimensions and crack length, the elastic J component, the plastic J component, and the total J component, as shown in Columns 4 to 10 of the spreadsheet. The data lines between 16 and 200 have been removed for brevity.

TABLE 3—Example multi-specimen data—HY80 steel.

Specimen ID	Crack Extension, mm	J, kJ/mm^2	CTOD, mm
MULTI-1	0.372	197	0.315
MULTI-2	0.391	239	0.355
MULTI-6	0.558	266	0.376
MULTI-5	0.713	291	0.339
MULTI-4	1.668	322	0.416
MULTI-8	1.739	344	0.439

The final calculation in the total J column is then the J input to this specimen when the test was stopped. This J value, with the corresponding ductile crack extension, make up the measured J-Δa pair for this specimen. For Specimen MULTI-4, the final (Δa,J) data pair is (1.668 mm, 322 kJ/m^2). Each specimen's load displacement data were input to the spreadsheet program in turn, and the resulting data are plotted in Fig. 30, showing that all six data points lie inside the exclusion lines. This means that we have met the requirement that at least five data points be present in this region for the J_{Ic} calculation.

An additional requirement applies here also, called the data point spacing requirement. For our data set to satisfy this requirement, at least two data points must fall in Zone A on Fig. 30, and at least one point must fall in Zone B, with the other points allowed to fall in either Zone A or Zone B. The data shown on Fig. 30 also satisfy this requirement even though the data spacing is far from uniform. Since both these requirements on number of data and on data spacing are satisfied by our data set, we can proceed to the evaluation of J_Q.

6.5 EVALUATION OF J_Q

Evaluation of J_{Ic} is a two-step process involving evaluating a tentative J_Q, then qualifying J_Q as J_{Ic}. J_Q will be evaluated in this subsection and will be qualified as a J_{Ic} in Section 8.9. J_Q is the intersection of the 0.2-mm offset line and a power law fit to the J-Δa data within the exclusion lines. The power law has the form:

$$J = c_1(\Delta a)^{c_2} \quad (43)$$

while the offset line has the equation:

$$J = 2\sigma_Y \ (\Delta a - 0.2 \text{ mm}) \quad (44)$$

To evaluate this intersection point, the power law is linearized using natural logarithms, and the following iterative

TABLE 4—Spreadsheet evaluations of J for specimen MULTI-4 (metric version).

Specimen Dimensions

1TCT	B, mm	Bn, mm	W, mm	a_o, mm	b_o, mm	a_o/W	B_e, mm	a_f, mm
	25.4	20.3	50.8	31.03	19.77	0.61	24.38	32.7

Material Properties			Calculated Quantities				
Flow Stress, MPa	E, MPa	Poisson Ratio	η[1]	$f(a/W)$[2]	CII[3], mm/kN	r_p[4]	α[5]
463	199 000	0.3	2.20	14.26	1.39E-02	0.46	0.12

Number	COD, mm	Load, kN	Tot. Area[6], N-m	El. Area[7], N-m	Pl. Area[8], N-m	K_i[9], Mpa·m/\	J_{el}[10], kJ/m/\2	J_{pl}[11], kJ/m/\2	J_{tot}[12], kJ/m/\2	Δ_{pl}[13], mm	Δ_{tot}[14], mm
10	0.0033	0.04	0.000	0.000	0.000	0.00	0.00	0.00	0.00	0.0000	0.0000
11	0.0033	0.04	0.000	0.000	−0.000	0.11	0.00	−0.00	−0.00	0.0007	0.0007
12	0.0030	0.04	−0.000	0.000	−0.000	0.10	0.00	−0.00	−0.00	0.0007	0.0007
13	0.0030	0.04	−0.000	0.000	−0.000	0.11	0.00	−0.00	−0.00	0.0007	0.0007
14	0.0028	0.04	−0.000	0.000	−0.000	0.10	0.00	−0.00	−0.00	0.0006	0.0006
15	0.0025	0.04	−0.000	0.000	−0.000	0.11	0.00	−0.00	−0.00	0.0006	0.0006
16	0.0023	0.04	−0.000	0.000	−0.000	0.11	0.00	−0.00	−0.00	0.0005	0.0005
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
200	1.4975	42.95	52.379	12.832	39.547	119.64	65.45	217.10	282.55	0.3394	0.4101
201	1.5201	42.73	53.347	12.696	40.650	119.01	64.76	223.16	287.92	0.3445	0.4145
202	1.5406	42.54	54.223	12.589	41.634	118.50	64.22	228.56	292.77	0.3492	0.4185
203	1.5604	42.32	55.063	12.454	42.609	117.87	63.53	233.91	297.43	0.3537	0.4223
204	1.5865	42.05	56.166	12.301	43.865	117.14	62.75	240.80	303.55	0.3596	0.4274
205	1.6117	41.75	57.219	12.125	45.094	116.30	61.85	247.55	309.40	0.3653	0.4321
206	1.6320	41.56	58.065	12.014	46.051	115.76	61.28	252.80	314.08	0.3699	0.4361
207	1.6543	41.38	58.991	11.911	47.080	115.27	60.76	258.45	319.21	0.3750	0.4406
208	1.6655	39.77	59.444	11.003	48.442	110.78	56.12	265.93	322.05	0.3775	0.4381

[1] $\eta = 2. + 0.522\, b_o/W$.
[2] Eq 17
[3] Eq 38
[4] Eq 27
[5] Eq 28
[6] Total area under the load versus COD record.
[7] Elastic area under the load versus COD record.
[8] Plastic area under the load versus COD record.
[9] Eq 15
[10] Eq 13
[11] Eq 19
[12] Eq 12
[13] Eq 26
[14] Eq 20

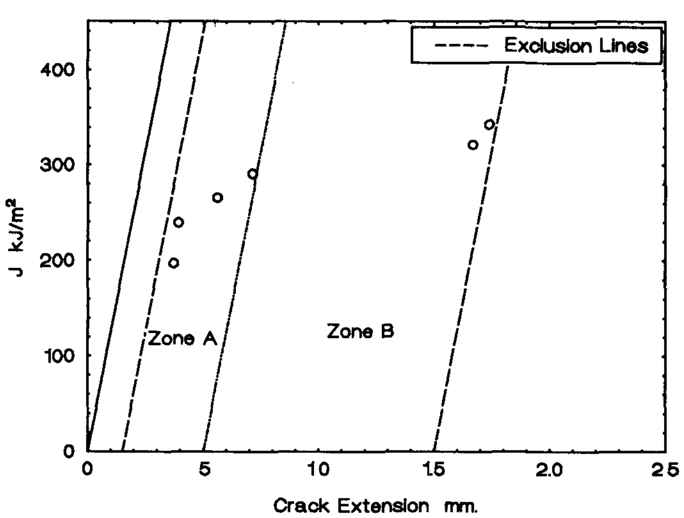


FIG. 30—***J-R*** **data for the initial six specimens of the HY steel.**

process is recommended. First fit a least squares linear regression line of the following form to the data within the exclusion lines:

$$\ln J = \ln C_1 + C_2 \ln \Delta a_p \tag{45}$$

Plot the regression line, exclusion lines, and 0.2-mm offset line as shown in Fig. 31. Estimate from this plot an initial J_Q value, denoted here as $J_{Q(1)}$. Then continue with the following iterative procedure:

1. Evaluate $\Delta a_{p(1)}$:

$$\Delta a_{p(1)} = \frac{J_{Q(1)}}{2\sigma_Y} + 0.2 \text{ (mm)} \tag{46}$$

2. Evaluate $J_{Q(2)}$ from:

$$J_{Q(2)} = C_1(\Delta a_{p(1)})^{C_2} \tag{47}$$

3. Stop and take $J_Q = J_{Q(2)}$ if:

$$\frac{J_{Q(2)} - J_{Q(1)}}{J_{Q(2)}} \leq 0.02 \tag{48}$$

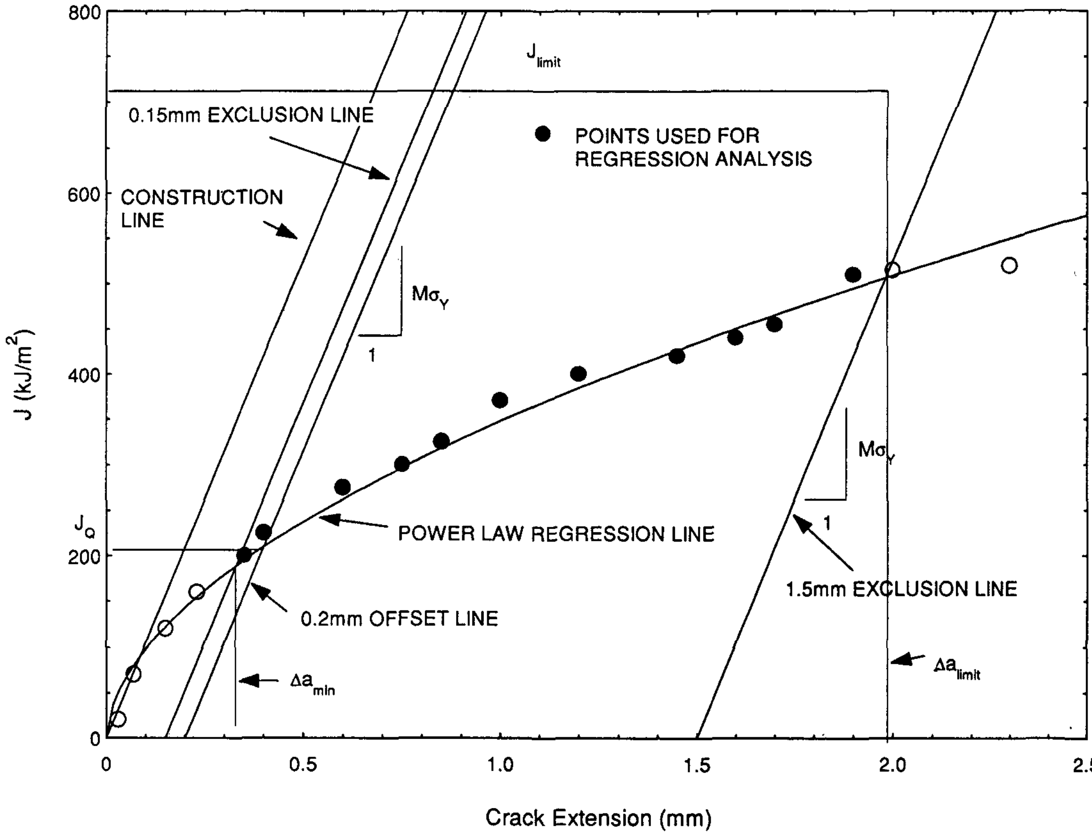


FIG. 31—Definitions for data qualification and evaluation of J_Q.

4. Otherwise, return to Step 1 and repeat this process until $J_{Q(i+1)}$ and $J_{Q(i)}$ converge within 2%.

Return to your data plot and from the J_Q intersection point drop a vertical line labeled Δa_{min} as shown in Fig. 32. Add the J_{limit} line, where $J_{limit} = b_o\sigma_Y/15$, and the Δa_{limit} line, where the Δa_{limit} line passes through the intersection of the 1.5-mm exclusion line and the power law fit curve. The region of valid data is then the zone enclosed by these lines as shown by the cross-hatched area. If these new lines eliminate any data used above to calculate J_Q, you must repeat the calculation without this data point or points to obtain a new value of J_Q. If five points no longer remain in the valid data region, additional tests must be run. The remaining data must meet the Zone A and Zone B data spacing requirements, also shown on Fig. 32.

A hand calculation for the example data set of Fig. 30 is shown in Example Calculation 1. For this case, since a very poor initial J_Q estimate is made, three iterations are required to obtain the final J_Q of 218.7 kJ/m². Generally, only two iterations are required if care is taken in estimating the $J_{Q(1)}$ value used. Nonetheless, if many data sets are to be analyzed, it is recommended that a computer program be written to evaluate J_Q, to check the data count and data spacing requirements, and to avoid the inevitable errors involved with hand calculations. Such a program would generally check many of the validation requirements of the method as well, and for this reason the use of an example program is delayed until Section 8.9.

When a J_Q is obtained from a data set that meets the data number and spacing requirements, continue to Section 8.9 to validate J_Q as J_{Ic}.

EXAMPLE CALCULATION 1

Evaluation of J_Q for the Multi-Specimen Data

Fitting (Eq 45) using a least squares procedure to the six data points in Fig. 30 and Table 3 gives:

$$C_1 = 293 \text{ kJ/m}^2$$

and

$$C_2 = 0.295$$

Taking $\sigma_Y = 632.0$ MPa and substituting into Eq 46 with a starting $J_{Q(1)} = 100$ kJ/m² gives:

$$\Delta a_{p(1)} = 100/1264 + 0.2 = 0.279 \text{ mm} \quad \text{(Eq 46)}$$

$$J_{Q(2)} = 293\,(0.279)^{0.295} = 201.1 \text{ kJ/m}^2 \quad \text{(Eq 47)}$$

Iterating:

$$\Delta a_{p(2)} = 206/1264 + 0.2 = 0.359 \text{ mm} \quad \text{(Eq 46)}$$

$$J_{Q(3)} = 293\,(0.359)^{0.295} = 216.6 \text{ kJ/m}^2 \quad \text{(Eq 47)}$$

Checking Eq 48 gives:

$$(216.6 - 201.1)/216.6 = 0.07 \geq 0.02$$

Iterating once more gives:

$$\Delta a_{p(3)} = 216.6/1264 + 0.2 = 0.371 \text{ mm} \quad \text{(Eq 46)}$$

$$J_{Q(4)} = 293(0.371)^{0.295} = 218.7 \text{ kJ/m}^2 \quad \text{(Eq 47)}$$

Now:

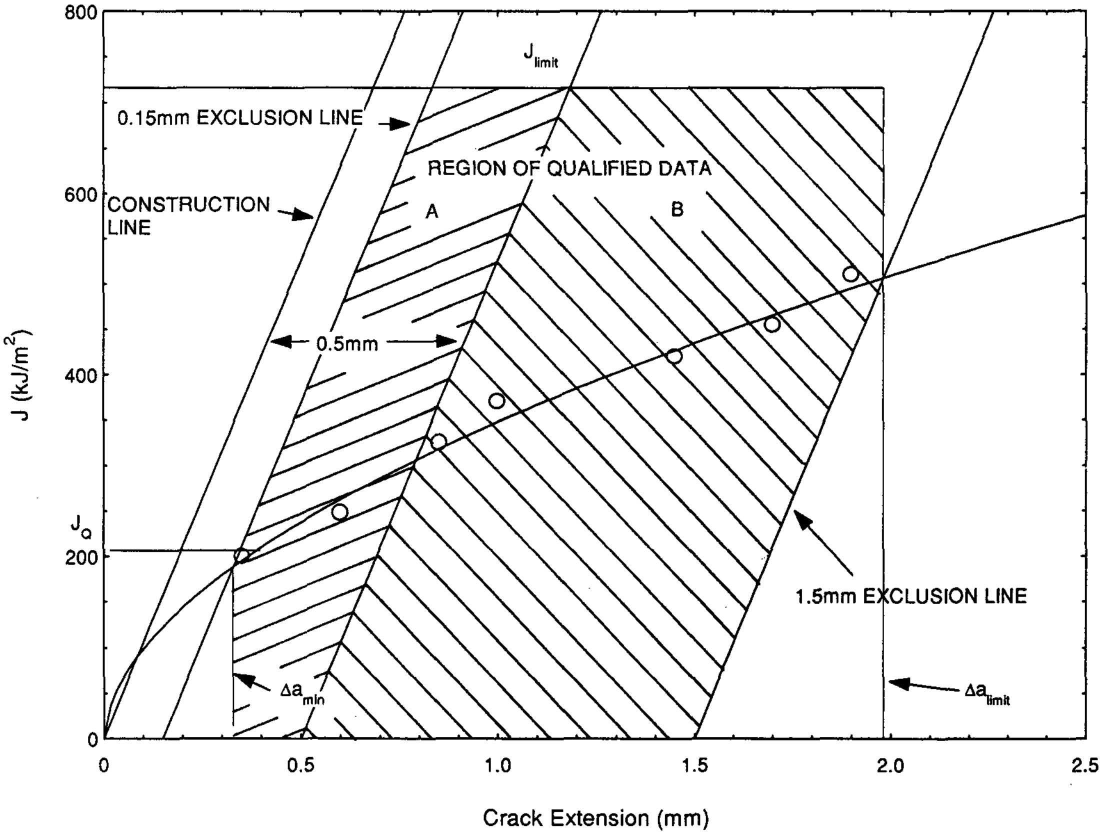


FIG. 32—Definition of region of qualified data.

$$(218.7 - 216.6)/218.7 = 0.0096 < 0.02, \quad \text{(Eq 48)}$$

giving, finally, that $J_Q = 218.7$ kJ/m^2.

6.6 ANALYSIS FOR J_c OR J_u USING BASIC TEST DATA

In many cases, the basic test procedure is used to investigate the ductile to brittle transition behavior of ferritic steels. This type of test was invalid according to early elastic plastic fracture toughness test standards (E 813-81, E 813-87, E 1152-87), but has become part of elastic plastic fracture toughness testing in E 1290 for CTOD and E 1737 for J. J_c and J_u can only be evaluated if the test sample demonstrates unstable fracture during test. Only one of the quantities can be evaluated in that case, and which results depends on two technical requirements. Basically, J_c is obtained if cleavage has occurred at relatively low J-integral levels, i.e., if the specimen is large enough that:

$$B, b > 200 \frac{J_{Qc}}{\sigma_Y} \quad (49)$$

where J_{Qc} is the J integral at cleavage evaluated according to the analysis of Eqs 2 to 6 or 7 to 11, depending on the specimen type. An additional requirement for J_{Qc} to be designated as J_c is that the nine-point average measured ductile crack extension before cleavage, Δa_{Qc}, satisfies:

$$\Delta a_{Qc} \leq 0.2 + \frac{J_{Qc}}{2\sigma_Y} \quad (50)$$

This requirement is intended to assure that little crack extension is present in the specimen before J_c, so that high constraint conditions prevail. If the measured J_{Qc} value fails either of these two requirements, it is a J_u value. A J_c quantity is considered to be independent of in-plane dimensions but somewhat thickness dependent (Wallin 1993). The thickness dependence can be described in statistical terms because it depends on the volume of stressed material along the crack front. The mean J_c will thus be smaller as the specimen crack length increases. A J_c value demonstrates considerable statistical variability, and, for determination of a lower bound for a structural application, the reader is referred to the new ASTM test practice being developed by Subcommittee E08.08.03. The J_u quantity is expected to be size dependent and a function of sample geometry, corresponding only to the size and type of geometry tested.

A typical data set terminated by a sudden cleavage is shown in Fig. 33. This specimen was a 1T SE(B) specimen of an ASTM A533B reactor pressure vessel steel with a/W = 0.57, tested at −7°C (20°F). First, the specimen's initial and cleavage initiation crack lengths are measured using the traveling microscope procedure described above. The results in this case are:

$$a_o = 29.03 \text{ mm}$$

$$a_f = 29.13 \text{ mm}$$

$$\Delta a_Q = 0.10 \text{ mm}$$

The calculation of J_{Qc} is shown in Example Calculation 2 in detail, with the final result being $J_{Qc} = 222.3$ kJ/m^2. Sub-

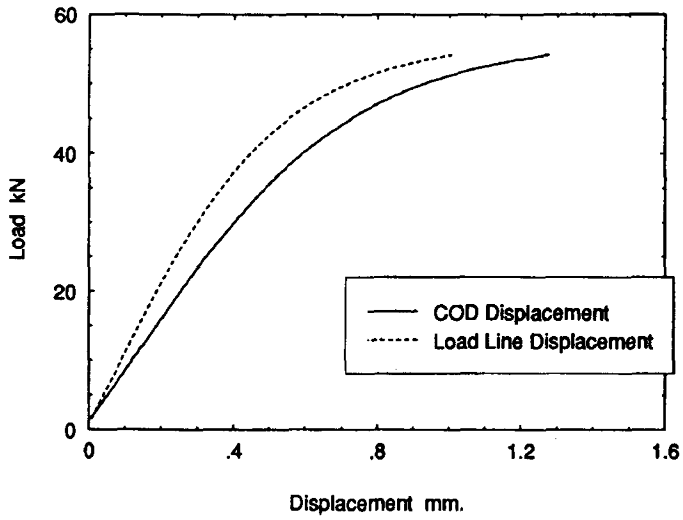


FIG. 33—Load displacement records for the SE(B) specimen GVR-B1C tested at −7°C.

stituting this J_{Qc} value into Eq 49 shows that B and b would both have to exceed 103 mm for this measured J_{Qc} to satisfy the J_c size requirement. The measured ductile crack extension of 0.1 mm is less than the allowed crack extension for this J level, which can be calculated as 0.46 mm by substituting this J_{Qc} into Eq 50. This specimen is not large enough for this J_{Qc} value to be given the J_c designation according to E 1737. A more complete validation of this result is included in Section 8.10.

EXAMPLE CALCULATION 2

Evaluation of J_{Qc} *At Fracture Instability*

Using a spreadsheet procedure like that described above, and the following material properties and specimen dimensions, allow the sequential calculation of the following quantities, leading to the calculation of J_{Qc}:

$$E = 199 \text{ GPa}$$

$$\nu = 0.3$$

$$\sigma_Y = 428 \text{ MPa}$$

$$W = 50.8 \text{ mm}$$

$$B = 25.4 \text{ mm}$$

$$B_N = 20.3 \text{ mm}$$

$$S = 203 \text{ mm}$$

$$a_o/W = 0.57$$

$$f(a/W) = 1.16 \quad \text{(Eq 5)}$$

$$P_{\text{crit}} = 55.2 \text{ kN}$$

$$K_{\text{Icrit}} = 145.6 \text{ MPa}\sqrt{\text{m}} \quad \text{(Eq 4)}$$

$$J_{el} = 97.0 \text{ kJ/m}^2 \quad \text{(Eq 3)}$$

$$C_{LL} = 0.0130 \text{ mm/kN} \quad \text{(Eq 36)}$$

$$A_{el} = P_{\text{crit}}^{\,2}\, C_{LL}/2 = 19.86 \text{ kN-m}$$

$$A_{\text{Tot}} = 47.64 \text{ N-m} \quad \text{(Spreadsheet—trapezoidal rule)}$$

$$A_{pl} = A_{\text{Tot}} - A_{el} = 27.78 \text{ kN-m}$$

$$\eta = 2 \quad \text{(SE(B))}$$

$$J_{pl} = 125.3 \text{ kJ/m}^2 \quad \text{(Eq 6)}$$

$$J_{Qc} = 222.3 \text{ kJ/m}^2 \quad \text{(Eq 2)}$$

6.7 ANALYSIS FOR δ_i, δ_u, OR δ_m USING THE BASIC TEST DATA

The basic test procedure is also commonly used to evaluate CTOD quantities at cleavage initiation according to ASTM E 1290. The CTOD quantities obtainable from a basic test are δ_c, δ_u, and δ_m. For the A533B specimen analyses in the above section, the δ_Q at fracture instability can be calculated as shown in Example Calculation 3. This quantity will then be validated as a δ_c or δ_u quantity according to E 1290 in Section 8.11. The δ_c and δ_u quantities of E 1290 correspond closely to the J_c and J_u quantities of E 1737 except the dividing line between δ_c and δ_u is taken as a fixed 0.2 mm of crack extension. For ASTM E 1290, δ_Q always becomes either a δ_c, δ_u, or a δ_m value for the thickness and temperature of test. The measured quantities are assumed to be transferrable to structural applications as long as the laboratory specimen thickness is the same as the thickness of the structural application. The δ_m quantity is evaluated at the first attainment of a maximum load plateau and is taken as the end of valid data even though cleavage can, and often does, occur beyond maximum load.

The result from Example Calculation 3 is that δ_Q = 0.355 mm. Since only 0.10 mm of ductile crack extension was measured, this value would be a δ_c quantity except that the crack length exceeds the E 1290 allowable maximum of a/W = 0.55 and side grooves were used in this specimen.

EXAMPLE CALCULATION 3

Evaluation of δ_Q *at Fracture Instability*

For the example specimen of the previous section, δ_Q can be evaluated at the onset of cleavage using the following procedure:

$$a_o = 29.03 \text{ mm}$$

$$z = 0.0$$

$$\sigma_{ys} = 398 \text{ MPa}$$

$$E = 199 \text{ GPa}$$

$$Y = 13.49 \quad \text{(Eq 23)}$$

$$r_p = 0.44 \quad \text{(Eq 27)}$$

$$P_{\text{crit}} = 55.24 \text{ kN}$$

$$C_{\text{COD}} = 0.0101 \quad \text{(Eq 37)}$$

$$v_{\text{Tot}} = 1.006 \text{ mm}$$

$$v_p = v_{\text{Tot}} - C_{\text{COD}} \times P_{\text{crit}} = 0.448 \text{ mm}$$

$$\delta_{pl} = 0.251 \text{ mm} \quad \text{(Eq 26)}$$

$$\delta_{el} = 0.104 \text{ mm} \quad \text{(Eq 21)}$$

giving finally:

$$\delta_Q = 0.355 \text{ mm} \quad \text{(Eq 20)}$$

6.8 SUMMARY OF THE BASIC METHOD

The basic test method can be used to obtain several important elastic plastic toughness quantities, including δ_c, δ_u, J_c, J_u, and one of several data pairs from which J_{Ic} can be obtained. Qualification of the example calculations presented in the previous sections will be addressed more completely in Section 8. The *J-R* curve obtained in this way is not accurate since crack growth correction of J has not been included. The *J-R* curve resulting from the basic method is only a construction used to evaluate J_{Ic}. In the next section, the advanced method will be described and it will be shown that all these quantities can be obtained from that method also, and that additional information like the *J-R* curve can be obtained as well.

7

Advanced Test Procedure

7.1 RUNNING THE TEST

THE REQUIREMENTS imposed by an advanced or single specimen procedure have been enumerated in previous sections. If a carefully aligned load train is combined with a proper set of clevises and a well-machined specimen, most of the problems associated with single specimen compliance tests will not be observed. If a d-c electric potential system is used, a crack opening displacement transducer signal quality corresponding to the basic test procedure is fully adequate. A test system schematic for an unloading compliance test system is shown in Fig. 34, while the additions required for an electric potential system are shown in Fig. 35.

Many of the steps involved in the use of the advanced test procedure are identical to those used in the basic test procedure. This includes the specimen precracking, the specimen crack length marking or heat tinting, breaking open the specimen, and measuring the initial and final crack lengths. These steps will not be repeated in this section, and the reader is referred to Section 6 for this material.

The example used in this section is an unloading compliance test of an HY80 1T C(T) specimen identical to those used for the multi-specimen basic test example in the previous section. The specimen should be precracked, side grooved, and installed in carefully aligned grips, as shown previously in Fig. 26 (see Section 6). As always, care must be taken to assure that the clip gage is properly seated on the knife edges and that the loading pins are centered on both clevis loading flats.

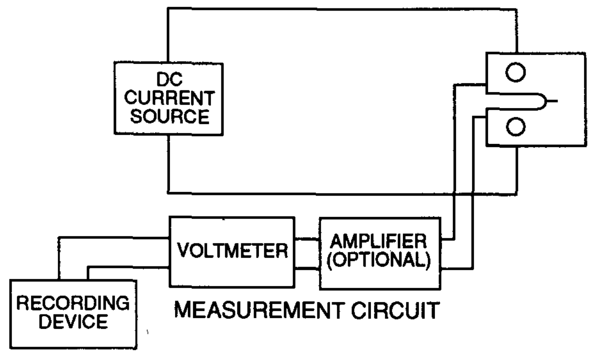


FIG. 35—Schematic diagram of a d-c potential drop system.

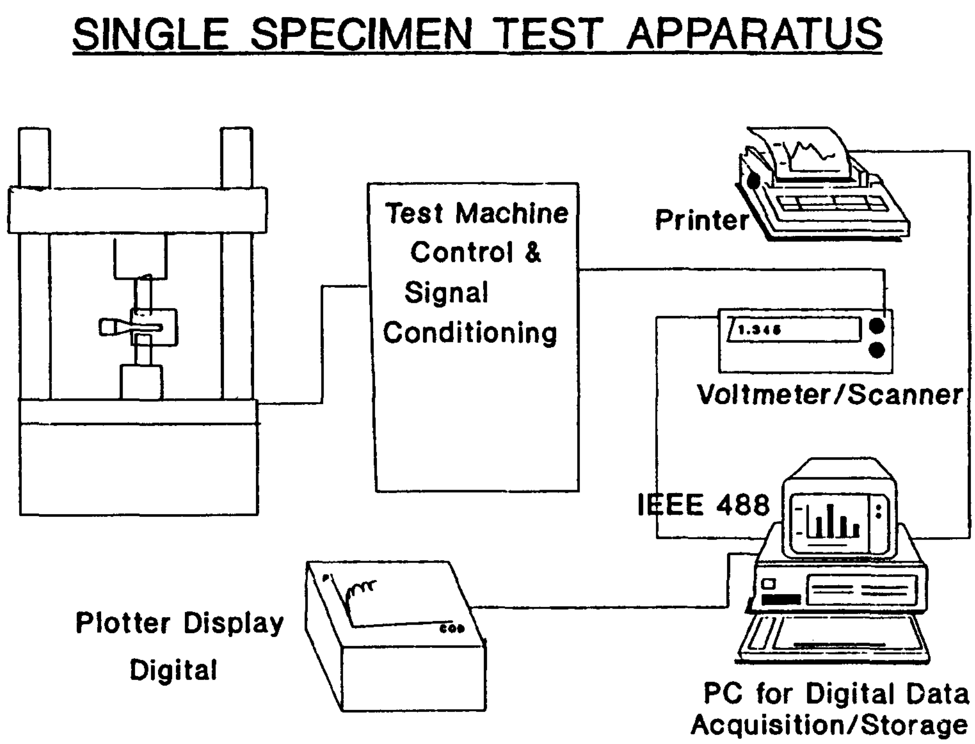


FIG. 34—Advanced test system schematic.

The system used for this test includes a PC for online evaluation of the specimen-compliance estimated crack length and J after the completion of each unloading. A listing of the program used is provided in Appendix A to this manual. The usual technique is to load and unload the specimen, staying below the final load used for precracking, and to estimate the crack length repeatedly until an accurate and repeatable value is obtained. The crack length should correspond to that which was present at the end of precracking, and the repeatability is generally on the order of $\pm 0.001W$.

Patience is a necessity during this process. If the crack length is not predicted accurately or the estimates are not repeatable, stop. Things will only get worse once the real test is started. Recheck the alignment of the load train, recheck the calibrations, recheck the electronic system for noise, and recheck the clip gage seating and the knife edges on which it rests. When everything is within the tolerance described in E 1737, and in previous sections, good results will be obtained.

When good results are achieved, the load should be returned to near zero so that the main test can commence. The program in Appendix A prepares an XY recorder plot at this stage so that the length and spacing of the unloadings can be clearly observed. The optimum plotter for this is a large flat bed digital pen plotter, preferably not one that hides the most recent part of the plot under the plotting mechanism, like an HP7475A. An online plot of load versus crack opening displacement can be displayed on the PC screen if the monitor size is large enough to give a clear display. An analog plotter can be used for this display, if necessary, since this plot is only for control of the test, i.e., the real data are being taken and stored digitally by the PC.

At this time the test should be started. An initial unloading should be taken starting at the load level where the pretest unloadings were taken to assure that things have not changed, and then unloadings should be taken so that the data spacing requirements of E 1737 are met. This basically means that three or more data are required before J_{Ic}, five or more data points are required in the J_{Ic} "exclusion zone" which is between crack extensions of about 0.25 and 1.75 mm, and ten or more data points are required before the crack extension reaches $0.1b_o$, a J-R curve requirement. For small specimens, $0.1b_o$ can be smaller than 1.75 mm, so all limits should be understood before starting the test. About 25 unloadings are recommended to define a J-R curve for a structural steel or aluminum alloy; more should be used if the crack extension is continued beyond $0.1b_o$.

The load displacement curve for the example HY80 specimen is shown in Fig. 36. The resulting J-R curve is shown in Fig. 37. A typical PC screen display after each unloading lists the following quantities:

1. Unloading number.
2. Number of data on the unloading.
3. Stiffness (slope).
4. Correlation.
5. Crack length.
6. Crack extension (based on a pretest average initial crack length estimate).
7. Load and COD at the start of the unloading.
8. Area under the load versus load line displacement record.

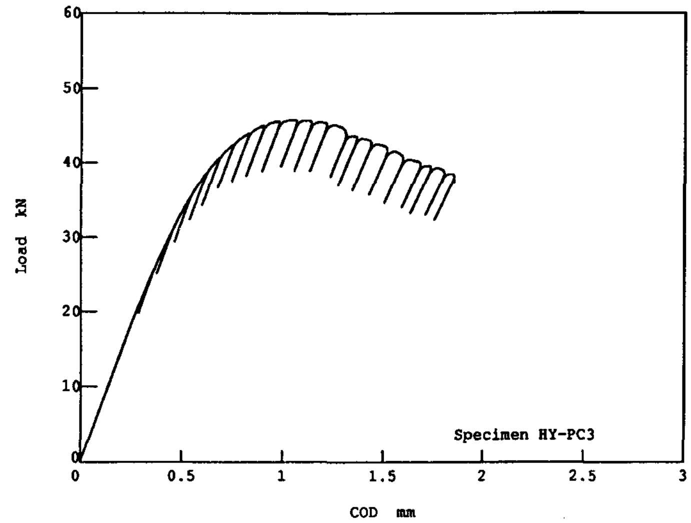


FIG. 36—Load versus COD record for the unloading compliance specimen HY-PC3.

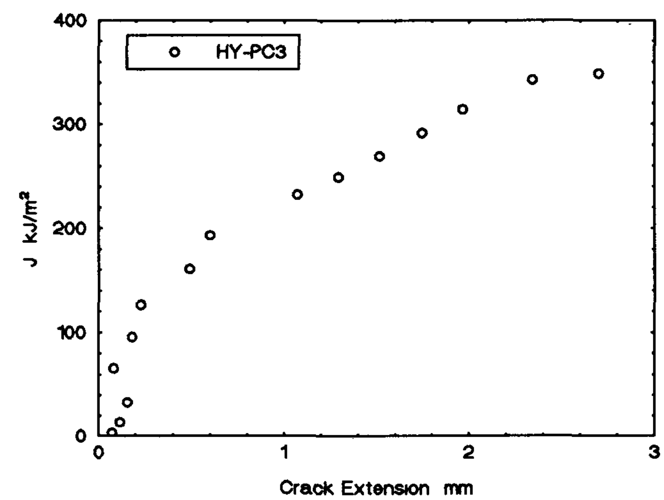


FIG. 37—Unloading compliance *J-R* curve for specimen HY-PC3.

9. Plastic area.
10. Plastic component of J.
11. Elastic component of J.
12. Total J-integral to that unloading.

To give some idea of the data quality present here, an enlarged plot of data near the tenth unloading of Fig. 36 is shown in Fig. 38. Clearly the data are smooth, and the loading and unloading slopes are very similar except at the top of the unloading. Generally, both the loading and unloading data are used for the calculation of the specimen compliance; in this case, that meant approximately 85 data points. The program in Appendix A decides that an unloading has initiated when the crack opening displacement reverses, establishes turn-around values of load and crack opening displacement, throws out the top 2% of unloading data based on load, and includes all subsequent data until the turn-around crack opening displacement value is again exceeded.

Other materials can behave quite differently from that shown in Fig. 38, and changes might be necessary in the criteria by which data are chosen to estimate the specimen crack length. Sometimes more than 2% of the data at the top of the unloading must be discarded, and sometimes data at the bottom of the unloading must be discarded. On occasion, only unloading data give the best results, and at other times only loading data are best. Making an enlarged plot of measured unloading records like that of Fig. 38 is a good starting point; then various data selection criteria can be tried until the best combination of data is found for the particular material being tested.

The test is usually stopped immediately after an unloading is completed so that a comparison can be made between the final estimated crack length and the final optically measured crack length. It is best not to extend the crack too far since the requirements of this final comparison become relatively tighter when the amount of crack extension exceeds $0.2b_o$. After stopping the data acquisition, the specimen should be returned to zero load and removed from the clevises. The specimen should now be heat tinted to mark the fatigue crack and ductile extension, chilled in liquid nitrogen, and broken open. The result in this case is the fracture surface shown previously in Fig. 28 (see Section 6).

For this stable tearing case, a large ductile crack extension is present. The initial and final crack lengths are now measured using the traveling microscope to obtain the data needed for the nine-point average measurements. The measured data for this case are shown in the spreadsheet of Table 4, and the results are:

$$a_o = 31.56 \text{ mm}$$

$$a_f = 34.09 \text{ mm}$$

$$\Delta a = 2.506 \text{ mm}$$

7.2 ANALYSIS OF ADVANCED TEST DATA

The advanced test data can give a fully qualified *J-R* curve and a J_{Ic} value. The *J-R* curve can also be fit with functional relationships so that the tearing modulus (Paris et al. 1979),

$$T = \frac{E}{\sigma_Y^2}\frac{dJ}{da} \tag{51}$$

can be evaluated for structural stability analyses. Functional relationships are also useful for extrapolation of the *J-R* curve (Joyce and Hackett 1991a; Landes 1992) when that is necessary. These curve fits are beyond the scope of this manual.

Two additional requirements are placed on single specimen data to assure that the crack length estimates are accurate. The first of these is the requirement in E 1737 that the predicted initial crack length, a_{oq}, match the measured average fatigue crack length within $0.01W$. The second requirement is that the predicted crack extension match the estimated crack extension within $\pm 15\%$. An initialization procedure has also been incorporated into E 1737 to establish a best estimate of the initial crack length for a particular data set. Figure 39 demonstrates four unloading compliance data sets that show why an initialization procedure is required. Two of the specimens, Specimens HY-PC4 and HY-PC7, behave in the expected fashion, but the other two specimens demonstrate somewhat irregular behavior. Specimen HY-PC3 demonstrates a "crack backup" phenomenon, while specimen HY-PC3N shows an initial offset at the start of the test, but then behaves in a reasonable manner. All of these specimens can be adjusted to give acceptable results using the initialization procedure of E 1737.

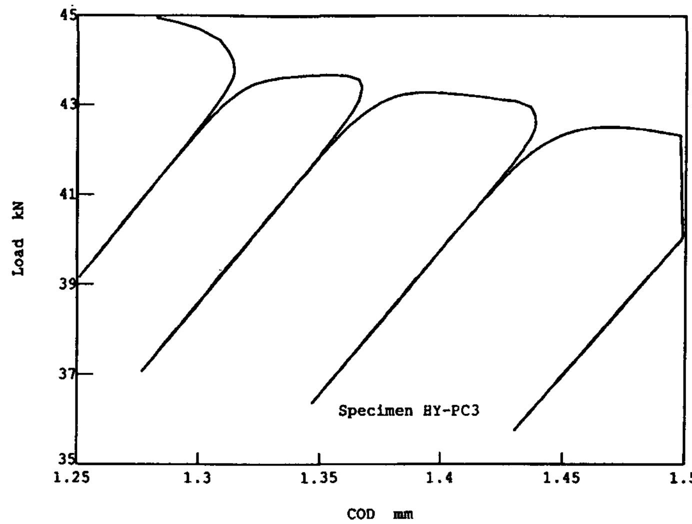


FIG. 38—Enlarged view of unloading data from the load COD record of Specimen HY-PC3.

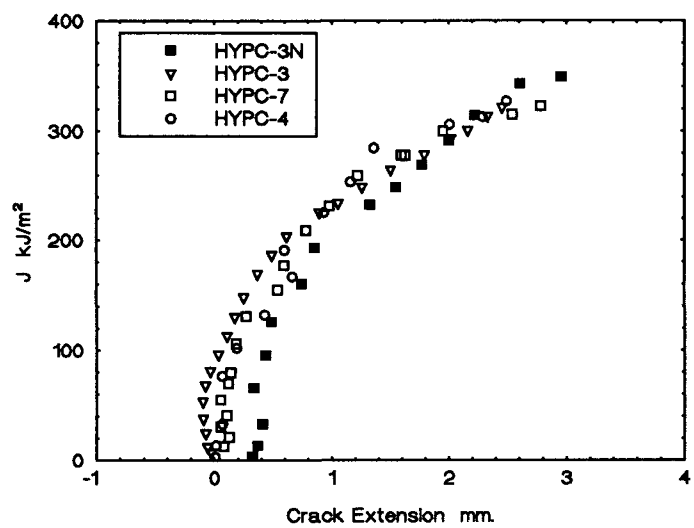


FIG. 39—*J-R* curves from four similar HY80 unloading compliance specimens.

The initialization procedure is as follows. The data are plotted as crack length versus J as shown in Fig. 40, and then a least squares curve fit procedure is used to fit the following equation to the data for which $P > P_M$ (see Eq 41 or Eq 42) and $a < a_{min} + 2.5$ mm:

$$a = a_{oq} + \frac{J}{2\sigma_Y} + BJ^2 + CJ^3 \tag{52}$$

To fit Eq 52 to the J_i, a_i data using the method of least

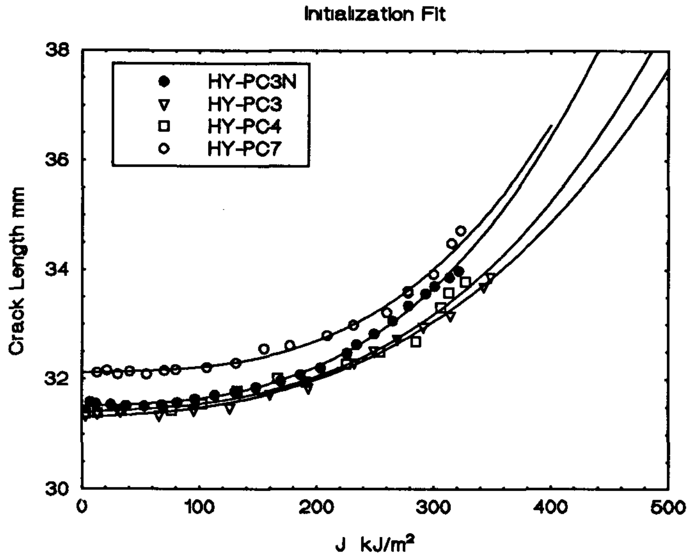


FIG. 40—Initialization fits for four HY steel specimens to obtain a_{oq} for each specimen.

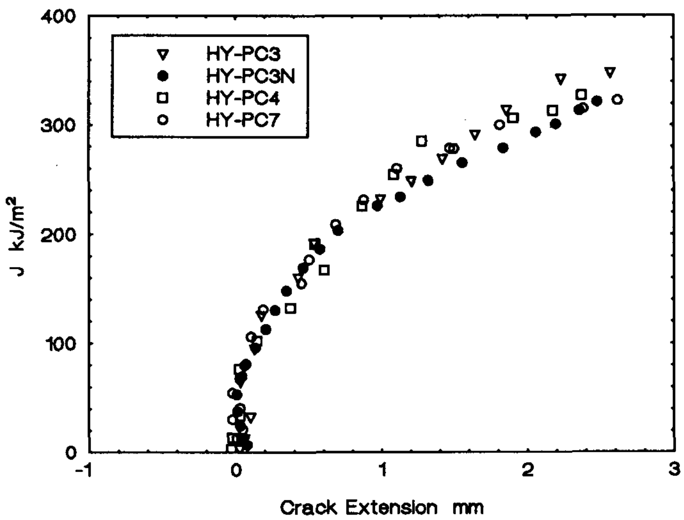


FIG. 41—J-R curves for the HY steel C(T) specimens after initialization.

squares, the following equation must be set up and solved for a_{oq}, B, and C:

$$\begin{Bmatrix} \sum a_i - \dfrac{\sum J_i}{2\sigma_Y} \\ \sum a_i J_i^2 - \dfrac{\sum J_i^3}{2\sigma_Y} \\ \sum a_i J_i^3 - \dfrac{\sum J_i^4}{2\sigma_Y} \end{Bmatrix} = \begin{bmatrix} n & \sum J_i^2 & \sum J_i^3 \\ \sum J_i^2 & \sum J_i^4 & \sum J_i^5 \\ \sum J_i^3 & \sum J_i^5 & \sum J_i^6 \end{bmatrix} \begin{Bmatrix} a_{oq} \\ B \\ C \end{Bmatrix} \quad (53)$$

This equation can be set up and solved using a standard spreadsheet, or a simple computer program can be used to do this fit. In this case, a program in Microsoft QuickBASIC called JIC_CALC.BAS was used. The program listing is presented in Appendix A2. A typical output of this program is shown in Example Calculation 4.

The results of this fit for specimens HY-PC3, HY-PC3N, HY-PC4, and HY-PC7 are shown in Fig. 40, with the coefficients tabulated in Table 5. Once a_{oq} is evaluated for each specimen, the J-R curves can be evaluated and plotted as shown in Fig. 41, now correctly adjusted according to E 1737. The accuracy of the final crack extensions can then be checked to see if they pass the 15% accuracy requirement. A comparison is presented in Table 6 for these four specimens showing the measured crack lengths, the crack extensions, and the unloading compliance predictions. Clearly the accuracy is within the required ±15% for all four specimens.

Qualifying the J-R curve of Fig. 41 according to E 1737 is done in Section 8.8. Calculating the J_{Ic} for the adjusted data sets is done using the program introduced above to adjust the J-R curve. These calculations are part of Example Calculation 4. An important advantage of the advanced test method over the basic method is that it obtains a J_{Ic} value for each specimen, saving money and giving important information on material variability that is lost when the multi-specimen method is used. For the four specimens of Fig. 41, the J_{Ic} results are tabulated in Table 7, showing that the results are, of course, not identical. These results show a variability of approximately +4 to −8%, which is typical of clean, homogeneous structural steel. Some of this variability is due to the test method, but for structural applications it is best to assume that the scatter is all due to material variability and design to the lower side of the scatter band for critical applications. If enough data are collected, small sample statistics can be applied to obtain confidence limits that might give even more meaning to the application of the laboratory data to the structural configuration.

Standard E 1290-89 would have allowed evaluation of a CTOD at ductile crack initiation, δ_i, from the data obtained from this specimen. This concept was removed from E 1290-93 and now only exists in a new test standard called the

TABLE 6—Crack length estimates and measurements—single specimen tests.

	Estimated			Measured		
Specimen	a_0	a_f, mm	Δa	a_0	a_f, mm	Δa
HY-PC3	31.31	33.88	2.57	31.5	34.0	2.5
HY-PC3N	31.51	33.97	2.48	31.5	33.9	2.4
HY-PC4	31.4	33.78	2.37	31.6	33.9	2.5
HY-PC7	32.11	34.73	2.62	31.6	34.1	2.5

TABLE 5—Initialization calculations—single specimen results.

Specimen	No. of Data	Correlation	a_{oq}, mm	B	C
HY-PC3	13	0.980	31.24	2.00×10^{-5}	-1.4×10^{-8}
HY-PC3N	22	0.999	31.486	2.44×10^{-6}	6.29×10^{-8}
HY-PC4	13	0.988	31.431	-8.36×10^{-6}	6.01×10^{-8}
HY-PC7	18	0.994	31.113	-4.91×10^{-6}	7.81×10^{-8}

TABLE 7—J_{Ic} results—single specimen tests.

Specimen	Amplitude, C_1	Power, C_2	Correlation	J_{Ic}, kJ/m²
HY-PC3	227.0	0.441	0.989	134.9
HY-PC3N	224.0	0.409	0.995	138.7
HY-PC4	247.9	0.576	0.972	123.4
HY-PC7	238.9	0.461	0.984	139.3

"Common Test Standard"[4]. For this reason it will not be included here.

EXAMPLE CALCULATION 4

Initialization fit and J_{Ic} *calculation for Specimen HY-PC3*

INPUT DATA (Metric) FOR THIS SPECIMEN IS:

W = 50.8
B = 25.4 B_n = 20.3
AZMEAS = 31.5 AFMEAS = 34.0
E = 199
SIGY = 562 SIGUTS = 700
I.D. = PC3

COEFFICIENTS OF INITIALIZATION ARRAY ARE:
31.241 1.9938E-05 −1.4316E-08
CORRELATION OF FIT = 0.980
ASHFT = 31.24 USING 13 POINTS

[4]ASTM Task Group E08.08.01.

THE FIT COEFFICIENTS ARE:
POWER COEFFICIENT (C_2) = 0.441
AMPLITUDE COEFFICIENT (C_1) = 227.0
FIT COEFFICIENT (R) = 0.9887

J_Q = 134.9 kJ/m/\2
CRACK EXTENSION AT J_Q = 0.307 mm
DEL A_{MIN} = 0.25 mm
DEL A_{LIM} = 1.73 mm

DATA SET PASSES ALL J_{Ic} REQUIREMENTS
J_{Ic} = 134.9 kJ/m^2
THE FINAL ESTIMATED CRACK LENGTH IS: 33.88 mm
THE ESTIMATED FINAL CRACK EXTENSION IS: 2.64 mm
THE MEASURED FINAL CRACK EXTENSION IS: 2.50 mm
THE PERCENT ERROR IN THE FINAL CRACK EXTENSION PREDICTION IS: −5.5%
THIS *J-R* CURVE PASSES ALL *J-R* CURVE REQUIREMENTS FOR THE REGION ENCLOSED BY:
J_{LIMIT} = 812.5 kJ/m^2
DEL A_{LIM} = 1.729 mm

8

Qualification of the Test Results

IN MOST FRACTURE TOUGHNESS test standards, the validity of the results of the test, i.e., J_Q, J_{Qc}, δ_Q, etc., would now be checked. Since the first fracture toughness standard (E 399), results could be considered nonvalid for two very different reasons. First, the data might not be of high enough quality: the crack front could be crooked, the precrack may not be of sufficient length, or the initial estimated crack length does not correspond to the result of the optical measurement. Second, the data were found not to satisfy the size requirements specified for the result to be considered, a K_{Ic}, a J_{Ic}, or whatever.

This essentially amounts to labeling both bad data and data that are of high quality but where the results have been found not to meet conditions specified for transferability in exactly the same way. Cases have arisen where company accountants have refused to pay test laboratories for perfectly good data because the laboratory very correctly reported that no valid K_{Ic} could be obtained from the E 399 standard for the size of the specimen sent for the test.

As has been pointed out many times, all data are valid for a particular specimen; if quality test practices were followed, the result just might not be directly transferrable to different configurations. The more recent fracture standard, E 1737, has separated these ideas, first qualifying the data and the test methodology, then qualifying the results as transferrable or not. This procedure will be followed here for each case: first the data are qualified, then the size criteria will be explored to determine whether the J_Q, J_{Qc}, δ_Q, and J-R curves can be considered transferrable.

8.1 QUALIFICATION OF THE DATA

In the preceding sections, three separate data sets were developed: the multiple specimen J_{Ic} data set, the J_i/δ_i instability specimen, and the unloading compliance J_{Ic}/J-R curve data set. To assure that meaningful results are obtained from these tests, the elastic-plastic fracture toughness standards E 1290 and E 1737 place stringent requirements on the quality of data recording, type of specimen, specimen preparation, and crack length and shape.

If these requirements are not met, the testing laboratory would probably be expected to repeat the test after changes had been made to eliminate the deficiency. Many recommendations are given in the two fracture standards and these are sometimes mixed into the requirements of the standards. What is recommended in one standard may be a requirement in the other, and it is the strong suggestion of this manual that all of the recommendations in the fracture test standards be treated as requirements if at all possible.

8.2 APPARATUS REQUIREMENTS

Both standards recommend similar fixtures for conducting tests on C(T), SE(B), and DC(T) specimens. The flat-loading-surface, hardened (R_c = 40) test clevises are essential for unloading compliance tests of compact specimens. As discussed, round-holed clevises should be used for precracking. Alignment requirements in the test procedure section effectively require that well-fabricated testing clevises be used for elastic-plastic fracture toughness tests.

8.3 TRANSDUCER REQUIREMENTS

The testing machine used for all tests is required to conform to ASTM E 4. The load transducer must be accurate to $\pm 1\%$ of its working range. In calibration, the maximum deviation of individual data points from a fit to the data shall be less than $\pm 0.2\%$ of the calibrated range of the transducer when using unloading compliance, and $\pm 1\%$ otherwise.

Displacement gages are required to meet this same requirement, that is, during a standard calibration, individual data points shall not deviate from a fit to the data by more than $\pm 0.2\%$ of the calibrated range when using unloading compliance, or $\pm 1\%$ for other tests. For an SE(B) test, two displacement transducers are required with the load line displacement meeting the $\pm 1\%$ calibration requirement.

8.4 SPECIMEN PREPARATION REQUIREMENTS

The specimen drawings for the C(T), DC(T), and SE(B) specimens given in E 1737 are recommended, not required, while in E 1290 one of the specimen drawings presented is required. In both standards, an envelope is given for the crack starter notch and fatigue crack, although the envelopes are somewhat different between the two standards. Caution is recommended with the E 1290 envelope since it appears to allow a 0.125-in. starter notch—a commercially convenient slitting saw thickness.

However, if the saw cuts a slightly wider notch than 0.125 in. or the fatigue crack wanders off center even slightly, the result will invalidate the test. For this reason, a starter notch width of less than 0.125 in. is recommended, and a 3/32-in.-thick slitting saw is a typical slitting saw that can be used safely to machine the starter notch. In a metric shop, a 3-mm-thick slitting saw conveniently avoids this problem.

In E 1290, the specimen thickness, B, is required to be at least equal to that of the application of interest, while in E 1737 the maximum thickness is recommended so that size requirements can be met to assure transferability of the results to other configurations.

Fatigue precracking requirements are present in both standards. These are requirements on the loads used during precracking and on the length and straightness of the resulting precrack. In both cases, the specimens must be precracked with the maximum load being less than P_M as given in Eq 41 and 42 for the final 50% of fatigue precrack or 1.3 mm, whichever is less. E 1290 also requires that the ratio of minimum load to maximum load not exceed 0.1 and that $\Delta K/E \leq 1.6 \times 10^{-4} \sqrt{m}$. The newer standard, E 1737, places no limit on the load ratio used and requires instead that $K_{max}/E \leq 1.6 \times 10^{-4} \sqrt{m}$.

This standard has the additional requirement, if fracture instability occurs, that $K_{max} \leq 0.6(J_{Qc}\ E)^{1/2}$, where J_{Qc} is the J-integral at the onset of fracture instability. It is quite often necessary to exceed these loads to initiate fatigue crack growth from the machined notch, but the final 50% of fatigue crack must be done at loads that satisfy the most stringent of the above requirements for the results to be considered for qualification as an acceptable J_c, J_{Ic}, δ_i, or J-R curve. All fatigue precracking must be done in the same heat-treated condition as that in which it will be tested.

8.5 TEST PROCEDURE REQUIREMENTS

Displacement-controlled loading, either actuator control or crack opening displacement gage control, is required for all elastic-plastic fracture toughness tests. E 1290 requires a loading rate such that the increase of the stress intensity factor to the load P_M (P_f in E 1290 notation) is between 0.55 and 2.75 MPa $\sqrt{m}$/s. E 1737 requires that the time to reach P_M be between 0.1 and 10 min and allows the rate of unloadings to be any convenient rate that does not exceed the above allowable loading rate. The E 1290 requirement is quite tight, probably unnecessarily so since its only intent is to exclude environmental effects of very slow rates and dynamic effects of very high rates.

E 1290 requires temperature stability within ±2°C, while E 1737 allows ±3°C. Both methods place the responsibility for establishing a proper soaking time to attain the correct temperature on those conducting the tests. E 1737 requires a direct measurement of the specimen temperature from the specimen surface within a distance of $W/4$ from the crack tip.

All fracture toughness tests require the measurement and recording of all transducers using an autographic or digital technique. If an autographic technique is used, E 1290 requires the initial slope of the load versus crack opening displacement plot to be between 0.7 and 1.5, while E 1737 requires that areas under the load versus load line displacement curve can be measured to within at least ±2%.

All specimen dimensions must be measured to within 0.1% of W for E 1290 and to within 0.5% for E 1737 and recorded on data records. Specimens and fixtures must be aligned as specified for the particular specimen type, and the clip gage is then carefully mounted on the specimen centerline using razor blades or knife edges.

After completion of the test, if fracture instability has not occurred, the final crack length must be marked and measured by heat tinting or fatigue. The specimen is then broken open to expose the crack surface, and the fatigue and final tearing crack lengths are then measured using the nine-point average measurement technique using an apparatus capable of measuring an individual point to within 0.03 mm. A typical example was presented previously in Fig. 29 (see Section 6). E 1290 places the following requirements on these surface measurements:

1. The difference between any two of the seven central crack length measurements of the crack cannot exceed $0.05W$.
2. The difference between the maximum and minimum of all nine measurements of the fatigue crack cannot exceed $0.10W$.
3. No part of the fatigue crack is closer to the machined notch than the lesser of $0.025W$ or 1.3 mm.
4. The plane of the fatigue crack surface does not exceed an angle of 10° from the plane of the notch.
5. The fatigue crack is not multi-planar or branched.

E 1737 places the following requirements on the surface measurements:

1. No part of the fatigue crack is closer to the machined notch than the lesser of $0.025W$ or 1.3 mm.
2. None of the nine measurements of fatigue crack size shall differ by more than 5% from the average.
3. None of the nine measurements of the final crack size shall differ by more than 5% from the average.
4. None of the nine measurements of crack extension shall be less than 50% of the average crack extension.
5. If crack extension is estimated by compliance or potential change, the last estimate shall agree with the measured average crack extension within 15%.

8.6 ADDITIONAL REQUIREMENTS

If a multi-specimen data set is used to evaluate J_{Ic}, at least five data points must fall inside the exclusion zone, and at least two data points must be in each of Zones A and B, as shown in Fig. 30 (see Section 6). If an unloading-compliance, single-specimen method is being used, the maximum range of unload must not exceed $0.5P_M$ or 50% of the existing maximum load, whichever is greater. For J-R curve determination, crack extension shall be determined so that evenly spaced data are obtained. Specifically (see Fig. 42), two data points are required to the left of the secant line defined by $J = (4/3)\sigma_Y\Delta a$, and eight data points are required between this secant line and the limit of the Δa_{max}, J_{max} region. It is also required that the data used to fit Eq 52 to obtain a_{oq} number eight or more and that the fit have a correlation of at least 0.96.

8.7 SUMMARY

All of the requirements in the above subsections relate directly to the quality of the data developed during the elastic-plastic fracture toughness test. These requirements are generally controllable by the test laboratory relating to test apparatus, fixtures, techniques, etc. If any one requirement is not met, the test is not acceptable and no fracture tough-

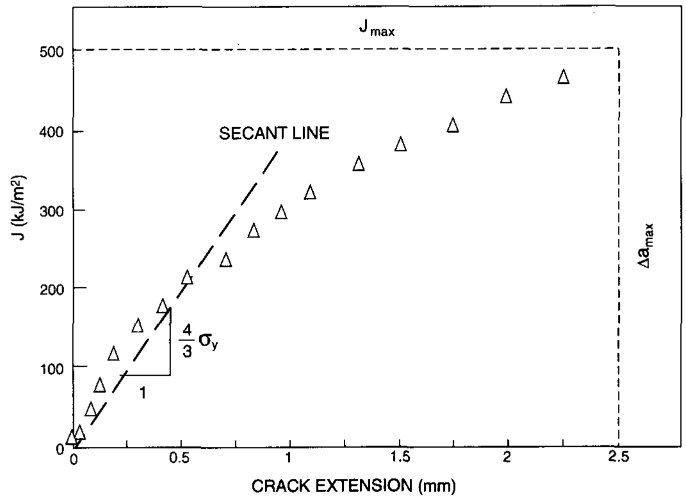


FIG. 42—Secant live data spacing requirement for the *J-R* curve.

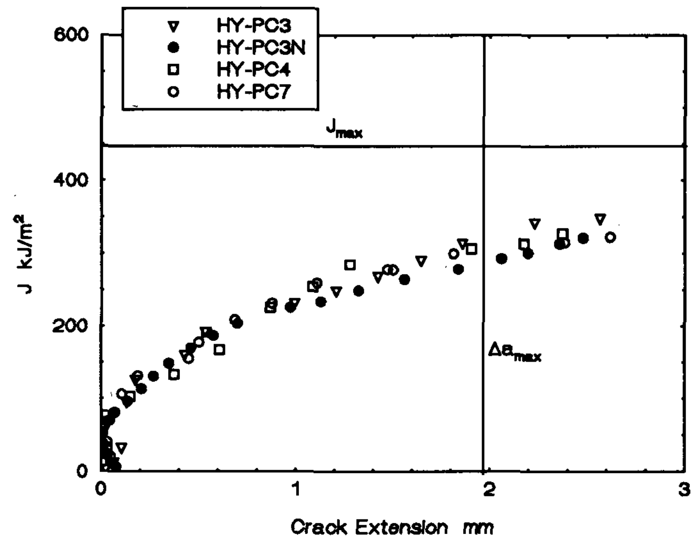


FIG. 43—Qualified *J-R* curve box according to E 1737.

ness quantity can be obtained according to the ASTM E 1290-93 or E 1737 test methods.

Occasionally an investigator can intentionally violate one of the above requirements, for example by ... or heat treating a specimen between the precracking and the test steps. The resulting data can be very useful for a particular application that the investigator is simulating, and the results are then not invalid for this specific application, but they are still invalid according to ASTM E 1290 or E 1737 standards. If the results were reported as valid, someone could easily misapply the results to a case where the invalidating process was not present, causing possibly catastrophic results.

8.8 QUALIFYING THE *J-R* CURVE

Satisfying all the data qualification requirements of the previous sections is only one part of qualifying a *J-R* curve according to E 1737. Even if all of the above requirements are met, it is possible that part or even all of the measured *J-R* curve is invalid by specimen size criteria. ASTM E 1737 defines a region that depends on the material flow stress, the specimen dimensions, and the amount of crack extension—only the portion of the *J-R* curve inside this region is a valid *J-R* curve according to this method. The limit of this region on the J axis, called J_{max}, is given by the smaller of:

$$J_{max} = b_o\,\sigma_Y/20 \tag{54}$$

or

$$J_{max} = B\,\sigma_Y/20 \tag{55}$$

while the corresponding limit on the crack extension axis, called Δa_{max}, is given by:

$$\Delta a_{max} = 0.1 b_o \tag{56}$$

These boundaries are shown on Fig. 43. In this case, the measured *J-R* curve falls below J_{max}, extending beyond the region on the Δa_{max} boundary. Example Calculation 5 shows a full qualification of the *J-R* curve of Specimen HY-PC3 according to E 1737.

8.9 QUALIFYING J_{Ic}

In Sections 6.5 and 7.2, J_Q values were obtained for multi-specimen and single-specimen data sets, respectively. For these results to be accepted as J_{Ic} values according to E 1737, the data sets must meet all of the requirements of the data qualification sections above plus the following size requirements:

$$B > 25\,J_Q/\sigma_Y \tag{57}$$

$$b_o > 25\,J_Q/\sigma_Y \tag{58}$$

and

$$dJ/da \text{ at } \Delta a_Q < \sigma_Y \tag{59}$$

This last requirement is clearly not, strictly speaking, a size requirement, but it is present in the standard to assure that a break in slope occurs near J_{Ic}, between the blunting region and the tearing region, so that a distinct and meaningful ductile initiation J_{Ic} result can be obtained. Example Calculation 6 goes through the details of qualifying the single-specimen case of Specimen HY-PC3, including evaluating these size criteria.

8.10 QUALIFYING J_c

When fracture instability occurs, a J_{Qc} value can be determined as described for Specimen GVR-B1C in Section 6.6. This data set must meet the applicable qualification criteria of E 1737 as outlined in Sections 8.1 to 8.6 and the following criteria:

$$B,\, a_o,\, b_o > 200\,J_{Qc}/\sigma_Y \tag{60}$$

$$\Delta a_p < 0.2 + J_{Qc}/(2\sigma_Y)\text{ mm} \tag{61}$$

$$K_{max} \text{ (during the final 50\% of precracking)} < 0.6(J_{Qc}E)^{1/2} \quad (62)$$

The first of these is the size criteria originally proposed by Anderson and Dodds (1991), while the second requirement limits the amount of ductile crack extension that can exist before fracture instability, while the third criterion is a safeguard to assure that the fatigue precracking was not done at too high a level in comparison to the fracture instability toughness value. For Specimen GVR-B1C of Section 6.6, the qualification calculations are shown in Example Calculation 7. These results show that for this specimen the first criterion is not met, so that the J_{Qc} cannot be reported as a J_c value according to E 1737.

EXAMPLE CALCULATION 5

Qualifying the J-R *curve of Specimen HY-PC3 according to E 1737*

$$J_{max} = b_o\, \sigma_Y/20 = 446.8 \text{ kJ/m}^2 \quad \text{(Eq 54)}$$

$$J_{max} = B\, \sigma_Y/20 = 588.0 \text{ kJ/m}^2 \quad \text{(Eq 55)}$$

$$\Delta a_{max} = 0.1\, b_o = 1.93 \text{ mm} \quad \text{(Eq 56)}$$

The qualified *J-R* curve is the portion on Fig. 43 inside the region shown. The data for this specimen were fully qualified according to Sections 8.2 to 8.6. As shown in Table 4 (see Section 7), the final crack length estimated by compliance after the adjustment of Section 7.2 was only 3% different than the optically measured result. This *J-R* curve, as bounded by the region defined by J_{max} and Δa_{max}, is qualified in accordance with E 1737.

EXAMPLE CALCULATION 6

Qualifying J_Q *as* J_{Ic} *for Specimen HY-PC3*

$25J_Q/\sigma_Y = 0.00728$ m $= 7.28$ mm

$$B = 25.4 > 7.28 \text{ mm} \quad \text{(Eq 57)}$$

$$b_o = 19.3 \text{ mm} > 7.28 \text{ mm} \quad \text{(Eq 58)}$$

dJ/da at Δa_Q can be evaluated using the results of Table 7 as:

$$dJ/da = C_1 \times C_2\, (\Delta a)^{(C2-1)}$$

$$= 0.441 \times 227.0(0.309)^{-0.559} \text{ MPa}$$

$$\text{So: } dJ/da = 193.0 < 463 \text{ MPa} \quad \text{(Eq 59)}$$

All three criteria are thus satisfied in this case, and the J_Q for this specimen can be reported as a qualified J_{Ic} according to E 1737.

EXAMPLE CALCULATION 7

Qualifying J_{Qc} *as* J_c *for Specimen GVR-B1C*

$J_{Qc} = 222.3$ kJ/m^2 from Example Problem 2: $200\, J_{Qc}/\sigma_Y = 0.104$ m $= 104$ mm

Also, from Example Calculation 2:

$$B = 25.4 \text{ mm.}$$

$$a_o = 31.31 \text{ mm.}$$

$$b_o = 19.1 \text{ mm.}$$

These are all less than 104 mm, so this first requirement is not satisfied.

$$0.2 + J_{Qc}/(2\sigma_Y) = 0.46 \text{ mm.}$$

This requirement is satisfied since the measured $\Delta a_p = 0.1$ mm < 0.46 mm.

$$0.6(J_{Qc}E)^{1/2} = 126 \text{ MPa}\sqrt{\text{m}}.$$

The K_{max} for precracking was only 22 MPa$\sqrt{\text{m}}$, so this requirement is also satisfied. These results show that for this specimen the three criteria are not met so J_{Qc} cannot be reported as a J_c value according to E 1737.

8.11 QUALIFYING δ_c AND δ_u

When the data meet all the requirements of Section 8.2 to 8.6, the only additional requirement for δ_c or δ_u to be valid according to E 1290-93 is that they be less than δ_m, the maximum load value of CTOD. For Example Calculation 3 of Section 6.6, the specimen was side grooved and thus did not pass the above requirement of being full thickness for the application, so the values obtained cannot be considered valid according to E 1290-93.

9

Future Developments in Elastic-Plastic Fracture Testing

IT IS IMPOSSIBLE to predict the future, but new developments in elastic-plastic fracture toughness testing are so imminent that they need to be presented here. Several changes have been incorporated into the new E 1737 standard, which is a combination of Standards E 813-89 and E 1152-87 but with the addition of a test procedure for obtaining J-integral fracture toughness data in the ductile-to-brittle transition regime.

A principal new enhancement is the ASTM "Common Test Standard" under development by committee E08.08.01. This standard combines J_{Ic}, J-R, CTOD, CTOD-R, and K_{Ic} testing so that an investigator can start with a test sample and obtain whatever fracture measures are valid for the material and specimen size from a single series of tests.

Many minor differences in specimen geometry, precracking requirements, crack length, test rate requirements, and many other aspects of present standards exist in Standards E 399, E 1290, and E 1737. These differences are often not essential to the toughness measurement being made, and in the Common Test Method the necessary changes have been made to allow for, for instance, measuring K_{Ic} from a side-grooved C(T) specimen. The basic size requirements of the existing methods have been preserved, as well as the basic definitions of the K_{Ic}, J_{Ic}, δ_i, etc., measurement points. In the ballot process, other changes might become necessary, but the basic idea of a common method—as far as it can be achieved—is a good one, and such a document should be available within two years.

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APPENDICES

Appendix A: Software Listings

LISTINGS ARE GIVEN BELOW for two programs. The first program is an interactive unloading compliance data acquisition similar to that described in Joyce and Gudas (1979). This program is written in Microsoft Quick BASIC Version 4.5 and uses a National Instruments IEEE 488 interface to communicate with a Keithley Model 199 (now Model 2000) digital multimeter scanner. The device-specific part of the program is limited and can easily be changed to accommodate other hardware. The second program is a data initialization program to calculate a "shifted" *J-R* curve and a J_{Ic} result in accordance with E 1737 and to qualify the results—except for crack straightness requirements. This program accepts the output of the first program as input.

The first program uses conventional inch and pound units, but it could use any set of consistent units, i.e., Newtons and metres. The use of typical metric units (kN and mm) would require changes to be made in this program. There are three outputs of the data acquisition program. First, a *.DAT file contains the raw data measured during the test. This data file is complete, containing all data taken on unloadings and between unloadings, and it can be used to "rerun" the test with modified equations, specimen dimensions, or material parameters, if desired, at a later date.

The data acquisition program can be converted easily to a replay program that will read data from a file rather than the digital multimeter and carry out all calculations exactly as done in the data acquisition program. The second output file is a *.JRA file that contains 15 columns of data with one row corresponding to each unloading taken during the test. Columns are identified as follows:

1. Unloading number.
2. Number of data on the unloading.
3. Crack opening displacement.
4. Crack opening stiffness.
5. Crack opening stiffness calculation correlation.
6. Load line displacement.
7. Load line stiffness.
8. Load line stiffness calculation correlation.
9. Load.
10. Load-crack opening displacement area.
11. Load-load line displacement.
12. Crack length.
13. Crack extension.
14. *J*-integral.
15. Plastic *J* component.

The third output file is a *.JRM file, which has the same format as the above *.JRA file except that it is in units of mm, kN, and kJ/m^2, as desired by the JIC-CALC.BAS program.

The data acquisition program below is intended for use with a screw-type testing machine. It relies on a machine operator to generate the unloadings by following the screen and pen plotter outputs of the program. Occasional, partial unloadings are harder to generate on a standard servohydraulic test machine and generally require additional equipment. An internal D/A card can be used for this purpose, or a commercial product like an MTS Microprofiler can be purchased for this purpose.

When the computer is in control of the unloading process, completely automated testing can be accomplished that eliminates the possible errors that test operators can sometimes produce. On the other hand, unless the test result is well known before the test is begun, more data must generally be taken to assure that good results are achieved. In general, the present author does not recommend fully automated tests, but if tests are fully automated they can, for instance, be run very slowly to study environmental effect, etc., but this is outside of the scope of E 1737.

A1 Unloading Compliance Data Acquisition Program

```
' $INCLUDE: 'QBDECL4.BAS'
' $DYNAMIC
        DECLARE SUB PLOTSETUP2 ()
        DECLARE SUB JCALC ()
        DECLARE SUB CODCALC ()
        DECLARE SUB ROTATE ()
        DECLARE SUB SLOPE ()
        DECLARE SUB CRKLEN ()
        DECLARE SUB SCANSUBK ()

        COMMON SHARED A0!, A2!, A9!, B1!, B2!, B3!, E1!, H!, H2!, I8!, J1!, J2!, J3!, J7!
        COMMON SHARED N%, P2!, U1!, W1!, Q1!, Q2!, Q3!, Q4!, X1!, X2!, Y1!, Y2!, R1!, E5!, G5
        COMMON SHARED XI!, YI!, G!(), O!(), DPLMAX#, A1!, SIGY!, D2#
        COMMON SHARED X$, Y$, T$
        COMMON SHARED D#(), B#(), DVM%, ISET%

        DIM D#(2), XB#(3), G!(10), O!(10)
        DIM B#(1 TO 3, 1 TO 3)

        CONST TRUE = 1
        CONST FALSE = 0
'
'  COMMANDS LIKE IBCLR, IBWRT, IBRD, ETC. ARE CALLS TO THE NATIONAL INSTRUMENTS
'  IEEE488 INTERFACE THAT COMMUNICATES WITH THE KEITHLEY DVM AND SCANNER.
'  THE INTERFACE CARD USED HERE IS THE MODEL PCIIA AND THE SOFTWARE TO DRIVE
'  IT FROM QuickBASIC 4.5 IS AVAILABLE FROM NATIONAL INSTRUMENTS
'
'  IEEE488 INTERFACE AND Keithley Model 2000 (Model 199) initialization here
'
        BDNAME$ = "Dev5"
        CALL IBFIND(BDNAME$, DVM%)           ' SET UP KEITHLEY AS DEVICE 5
        CALL IBCLR(DVM%)                     ' CLEAR THE KEITHLEY
        WRT$ = "F0 R3 Z0 P0 S1 W50 G1 Q20 X" ' INITIALIZATION STRING
        CALL IBWRT(DVM%, WRT$)                        ' SEND INITIALIZATION STRING
'
        KEY 1, "STOP"
        ON KEY(1) GOSUB STOPIT
        KEY(1) ON

        CLS
'
'   SETUP OF TRANSDUCERS
'   PUT COD GAGE SIGNAL INTO CHANNEL 1 OF KEITHLEY Model 2000 Scanner
'   PUT LOAD SIGNAL INTO CHANNEL 2 OF KEITHLEY Model 2000 Scanner
'
'
        OPEN "LPT1" FOR OUTPUT AS #2 'Set Up Printer
'
'       OPEN "COM2:2400,E,7,1,CD5000,CS5000,DS5000" FOR OUTPUT AS #3 ' PLOTTER COM PORT
        OPEN "COM2" FOR OUTPUT AS #3 ' PLOTTER COM PORT
'
PRINT "BACK FROM COM2 CALL"
        PRINT "JPLAY Computer Interactive Data Acquisition Program "
        PRINT "1995 Version Using QuickBASIC 4.5"
        PRINT #2, "JPLAY Computer Interactive Data Acquisition Program "
        PRINT #2, " 1995 Version Using QuickBASIC 4.5"

'  INITIALIZE FLAGS
'
        F1! = 0
'
'   Here we introduce the SETUP file
'
        PRINT
        PRINT
        PRINT "DO YOU WISH TO READ PARAMETERS FROM A SETUP FILE? (YES/NO)"
        INPUT X$
        IF X$ = "STOP" THEN 6250
        IF X$ <> "YES" THEN CLS : GOTO 1200
        PRINT "THE SETUP FILE I.D. IS? ";
        INPUT SET$
        OPEN SET$ FOR INPUT AS #8
'
'      Input here from an existing SETUP file
'
        INPUT #8, G!(1), O!(1), G!(2), O!(2), E1!, U1!, SIGY!, W1!, B1!, B2!
        INPUT #8, X1!, X2!, Y1!, Y2!, XI!, YI!
        INPUT #8, T$
        INPUT #8, X$
```

```
        INPUT #8, Y$
        INPUT #8, B$
        CLOSE #8
        GOTO MENU
'
'      Menu questions asked here
'
1200     GOTO QUESTS


MENU:    K7% = 1
        B3! = B1! - (B1! - B2!) ^ 2 / B1!
'
'      Print the menu
'
        CLS
        PRINT
        PRINT
        PRINT "1 - COD CALIBRATIONS (QUAN/VOLT) = "; G!(1); ", "; O!(1)
        PRINT "2 - LOAD CALIBRATIONS (QUAN/VOLT) = "; G!(2); ", "; O!(2)
        PRINT "3 - MATERIAL PROPERTIES E, NU, SIGY = "; E1!; ","; U1!; ","; SIGY!
        PRINT "4 - SPECIMEN WIDTH W = "; W1!
        PRINT "5 - SPECIMEN GROSS B AND NET Bn B, Bn = "; B1!; " , "; B2!
        PRINT "6 - SPECIMEN IDENTIFICATION = "; B$
        PRINT "7 - X AXIS MIN AND MAX = "; X1!; ", "; X2!
        PRINT "8 - Y AXIS MIN AND MAX = "; Y1!; ", "; Y2!
        PRINT "9 - X AXIS TIC INTERVAL = "; XI!
        PRINT "10 - Y AXIS TIC INTERVAL = "; YI!
        PRINT "11 - PLOT TITLE = "; T$
        PRINT "12 - X AXIS LABEL = "; X$
        PRINT "13 - Y AXIS LABEL = "; Y$
        PRINT
        PRINT
        IF F7% = 1 THEN F7% = 0: RETURN
        Z5% = 1
        PRINT "ENTER HERE THE NUMBER OF THE ITEM THAT YOU WISH TO"
        PRINT "CHANGE OR RETURN IF ALL IS CORRECT ";
        INPUT Z$
        IF Z$ = "STOP" OR Z$ = "999" THEN 6250
        IF Z$ = "" THEN 2350
        Z7% = VAL(Z$)
        IF Z7% = 999 THEN 6250
        ON Z7% GOTO 10, 20, 30, 40, 40, 60, 70, 80, 90, 100, 110, 120, 130
2350     IF F7% = 1 THEN RETURN
        PRINT "DO YOU WISH TO SAVE THESE PARAMETERS IN A SETUP FILE? (YES/NO)"
        INPUT QS$
        IF QS$ = "STOP" THEN 6250
        IF QS$ <> "YES" THEN 200
'
'    Print the SETUP File to Disk here
'
        PRINT "YOUR SETUP FILE I.D. IS: ";
        INPUT SET$
        OPEN SET$ FOR OUTPUT AS #8
        PRINT #8, G!(1); ","; O!(1); ","; G!(2); ","; O!(2); ",;^E'1!; ","; U1!; ","; SIGY!; ",";
        PRINT #8, W1!; ","; B1!; ","; B2!; ",";
        PRINT #8, X1!; ","; X2!; ","; Y1!; ","; Y2!; ","; XI!; ","; YI!
        PRINT #8, T$
        PRINT #8, X$
        PRINT #8, Y$
        PRINT #8, B$
        CLOSE #8
        GOTO 200
QUESTS:
60       PRINT
        PRINT "INPUT FOR THIS SPECIMEN AN I.D. STRING AS A DISK FILE HEADER "
        INPUT B$
        IF Z5% = 1 THEN GOTO MENU
40       PRINT
        PRINT "INPUT HERE THE SPECIMEN GEOMETRY: W, B, AND Bnet "
        INPUT W1!, B1!, B2!
        IF Z5% = 1 THEN GOTO MENU
30       PRINT
        PRINT "INPUT FOR THIS SPECIMEN THE MATERIAL CONSTANTS E, NU, AND YIELD STRESS "
        INPUT E1!, U1!, SIGY!
        IF Z5% = 1 THEN GOTO MENU
        PRINT
        PRINT #2, "  INPUT DATA FOR THIS SPECIMEN IS: "
        PRINT #2, "          W  = "; W1!
        PRINT #2, "          B  = "; B1!
        PRINT #2, "          BN = "; B2!
        PRINT #2, "          E  = "; E1!
        PRINT #2, "        SIGY = "; SIGY!
        PRINT #2, "        I.D. = "; B$
```

```
        PRINT #2,
        PRINT #2,
10      PRINT
        PRINT "INPUT FOR THE CLIP GAGE THE CALIBRATION SLOPE AND INTERCEPT "
        INPUT G!(1), O!(1)
        IF Z5% = 1 THEN GOTO MENU
20      PRINT
        PRINT "INPUT FOR THE LOAD CELL THE CALIBRATION SLOPE AND INTERCEPT "
        INPUT G!(2), O!(2)
        IF Z5% = 1 THEN GOTO MENU
        PRINT #2, "THE CALIBRATION FACTORS ARE"
        PRINT #2,
        PRINT #2, "CHANNEL NO.", "OUTPUT QUAN/VOLT", "INTERCEPT"
        FOR I% = 1 TO 2
                PRINT #2, " "; I%; " "; G(I%); " "; O(I%)
        NEXT I%
        PRINT #2,
        PRINT #2,
70      PRINT
        PRINT "INPUT THE MIN AND MAX X PLOTTER VALUES ";
        INPUT X1!, X2!
        IF Z5% = 1 THEN GOTO MENU
80      PRINT
        PRINT "INPUT THE MIN AND MAX Y PLOTTER VALUES ";
        INPUT Y1!, Y2!
90      PRINT
        PRINT "INPUT THE X TIC INTERVAL ";
        INPUT XI!
        IF Z5% = 1 THEN GOTO MENU
100     PRINT
        PRINT "INPUT THE Y TIC INTERVAL ";
        INPUT YI!
        IF Z5% = 1 THEN GOTO MENU
110     PRINT
        PRINT "INPUT THE PLOT TITLE ";
        INPUT T$
        IF Z5% = 1 THEN GOTO MENU
120     PRINT
        PRINT "INPUT THE X AXIS LABEL ";
        INPUT X$
        IF Z5% = 1 THEN GOTO MENU
130     PRINT
        PRINT "INPUT THE Y AXIS LABEL ";
        INPUT Y$
        GOTO MENU
200     CLS
        PRINT "INSERT A FILE I.D FOR YOUR OUTPUT DATA FILE <CR> "
        INPUT M$
        O$ = M$ + ".JRA"
        N$ = M$ + ".JRM"
        M$ = M$ + ".DAT"
        CLS
        PRINT
        PRINT "PLOTTING PLEASE BE PATIENT "
'
'    Call Plot Setup to Draw Axes and Titles
'
        CALL PLOTSETUP2
'
        PRINT #2,
        PRINT #2, "START OF CRACK LENGTH ESTIMATION ROUTINE HERE "
        PRINT #2,
        PRINT #2,
        PRINT
        PRINT "WE NEED HERE AN INITIAL SPECIMEN CRACK LENGTH ESTIMATE."
        PRINT "LOAD AND UNLOAD HERE AS OFTEN AS YOU LIKE - BUT DO NOT "
        PRINT "EXCEED THE LINEAR PORTION OF THE LOAD DISPLACEMENT CURVE "
        PRINT "FOR THIS SPECIMEN."
        PRINT
        PRINT "INSTALL YOUR SPECIMEN, TURN ON HYDRAULIC PRESSURE "
        PRINT
        PRINT "CHECK THAT THE LOAD PINS ARE CENTERED AND TYPE <ENTER> TO CONTINUE "
        INPUT QUES$
        PRINT
                PRINT "WHEN YOU ARE READY TO BEGIN THIS LOADING TYPE GO/RETURN"
                PRINT
                PRINT "TO STOP PRESS <s> or <S>"
                INPUT H$
        DO
                PRINT
                PRINT "TO START TAKING DATA TYPE <G> "
                PRINT
        DO
                IF INKEY$ = "G" THEN GOTO 380
```

```
        LOOP
380            FOR I% = 1 TO 3 ' INITIALIZE B# MATRIX
                    FOR J% = 1 TO 3
                         B#(I%, J%) = 0!
                     NEXT J%
               NEXT I%
               K% = 1
'   START DATA ACQUISITION LOOP HERE
               DO
                       CALL SCANSUBK
                       IF INKEY$ = "S" OR INKEY$ = "s" THEN GOTO DUN
'
                       D#(1) = D#(1) * G!(1) + O!(1) 'CALIBRATE
                       D#(2) = D#(2) * G!(2) + O!(2)
                       XB#(1) = 1 ' SET UP THE B MATRIX
                       XB#(2) = D#(1)
                       XB#(3) = D#(2)
                       FOR I% = 1 TO 3
                                FOR J% = I% TO 3
                                 B#(I%, J%) = B#(I%, J%) + XB#(I%) * XB#(J%)
                                NEXT J%
                       NEXT I%
                       K% = K% + 1
                       D1! = D#(1)
                       P1! = D#(2)
               LOOP
DUN:            CALL SLOPE ' GET SLOPE AS H!
               CALL CRKLEN ' GET CRACK LENGTH
               A1! = A2!
               PRINT "THE CRACK LENGTH FROM COMPLIANCE IS: "; A1!
               PRINT #2, A1!
               PRINT "NUMBER OF DATA POINTS TAKEN = "; K%
               PRINT #2, "NUMBER OF DATA POINTS TAKEN = "; K%
               PRINT #2,
               PRINT
               PRINT "DO YOU WANT TO REPEAT THIS STEP ";
               INPUT H$
               LOOP UNTIL H$ = "NO" OR H$ = "N"
        PRINT
        PRINT "BRING THE LOAD DOWN TO A STARTING VALUE - TYPE <S> TO CONTINUE "
        PRINT
        DO
                IF INKEY$ = "S" THEN 390
        LOOP
390      CLS
        PRINT
300      PRINT "DO YOU WISH TO INPUT AN AVERAGE A0 AND COMPLIANCE?";
                INPUT H$
        IF H$ = "YES" OR H$ = "Y" THEN
                PRINT "INPUT YOUR A0 AND COMPLIANCE HERE"
                INPUT A1!, C1!
                PRINT #2, "INPUT VALUES OF INITIAL A0 AND COMPLIANCE ARE: "; A1!, C1!
                H! = 1 / C1!
        END IF
        S0! = H! ' INITIALIZE FILES
        OPEN M$ FOR OUTPUT AS #8 ' OPEN OUTPUT DATA FILES
        OPEN N$ FOR OUTPUT AS #9
        OPEN O$ FOR OUTPUT AS #7
'
        F1% = 0 ' INITIALIZE VARIABLES
        L% = 1
        P1! = 0
        A2! = A1!
        D1# = 0
        D4# = 0
        K% = 1
        A0! = 0
        I1% = 0
        I8! = 0
        P2! = 0
        D2# = 0
        K1% = 0
        COUNT% = 0
        J7! = 0
        A9! = A1!
        B4! = W1! - A1!
        E5! = 2. + .522 * B4!/W1!
        G5! = 1. + .76 * B4!/W1!
        DMAX# = -.2
        KEY ON
'
        CLS
```

```
                                    'START MAIN TEST LOOP HERE

        LOCATE 8, 20: PRINT " TO PAUSE TEST PRESS <p> OR <P> AND PUSH HOLD KEY (F10) '
        PRINT #2,
        PRINT #2, " J TEST BEGUN "
        LOCATE 10, 20: PRINT "WHEN READY TO START TYPE <S> "
        DO
                IF INKEY$ = "S" THEN GOTO 29
        LOOP

29       FOR I% = 1 TO 3
                FOR J% = 1 TO 3
                        B#(I%, J%) = 0
                NEXT J%
        NEXT I%
        CLS
        PRINT
        PRINT "J TEST STARTED"
        PRINT
        DO WHILE F1% <> 999 'BEGIN MAIN TEST LOOP
                IF F1% = 999 THEN 3520
                IF I1% = 0 THEN
                 START! = TIMER ' USE TIMER TO GET 1 SEC. DATA
                        DO
                        STP! = TIMER
                        LOOP WHILE (STP! - START!) < 1
                END IF
'
'        Read data from channels 1 and 2 with slow scan
                CALL SCANSUBK
'
'        CALIBRATE THE RESULTS
'
                FOR I% = 1 TO 2 ' Calibrate
                 D#(I%) = D#(I%) * G!(I%) + O!(I%)
                NEXT I%
2720     IF K% > 1 THEN 2750
                PRINT #3, "PA", Q1! * D#(1) + Q3!, Q2! * D#(2) + Q4!
                GOTO 2760
2750     PRINT #3, "PD"
                PRINT #3, "PA", D#(1) * Q1! + Q3!, Q2! * D#(2) + Q4!
        DH! = D#(1)
        PH! = D#(2)
2760     PRINT #8, K%; " "; I1%; " "; DH!; " "; PH!
                IF (INKEY$ = "P") OR (INKEY$ = "p") THEN
                 INPUT "PRESS RETURN TO RESTART DATA TAKING ", DUMMY$
                END IF
2830     P2! = D#(2)
                D2# = D#(1)
                IF D2# > DMAX# THEN DMAX# = D2# ' UNLOAD LIMIT
                IF K% < 20 THEN 3430 'BEGIN K LOOP
                DTEST# = D2# - DMAX#
                IF DTEST# < -.00005 THEN 2920 'CHECK FOR AN UNLOADING
                IF I1% = 0 THEN 3430
                IF D2# >> D9# THEN 2980
                GOTO 3330
2920     IF I1% = 0 THEN
                P9! = P2! ' START OF AN UNLOADING
                I1% = 1
'
'        Read data from channels 1 and 2 with slow scan
                CALL SCANSUBK
'
'        CALIBRATE THE RESULTS
'
                D9# = D#(1) * G!(1) + O!(1) ' CALIBRATED END OF UNLOADING
                DMAX# = D9#
                DPLMAX# = DMAX# - P9! / H!
        END IF
        GOTO 3330
2980     IF L% < 5 THEN 3290
                K1% = K1% + 1
                CALL SLOPE ' GET STIFFNESS
                H2! = H!
                CALL ROTATE ' ROTATION CORRECTION
                CALL CRKLEN ' CRACK LENGTH
                A3! = A2! - A1!
                A4! = A2!
                PRINT "A = "; A2!; " DELTA A = "; A3!; " K = "; K%; " L = "; L%
                CALL JCALC ' GET J QUANTITIES
                PRINT #2, "A = "; A2!; " DELTA A = "; A3!; "K = "; K%; " L = "; L%
                PRINT "PLASTIC AREA = "; I8!; " Jpl = "; J3!; " J = "; J1!
                PRINT #2, "PLASTIC AREA = "; I8!; " Jpl = "; J3!; " J = "; J1!
```

```
            FOR I% = 1 TO 3
            FOR J% = 1 TO 3
             B#(I%, J%) = 0!
            NEXT J%
            NEXT I%
'
' OUTPUT CALCULATED RESULTS
'
            D9! = D9#
            OUT$ = "### ### ##.#### #########.# #.##### ##.#### #########.# #.##### ######.## #####.# #####.# ###.### ###.###
            #####.## ######.##"
            PRINT #7, USING OUT$; K1%; L%; D9!; H!; R1!; D9!; H!; R1!; P9!; I8!; I8!; A2!; A3!; J1!; J3!
            PRINT #9, USING OUT$; K1%; L%; D9!*25.4; H!/5708.; R1!; D9!*25.4; H!/5708.; R1!; P9!*.00445; I8!*.113; I8!*.113;
            A2!*25.4; A3!*25.4; J1!*.1751; J3!*.1751

            IF A3! > 0 THEN
             PRINT USING "##.####";" DEL A = ", A3!;
             PRINT #2, USING "##.####";" DEL A = ", A3!;
             PRINT
             PRINT #2,
            ELSE
                    IF A3! <^0 THEN
                     PRINT "NO CRACK EXTENSION TO THIS POINT."
                     PRINT #2, "NO CRACK EXTENSION TO THIS POINT."
                    END IF
            END IF
            PRINT
            PRINT #2,
3290     IF L% < 3 THEN 3330 ' CLEAN UP TO RETURN TO TAKING DATA
            I1% = 0
            DMAX# = 0!
            L% = 0
            GOTO 3430
'
' TAKE DATA INTO SLOPE CALCULATION (I1% = 1)
'
3330     IF P2! > .98 * P9! THEN 3430
            XB#(1) = 1
            XB#(2) = D2#
            XB#(3) = P2!
            L% = L% + 1
            FOR I% = 1 TO 3
            FOR J% = I% TO 3
             B#(I%, J%) = B#(I%, J%) + XB#(I%) * XB#(J%)
            NEXT J%
            NEXT I%
3430     K% = K% + 1 'END OF K LOOP
            IF F1% = 999 THEN 3520
            IF I1% = 1 THEN 3490
'
' CALCULATE PLASTIC AREA IF NOT ON UNLOADING
'
            Dpl# = D2# - P2! / H!
            I8! = I8! + (Dpl# - D4#) * (P2! + P1!) / 2 ' ACCUMULATED PLASTIC AREA
            D4# = Dpl#
3490     P1! = P2!
            D1# = D2#
            IF (INKEY$ = "S") OR (INKEY$ = "s") THEN F1% = 999 ' STOP POINT
        LOOP ' END MAIN LOOP
'
' CLOSE UP FILES BEFORE GETTING OUT
'
3520     PRINT " 2 COLUMNS OF "; K%; " NUMBERS HAVE BEEN PUT INTO "; M$
        PRINT #2, " 2 COLUMNS OF "; K%; " NUMBERS HAVE BEEN PUT INTO "; M$
        PRINT #2, "DEL A J DATA ON "; K1%; " UNLOADINGS HAS BEEN PUT INTO "
        PRINT "DEL A J DATA ON "; K1%; " UNLOADINGS HAS BEEN PUT INTO "
        PRINT #2, "FILES "; O$;" AND ";N$
        PRINT "FILE "; O$;" AND "·6250     PRINT "THAT'S ALL FOLKS"
        PRINT #2, "THAT'S ALL FOLKS"; Page$
        CLS
6300     PRINT
        PRINT
        PRINT "BRING THE LOAD TO ZERO AND REMOVE THE TEST PIECE "
        PRINT
        PRINT "INPUT <CR> TO CONTINUE ";
        INPUT QUES$
        PRINT
        PRINT "THAT'S ALL FOLKS"

' SHUT DOWN IEEE-488 CARD AND METER
        CALL IBCLR(DVM%)
        CALL IBONL(DVM%, (0))
        CLOSE
        END ' END OF MAIN
```

```
'
' COMPLIANCE COEFFICIENTS FOR LOAD LINE CT SPECIMEN
'
        DATA 1.000196,-4.06319,11.242,-106.043,464.335,-650.677

' STOPIT GOSUB - KEY 1

STOPIT:
        PRINT "DO YOU REALLY WISH TO STOP (Y/N) ";
        INPUT QUES$
        IF QUES$ <> "Y" THEN RETURN
        F1% = 999
        RETURN
'
' * * * SUBROUTINES START HERE * * * * * * *
'
        SUB CRKLEN ' CRACK LENGTH BY HUDAK RELATIONSHIP - C(T) SPECIMEN
        DIM JIM!(9), DA!(6)
        FOR I% = 1 TO 6
         READ JIM!(I%)
        NEXT I%
        C! = SQR(E1! * B3! / H!)
        C! = 1 / (C! + 1)
        DA!(1) = C!
        FOR I% = 2 TO 5
         DA!(I%) = DA!(I% - 1) * DA!(1)
        NEXT I%
        F! = JIM!(1)
        FOR I% = 1 TO 5
         F! = F! + JIM!(I% + 1) * DA!(I%)
        NEXT I%
        A2! = F! * W1!
        RESTORE
        END SUB ' END CRKLEN

        SUB JCALC ' GET J FOR C(T) SPECIMEN
        E4! = A2! / W1!
        F0! = (.886 + 4.64 * E4! - 13.32 * E4!   2 + 14.72 * E4!   3 - 5.6 * E4!   4) * (2 + E4!)
        F0! = F0! / (1 - E4!)   1.5
        K4! = P2! / SQR(B1! * B2! * W1!) * F0!
        J2! = K4! * K4! * (1 - U1! * U1!) / E1! ' ELASTIC J
        J3! = (J7! + E5! / B4! * (I8! - A0!) / B2!) * (1 - G5! / B4! * (A2! - A9!))
        J1! = J2! + J3! ' TOTAL J
        B4! = W1! - A2!
        E5! = 2 + .522 * B4! / W1!
        G5! = 1 + .76 * B4! / W1!
        A9! = A2!
        J7! = J3!
        A0! = I8!
        END SUB ' END JCALC

        SUB PLOTSETUP2 'PLOTTER SUBROUTINE FOR A HPGL PLOTTER
'
' THIS PROGRAM WILL DRIVE AN HPGL OR EMULATOR PLOTTER CONNECTED TO A COM
' PORT. THIS SETUP PROGRAM DRAWS AXES AND LABELS - DATA IS PLOTTED IN
' THE MAIN SECTION OF THE PROGRAM
'
        PRINT #3, "SP1;"
'        PRINT #3, "PU;"
        A3 = X1
        P2 = 2000
        P4 = 1500
        P3 = 14500
        P5 = 9200
        P6 = ((P3 - P2) / (X2 - X1)) * XI
        Z$ = CHR$(3)
        PRINT #3, "TL", 74.5
        PRINT #3, "PA", P2, P4
        PRINT #3, "SR .7, 1.5"
        FOR I = P2 TO P3 STEP P6
        PRINT #3, "PA", I, P4, "PD;"
        PRINT #3, "PA", I, P5, ";"
        PRINT #3, "PA", I, P4, "PU;"
        A3 = A3 * 1000
        A3 = CINT(A3)
        A3 = A3 / 1000
        A$ = STR$(A3)
        L7 = LEN(A$) + 1
        PRINT #3, "SR,.7,1.5"
        PRINT #3, "CP", -L7 / 2, -1
        PRINT #3, "LB"; A$; Z$
        A3 = A3 + XI
        NEXT I
        A3 = Y1
```

```
        P7 = ((P5 - P4) / (Y2 - Y1)) * YI
        Z$ = CHR$(3)
        PRINT #3, "TL", 83
        PRINT #3, "PA", P2, P4
        A$ = STR$(A3)
        FOR I = P4 TO P5 STEP P7
        PRINT #3, "PA", P2, I, "PD;"
        PRINT #3, "PA", P3, I, ";"
        PRINT #3, "PA", P2, I, "PU;"
        A$ = STR$(A3)
        L7 = LEN(A$)
        PRINT #3, "SR,.7,1.5"
        PRINT #3, "CP", -L7, 0
        PRINT #3, "LB"; A$; Z$
        A3 = A3 + YI
        NEXT I
        L6 = LEN(T$) / 2
        PRINT #3, "SP1"
        PRINT #3, "PA", (P2 + P3) / 2 - 120 * L6, P5 + 300
        PRINT #3, "SR 1.5,3"
        PRINT #3, "CP -L6,0.3"
        PRINT #3, "PD"
        PRINT #3, "LB"; T$; Z$
        PRINT #3, "SR"
        PRINT #3, "PU"
        L6 = LEN(X$) / 2
        PRINT #3, "SP1"
        PRINT #3, "SR 1,2"
        PRINT #3, "PA", (P2 + P3) / 2 - 80 * L6, 800
        PRINT #3, "CP -L6,-3"
        PRINT #3, "PD"
        PRINT #3, "LB"; X$; Z$
        PRINT #3, "PU"
        PRINT #3, "PA", P2, (P4 + P5) / 2
        L6 = LEN(Y$) / 2
        PRINT #3, "DI 0,1"
        PRINT #3, "SR 1,2"
        PRINT #3, "PA", 1200, (P4 + P5) / 2 - 80 * L6
        PRINT #3, "CP -L6,3"
        PRINT #3, "PD"
        PRINT #3, "LB"; Y$; Z$
        PRINT #3, "PU"
        PRINT #3, "DI 1,0"
        PRINT #3, "SR"
        Q1! = (P3 - P2) / (X2 - X1)
        Q2! = (P5 - P4) / (Y2 - Y1)
        Q3! = P2 - Q1! * X1
        Q4! = P4 - Q2! * Y1
        END SUB

        SUB ROTATE ' ROTATION CORRECTION
        R3! = .5 * (W1! + A2!)
        H3! = .5 * W1!
        DSPACE! = .1 ' 1/2 OF THE INITIAL CLIP GAGE OPENING
        T2! = (D2# / 2 + DSPACE!) / SQR(DSPACE!   2 + R3!   2)
        T2! = ATN(T2! / SQR(1 - T2!   2)) - ATN(DSPACE! / R3!)
        H! = (H3! / R3! * SIN(T2!) - COS(T2!)) * (DSPACE! / R3! * SIN(T2!) - COS(T2!)) * H2!
        END SUB ' END ROTATE
'
'*************************************************************************
SUB SLOPE ' SLOPE CALCULATION
'
        Qs1# = (B#(1, 1) * B#(2, 2) - B#(1, 2)   2) / (B#(1, 1) * (B#(1, 1) - 1))
        Qs2# = (B#(1, 1) * B#(3, 3) - B#(1, 3)   2) / (B#(1, 1) * (B#(1, 1) - 1))
        H! = (B#(1, 1) * B#(2, 3) - B#(1, 2) * B#(1, 3)) / (B#(1, 1) * B#(2, 2) - B#(1, 2)   2)
        IF H! < 0 THEN
         PRINT "POOR DATA SLOPE <0"
         H! = 333333.3
         R1! = 0
        ELSE
         R1! = H! * SQR(Qs1# / Qs2#)
         PRINT "SLOPE = "; H!; " COMPLIANCE = "; 1 / H!; "CORR. = "; R1!
         PRINT #2, "SLOPE = "; H!; " COMPLIANCE = "; 1 / H!; "CORR. = "; R1!
         N7% = B#(1, 1)
        END IF
END SUB ' END SLOPE
'
SUB SCANSUBK
'
        WRT$ = "I2 M08 N22 T5 X"        'TRIGGER STRING - 2 CHANNELS
        CALL IBWRT(DVM%, WRT$)                  ' SEND TRIGGER SIGNAL
        MASK% = &H5800
        CALL IBWAIT(DVM%, MASK%)        ' WAIT FOR SRQ, ERROR, OR TIMEOUT
        CALL IBRSP(DVM%, SPR%)                  ' DO A SERIAL POLL
```

```
'
        RD1$ = SPACE$(16)
        FOR ILOOP% = 1 TO 2
        CALL IBRD(DVM%, RD1$)
        D#(ILOOP%) = VAL(RD1$)              ' READ TWO CHANNELS OF DATA
        NEXT ILOOP%
'
END SUB                         ' END OF SCANSUBK
```

A2 Initialization Fit Program

```
' $DYNAMIC
        DECLARE SUB JQCALC ()
        DECLARE SUB SLOPE ()
        DECLARE SUB JFIT ()
        DECLARE SUB GAUSS ()

        COMMON SHARED B1!, B2!, E1!, E1p!, U1!, W1!, SPAN!, SFLOW!
        COMMON SHARED JQ!, AQ#, MQ#, BQ#, RQ#, JZ!(), AZ!(), XY!()
        COMMON SHARED JM!(), AM!(), X!(), Y!(), AN!(), XN!(), AX!(), JX!()
        COMMON SHARED NUMDAT%, NFIT%, SLOPEM!, AZMEAS!, AFMEAS!, RFIT!
        COMMON SHARED FF!(), RDAT%, DELAMIN!, DELALIM!, JLIMIT!, DELASEC!
        COMMON SHARED ASHFT!

        DIM XB#(3), JZ!(100), AZ!(100), JM!(100), AM!(100), XY!(17)
        DIM AX!(100), JX!(100), X!(100), Y!(100), AC!(100), FF!(100)
        DIM XN!(3), PM!(100)
        DIM AN!(1 TO 3, 1 TO 4)
'
'        INITIALIZATION FIT VERSION DECEMBER 1994 - WITH BLUNTING LINE SLOPE
'
'        PROGRAM TO EVALUATE A SHIFTED J-R CURVE AND A Jic ACCORDING TO ASTM E1737
'
        CONST TRUE = 1
        CONST FALSE = 0
        DIAM! = 2!
        W1! = 2!
        Page$ = CHR$(12)
        CLS
'
'        THIS VERSION IS FOR THE C(T), DC(T), and SE(B) SPECIMENS ONLY ******************
'
        OPEN "LPT1" FOR OUTPUT AS #2 'PRINTER
        PRINT "INITIALIZED J-R CURVE AND Jic EVALUATION "
        PRINT "****** METRIC VERSION - WATCH THE UNITS ******* "
        PRINT #2, "INITIALIZED J-R CURVE AND Jic EVALUATION"
        PRINT #2,
        PRINT #2, "JOYCE/ASTM MANUAL VERSION OF DECEMBER 1994"
        PRINT #2,
        PRINT
'
'   Here we introduce the SETUP file
'
        PRINT
        PRINT "DO YOU WISH TO READ PARAMETERS FROM A REPLAY SETUP FILE? (YES/NO)"
        INPUT QUES$
        IF QUES$ <> "YES" THEN CLS : GOTO 5
        PRINT "THE SETUP FILE I.D. IS? ";
        INPUT SET$
        OPEN SET$ FOR INPUT AS #6
'
'     Input here from an existing SETUP file
'
        INPUT #6, E1!, U1!, SIGY!, SIGUTS!, W1!, B1!, B2!, SPAN!
        INPUT #6, AZMEAS!, AFMEAS!, SLOPEM!
        INPUT #6, PQUES$
        INPUT #6, B$
        INPUT #6, SPEC$
        CLOSE #6
        SFLOW! = (SIGY! + SIGUTS!) / 2
        JLIMIT! = SFLOW! * (W1! - AZMEAS!) / 15!
        GOTO MENU
'
'      Menu questions asked here
'
5        GOTO QUESTS
'
MENU:
        E1p! = E1! / (1 - U1! * U1!)
'
'      Print the menu
```

```
        CLS
        PRINT
        PRINT "1 - MATERIAL PROPERTIES E (GPa), NU = "; E1!; ","; U1!
        PRINT "2 - MATERIAL PROPERTIES SIGY, SIGUTS(MPa) = "; SIGY!; ", "; SIGUTS!
        IF SPEC$ = "CT" OR SPEC$ = "DCT" THEN PRINT "3 - SPECIMEN WIDTH W (mm)
  = ";  W1!
        IF SPEC$ = "SEB" THEN PRINT "3 - SPECIMEN WIDTH W and SPAN (mm) = "; W1!; ", "; SPAN!
        PRINT "4 - SPECIMEN GROSS B AND NET Bn B, Bn (mm) = "; B1!; " , "; B2!
        PRINT "5 - SPECIMEN IDENTIFICATION = "; B$
        PRINT "6 - SPECIMEN MEASURED AZ AND AF (mm) = "; AZMEAS!; ", "; AFMEAS!
        PRINT "7 - SPECIMEN TYPE (CT, DCT, OR SEB)                = "; SPEC$
        PRINT "8 - CONSTRUCTION LINE SLOPE (M)          = "; SLOPEM!
        PRINT
        PRINT
        IF F7% = 1 THEN F7% = 0: RETURN
        Z5% = 1
        PRINT "ENTER HERE THE NUMBER OF THE ITEM THAT YOU WISH TO"
        PRINT "CHANGE OR RETURN IF ALL IS CORRECT ";
        INPUT Z$
        IF Z$ = "" THEN 10
        Z7% = VAL(Z$)
        ON Z7% GOTO 30, 31, 40, 40, 60, 34, 44, 50
10 IF F7% = 1 THEN RETURN
        PRINT "DO YOU WISH TO SAVE THESE PARAMETERS IN A SETUP FILE? (YES / NO)"
        INPUT QS$
        IF QS$ <> "YES" THEN 200
'
' Print the SETUP File to Disk here
'
        PRINT "YOUR SETUP FILE I.D. IS: ";
        INPUT SET$
        OPEN SET$ FOR OUTPUT AS #6
        PRINT #6, E1!; ","; U1!; ","; SIGY!; ","; SIGUTS!; ",";
        PRINT #6, W1!; ","; B1!; ","; B2!; ","; SPAN!
        PRINT #6, AZMEAS!; ","; AFMEAS!; ","; SLOPEM!
        PRINT #6, PQUES$
        PRINT #6, B$
        PRINT #6, SPEC$
        CLOSE #6
        GOTO 200

QUESTS:
60 PRINT
        PRINT "INPUT FOR THIS SPECIMEN AN I.D. STRING AS A DISK FILE HEADER "
        INPUT B$
        IF Z5% = 1 THEN GOTO MENU
40 PRINT
        PRINT "INPUT HERE THE SPECIMEN GEOMETRY: W, B, AND Bnet (mm) "
        INPUT W1!, B1!, B2!
        IF Z5% = 1 THEN GOTO MENU
30 PRINT
        PRINT "INPUT FOR THIS SPECIMEN THE MATERIAL CONSTANTS E (GPa), NU "
        INPUT E1!, U1!
        IF Z5% = 1 GOTO MENU
31 PRINT
        PRINT "INPUT THE MATERIAL YIELD STRESS AND UTS (MPa) ";
        INPUT SIGY!, SIGUTS!
        SFLOW! = (SIGY! + SIGUTS!) / 2!
        IF Z5% = 1 THEN GOTO MENU
34 PRINT "INPUT MEASURED INITIAL AND FINAL CRACK LENGTHS (mm) "
        INPUT AZMEAS!, AFMEAS!
        IF Z5% = 1 THEN GOTO MENU
44 PRINT "INPUT THE SPECIMEN TYPE (CT, DCT, OR SEB) ";
        INPUT SPEC$
        SPAN! = 203.2
        IF SPEC$ = "SEB" THEN INPUT "INPUT BEND SPAN (mm) ", SPAN!
        IF Z5% = 1 THEN GOTO MENU
50 PRINT "INPUT THE DESIRED CONSTRUCTION LINE SLOPE (USUALLY 2.0) ";
        INPUT SLOPEM!
        GOTO MENU
200 PRINT
        PRINT #2, " INPUT DATA FOR THIS SPECIMEN IS: "
        PRINT #2,
        IF SPEC$ = "CT" OR SPEC$ = "DCT" THEN PRINT #2, " W (mm) = "; W1!
        IF SPEC$ = "SEB" THEN PRINT #2, " W (mm) = "; W1!; " SPAN (mm) = "; SPAN!
        PRINT #2, " B (mm) = "; B1!; " Bn (mm) = "; B2!
        PRINT #2, " AZMEAS (MPa) = "; AZMEAS!; " AFMEAS (MPa) = "; AFMEAS!
        PRINT #2, " E (GPa) = "; E1!; " U1 = "; U1!
        PRINT #2, " SIGY (MPa) = "; SIGY!; " SIGUTS (MPa) = "; SIGUTS!
        PRINT #2, " I.D. = "; B$; " SPECIMEN TYPE = "; SPEC$
        PRINT #2, " M = "; SLOPEM!
        PRINT #2,
```

```
        INPUT "INPUT THE DATA FILE I.D. FOR THIS SPECIMEN (WITHOUT THE *.JRM): ", DT$
        DTN$ = DT$ + ".JRM"                ' READS METRIC SPECIMEN RESULTS FILE
'
' Calculate PmLim in kN
'
        IF SPEC$ = "CT" OR SPEC$ = "DCT" THEN PMLIM! = .4 * B1! * (W1! - AZMEAS!)   2 * SFLOW! / (2! * W1! + AZMEAS!) /
        IF SPEC$ = "SEB" THEN PMLIM! = .5 * B1! * (W1! - AZMEAS!)   2 * SFLOW! / SPAN! / 1000!
        JLIMIT! = SFLOW! * (W1! - AZMEAS!) / 15!
'
' Input data must be in kN and mm, J in kJ/m 2
'
        I% = 1 'DATA COUNTER
        OPEN DTN$ FOR INPUT AS #1
        AMIN! = 500!
        DO UNTIL EOF(1)
                FOR K% = 1 TO 15
                        INPUT #1, XY!(K%)
                NEXT K%
' FIND Amin
                AM!(I%) = XY!(12)
                IF AM!(I%) < AMIN! THEN AMIN! = AM!(I%)
                JM!(I%) = XY!(14)
                PM!(I%) = XY!(7)
        I% = I% + 1
        LOOP
        NUMDAT% = I% - 1
        CLOSE #1
'
' REDUCE THE DATA SET FOR THE INITIALIZATION FIT
'
        J% = 0
        FOR I% = 1 TO NUMDAT%
                IF PM!(I%) > PMLIM! AND AM!(I%) < AMIN! + 2.5 THEN
                        J% = J% + 1
                        JX!(J%) = JM!(I%)
                        AX!(J%) = AM!(I%)
                END IF
        NEXT I%
        PRINT #2,
        PRINT
'
' CALL THE INITIALIZATION FIT SUBROUTINE
'
        RDAT% = J%
        CALL JFIT
        ASHFT! = XN!(1)
        PRINT #2,
        PRINT #2, USING "& ###.## & ### "; " ASHFT! = "; ASHFT!; " USING "; RDAT%; " POINTS"
        PRINT USING "& ###.## & ### "; " ASHFT! = "; ASHFT!; " USING "; RDAT%; " POINTS"
'
' NOW GET JQ!, DELAMIN, AND DELALIM
'
        DELAMIN! = -100
        DELALIM! = 500
'
        CALL JQCALC
'
'
' THIS ENDS THE INITIALIZATION FIT
'
' CHECK FOR DATA EXCLUDED BY DELAMIN, DELALIM, OR JLIMIT RESTRICTIONS
'
        J% = 1
        FOR I% = 1 TO NUMDAT%
                IF AM!(I%) - ASHFT! < DELAMIN! THEN GOTO 300
                IF AM!(I%) - ASHFT! > DELALIM! THEN GOTO 300
                IF JM!(I%) > JLIMIT! THEN GOTO 300
                IF AM!(I%) - ASHFT! < JM!(I%) / (SLOPEM! * SFLOW!) + .15 THEN GOTO 300
                IF AM!(I%) - ASHFT! > JM!(I%) / (SLOPEM! * SFLOW!) + 1.5 THEN GOTO 300
                J% = J% + 1
300 NEXT I%
         IF J% = NFIT% + 1 THEN 320
                PRINT #2, "DATA FOUND THAT MUST BE EXCLUDED - RE-SOLVE FOR JQ"
'
                CALL JQCALC
320 :
'
' CHECK ASHFT! AGAINST AMEAS! - INITIAL CRACK LENGTH ACCURACY
'
        FI% = 0
        IF (ABS(ASHFT! - AZMEAS!)) > .01 * W1! THEN
                PRINT
                PRINT #2,
                PRINT "DATA SET FAILS CRACK LENGTH ACCURACY REQUIREMENT "
```

```
                PRINT #2, "DATA SET FAILS CRACK LENGTH ACCURACY REQUIREMENT "
                PRINT #2, USING "& ###.## & ###.##"; " AZMEAS = "; AZMEAS!; " ASHFT! = "; ASHFT!
                PRINT USING "& ###.## & ###.##"; " AZMEAS! = "; AZMEAS!; " ASHFT! = "; ASHFT!
        FI% = 1
        END IF
'
' CHECK QUALITY OF INITIALIZATION FIT
'
        IF RFIT! < .96 OR RDAT% < 8 THEN
                PRINT "INITIALIZATION FIT FAILED STANDARD REQUIREMENTS "
                PRINT USING "& #.### & ##."; " CORRELATION = "; RFIT!; " RDAT = "; RDAT%
                PRINT #2, "INITIALIZATION FIT FAILED STANDARD REQUIREMENTS "
                PRINT #2, USING "& #.### & ##."; " CORRELATION = "; RFIT!; " RDAT = "; RDAT%
                FI% = 1
                END IF
'
' CHECK E1737 Jic QUALIFICATION REQUIREMENTS
'
        FJ% = 0
        IF NFIT% > 4 THEN GOTO COUNTOK
                PRINT "DATA COUNT IN INCLUSION REGION IS NOT ADEQUATE, N = "; NFIT%
                PRINT #2, "DATA COUNT IN INCLUSION REGION IS NOT ADEQUATE, N = "; NFIT%
                FJ% = 1
COUNTOK:
' CHECK JQ FIT POWER COEFFICIENT
'
        IF MQ# < 1! THEN GOTO POWEROK
                PRINT USING "& #.###"; "C2 COEFFICIENT IS UNACCEPTABLE - C2 = "; MQ#
                PRINT #2, USING "& #.###"; "C2 COEFFICIENT IS UNACCEPTABLE - C2 = "; MQ#
                FJ% = 1
POWEROK:
' CHECK SLOPE REQUIREMENT
        JTEST! = MQ# * BQ# * AQ#   (MQ# - 1)
        IF JTEST! < SFLOW! THEN GOTO SLOPEOK
                PRINT "DATA FIT FAILS SLOPE REQUIREMENT "
                PRINT #2, "DATA FIT FAILS SLOPE REQUIREMENT "
                FJ% = 1
SLOPEOK:
' CHECK DATA CLUSTERING REQUIREMENT
                FOR I% = 1 TO NFIT%
                        IF (AZ!(I%) - AQ#) > (DELALIM! - AQ#) / 3 THEN GOTO CLUSTOK
                NEXT I%
                PRINT AZ!(1) - AQ#, (DELALIM! - AQ#) / 3
                PRINT "DATA FAILS - NO DATA IN REGION B "
                PRINT #2, "DATA FAILS - NO DATA IN REGION B "
                FJ% = 1
CLUSTOK:
'
' CHECK EARLY DATA COUNT REQUIREMENT
        J% = 0
        FOR I% = 1 TO NUMDAT%
                IF JM!(I%) < .4 * JQ! THEN GOTO 700
                IF AM(I%) - ASHFT! > AQ# THEN GOTO 700
                J% = J% + 1
700 NEXT I%
        IF J% > 3 THEN GOTO ECOUNTOK
        FJ% = 1
        PRINT "DATA SET FAILS EARLY DATA COUNT REQUIREMENT - COUNT = "; J%
        PRINT #2, "DATA SET FAILS EARLY DATA COUNT REQUIREMENT - COUNT = "; J%
ECOUNTOK:
'
' CHECK SPECIMEN SIZE REQUIREMENTS
        REQSIZE! = 25 * JQ! / SFLOW!
        IF (W1! - AZMEAS!) > REQSIZE! AND B1! > REQSIZE! THEN GOTO SIZEOK
        PRINT USING "& ###.##"; "SPECIMEN FAILS SIZE REQUIREMENTS, 25*JQ/SFLOW = "; REQSIZE!
        PRINT #2, USING "& ###.##"; "SPECIMEN FAILS SIZE REQUIREMENTS, 25*JQ/SFLOW = "; REQSIZE!
        FJ% = 1
SIZEOK:
'
        IF FJ% > 0 THEN GOTO JRTEST
                PRINT
                PRINT #2,
                PRINT "DATA SET PASSES ALL Jic QUALIFICATION REQUIREMENTS "
                PRINT #2, "DATA SET PASSES ALL Jic QUALIFICATION REQUIREMENTS "
                PRINT
                PRINT #2,
                PRINT #2, USING "& ####.#"; " Jic = "; JQ!; " kJ/m 2"
                PRINT USING "&####.#"; " Jic = "; JQ!; " kJ/m 2"
'
JRTEST:
'
' CHECK J-R CURVE QUALIFICATION REQUIREMENTS
'
        FR% = 0
```

```
' CHECK NUMBER OF J-R CURVE DATA
'
        J% = 0
        FOR I% = 1 TO NUMDAT%
                IF AM!(I%) - ASHFT! < AMIN! - ASHFT! THEN GOTO 800
                IF AM!(I%) - ASHFT! > DELALIM! THEN GOTO 800
                IF JM!(I%) > JLIMIT! THEN GOTO 800
                J% = J% + 1
                AC!(J%) = AM!(I%) - ASHFT!
800 NEXT I%
        IF J% > 10 THEN GOTO NUMDATOK
        PRINT "J-R CURVE DATA COUNT INADEQUATE - COUNT = "; J%
        PRINT #2, "J-R CURVE DATA COUNT INADEQUATE - COUNT = "; J%
        FR% = 1
NUMDATOK:
' CHECK SECANT LINE REQUIREMENT
'
        DELASEC! = ((3 * BQ#) / (4 * SFLOW!))   (1 / (1 - MQ#))
        JB% = 0
        JA% = 0
        FOR I% = 1 TO J%
                IF AC!(I%) < DELASEC! THEN
                        JB% = JB% + 1
                        ELSE JA% = JA% + 1
                END IF
        NEXT I%
        IF JA% < 2 OR JB% < 8 THEN
                PRINT "J-R CURVE DATA FAILS SECANT SPACING REQUIREMENT "
                PRINT #2, "J-R CURVE DATA FAILS SECANT SPACING REQUIREMENT "
                FR% = 1
        END IF
SECANTOK:

        PRINT
        PRINT #2,
        PRINT USING "& ###.##"; "THE FINAL ESTIMATED CRACK LENGTH IS: "; AM!(NUMDAT%); " mm"
        PRINT #2, USING "& ###.##"; "THE FINAL ESTIMATED CRACK LENGTH IS: "; AM!(NUMDAT%); " mm"
        PRINT
        PRINT #2,
        PRINT USING "& ##.##"; "THE ESTIMATED FINAL CRACK EXTENSION IS: "; AM!(NUMDAT%) - ASHFT!; " mm"
        PRINT USING "& ##.##"; "THE MEASURED FINAL CRACK EXTENSION IS: "; AFMEAS! - AZMEAS!; " mm"
        PRINT
        PRINT #2, USING "& ##.##"; "THE ESTIMATED FINAL CRACK EXTENSION IS: "; AM!(NUMDAT%) - ASHFT!; " mm"
        PRINT #2, USING "& ##.##"; "THE MEASURED FINAL CRACK EXTENSION IS: "; AFMEAS! - AZMEAS!; " mm"

        PRINT #2,
        FDIFF! = ((AFMEAS! - AZMEAS!) - (AM!(NUMDAT%) - ASHFT!)) / (AFMEAS! - AZMEAS!) * 100
        PRINT USING "& ##.#"; "THE PERCENT ERROR IN THE FINAL CRACK EXTENSION PREDICTION IS: "; FDIFF!; " %"
        PRINT #2, USING "& ##.#"; "THE PERCENT ERROR IN THE FINAL CRACK EXTENSION PREDICTION IS: "; FDIFF!; " %"
        IF ABS(FDIFF!) > 15 THEN
                PRINT "THIS FINAL CRACK EXTENSION ACCURACY IS NOT SATISFACTORY!! "
                PRINT #2, "THIS FINAL CRACK EXTENSION ACCURACY IS NOT SATISFACTORY!! "
                FR% = 1
        END IF
'
' TEST J-R CURVE FLAG
        IF FR% = 0 AND FI% = 0 THEN GOTO JROK
                PRINT "THE J-R CURVE HAS NOT PASSED ALL REQUIREMENTS "
'
JROK:
        PRINT
        PRINT #2,
        PRINT "THIS J-R CURVE PASSES ALL J-R CURVE QUALIFICATION REQUIREMENTS"
        PRINT "FOR THE REGION ENCLOSED BY JLIMIT AND DELALIM."
        PRINT #2, "THIS J-R CURVE PASSES ALL J-R CURVE QUALIFICATION REQUIREMENT "
        PRINT #2, " FOR THE REGION ENCLOSED BY:"
        PRINT #2, USING "& ####.# "; " JLIMIT = "; JLIMIT!; " kJ/m 2"
        PRINT #2, USING "& ##.###"; " DELALIM = "; DELALIM!; " mm"
'
'
PRINTOUT:
'
' PRINT OUT A MODIFIED *.JRI FILE WITH CHANGES ONLY IN THE DEL A COLUMN
        ET$ = DT$ + ".JRI"
        OPEN ET$ FOR OUTPUT AS #1
        OPEN DTN$ FOR INPUT AS #7
        I% = 1
        DO UNTIL EOF(7)
        FOR K% = 1 TO 15
                INPUT #7, XY!(K%)
        NEXT K%
' PRINT OUT IN *.JRA FORMAT (15 COLUMNS)
        PRINT #1, XY!(1); " "; XY!(2); " "; XY!(3); " "; XY!(4); " "; XY!(5); " "; XY!(6); " "; XY!(7); " "; XY!(8);
XY!(10); " "; XY!(11); " "; XY!(12); " "; XY!(12) - ASHFT!; " "; XY!(14); " "; XY!(15)
```

```
        I% = I% + 1
        LOOP
'
' SHUT THINGS DOWN
'
        CLOSE #1, #7
        PRINT #2, Page$
        END

'
SUB GAUSS
' INPUT DATA IS IN AN!(3,4) - OUTPUT IS XN!(3)
' SUBROUTINE IN BASIC TO DO A GAUSS ELIMINATION SOLUTION
' SET NOW FOR 3X3 MATRIX
' OUTPUT IS A VECTOR XN
N% = 3
M% = N% + 1
L% = N% - 1
' START REDUCTION TO TRIANGULAR FORM
FOR K% = 1 TO L%
         K1% = K% + 1
        JJ% = K%
        BG! = ABS(AN!(K%, K%))
' REM START OF SEARCH FOR LARGEST PIVOT ELEMENT
FOR I% = K1% TO N%
        AB! = ABS(AN!(I%, K%))
        IF BG! > AB! THEN BG! = AB!: JJ% = I%
NEXT I%
IF JJ% = K% GOTO REDUCE
' INTERCHANGES ROWS TO GET MAX PIVOT ELEMENT
FOR J% = K% TO M%
        TE! = AN!(JJ%, J%)
        AN!(JJ%, J%) = AN!(K%, J%)
        AN!(K%, J%) = TE!
NEXT J%
' DETERMINES REDUCED ELEMENTS OF TRIANGULAR SET
REDUCE:
FOR I% = K1% TO N%
         Q! = AN!(I%, K%) / AN!(K%, K%)
        FOR J% = K1% TO M%
                AN!(I%, J%) = AN!(I%, J%) - Q! * AN!(K%, J%)
        NEXT J%
NEXT I%
FOR I% = K1% TO N%
         AN!(I%, K%) = 0!
NEXT I%
NEXT K%
' BACK SUBSTITUTION FOR THE SOLUTIONS
XN!(N%) = AN!(N%, M%) / AN!(N%, N%)
FOR NN% = 1 TO L%
        SU! = 0!
        I% = N% - NN%
        I1% = I% + 1
        FOR J% = I1% TO N%
                SU! = SU! + AN!(I%, J%) * XN!(J%)
        NEXT J%
        XN!(I%) = (AN!(I%, M%) - SU!) / AN!(I%, I%)
        NEXT NN%
END SUB

SUB JFIT
'
' SUBROUTINE TO SET UP FUNCTION FOR A0 EVALUATION
' USES EQUATION aA Q \ + J/(2*SIGF) +B J ^ 2 + C J ^ 3, USES EQUATION a Q a0Q + J/(2*SIGF) + B J ^ 2 + C J ^ 3
'
' INPUT IS RDAT% PAIRS OF a AND J IN VECTOR ARRAYS AM! AND JM!
'
FOR I% = 1 TO 3
         FOR J% = 1 TO 4
                 AN!(I%, J%) = 0!
        NEXT J%
NEXT I%
         JSUM! = 0
' DO SUMMATIONS FOR LEAST SQUARES
AN!(1, 1) = RDAT%
FOR I% = 1 TO RDAT%
                JSUM! = JSUM! + JX!(I%)
        AN!(1, 2) = AN!(1, 2) + JX!(I%)   2
        AN!(2, 2) = AN!(2, 2) + JX!(I%)   4
        AN!(1, 3) = AN!(1, 3) + JX!(I%)   3
        AN!(2, 3) = AN!(2, 3) + JX!(I%)   5
        AN!(3, 3) = AN!(3, 3) + JX!(I%)   6
        AN!(1, 4) = AN!(1, 4) + AX!(I%)
        AN!(2, 4) = AN!(2, 4) + AX!(I%) * JX!(I%)   2
```

```
        AN!(3, 4) = AN!(3, 4) + AX!(I%) * JX!(I%)   3
NEXT I%
         AN!(1, 4) = AN!(1, 4) - JSUM! / (2 * SFLOW!)
         AN!(2, 4) = AN!(2, 4) - AN!(1, 3) / (2 * SFLOW!)
         AN!(3, 4) = AN!(3, 4) - AN!(2, 2) / (2 * SFLOW!)
AN!(2, 1) = AN!(1, 2)
AN!(3, 1) = AN!(1, 3)
AN!(3, 2) = AN!(2, 3)
' NOW SOLVE THESE EQUATIONS USING GAUSS ELIMINATION FOR XN!
CALL GAUSS
'
PRINT "COEFFICIENTS OF INITIALIZATION ARRAY ARE: "
PRINT XN!(1), XN!(2), XN!(3)
PRINT #2, "COEFFICIENTS OF INITIALIZATION ARRAY ARE: "
PRINT #2, XN!(1), XN!(2), XN!(3)
' CHECK THE FIT
FOR I% = 1 TO RDAT%
        FF!(I%) = XN!(1) + JX!(I%) / (2 * SFLOW!) + XN!(2) * JX!(I%)   2 + XN!(3) * JX!(I%)
NEXT I%
' CALCULATION OF THE CORRELATION OF THE FIT
YM! = 0!
FOR I% = 1 TO RDAT%
         YM! = YM! + AX!(I%) / RDAT%
NEXT I%
SY2! = 0!
SYX2! = 0!
FOR I% = 1 TO RDAT%
         SY2! = SY2! + (AX!(I%) - YM!)   2 / (RDAT% - 1)
        SYX2! = SYX2! + (AX!(I%) - FF!(I%))   2 / (RDAT% - 2)
NEXT I%
RFIT! = SQR(1! - SYX2! / SY2!)
PRINT USING "& #.###"; "CORRELATION OF FIT = "; RFIT!
PRINT #2, USING "& #.###"; "CORRELATION OF FIT = "; RFIT!
END SUB

'
' ************************ SUBROUTINES ******************************
'
        SUB JQCALC
'
' SUBROUTINE TO GET JQ ESSENTIALLY USING E813-1987 VERSION
'
' PARAMETER DEFINITION
'
' FIT EQUATION J = C1 (DEL A ) ^ C2
'
        IF NUMDAT% < 4 THEN
        PRINT "TOO FEW DATA FOUND - FIX AND RE-RUN"
        STOP
        END IF
' OBTAIN THE REDUCED DATA SET FOR Jic CALCULATION
        J% = 1
        FOR I% = 1 TO NUMDAT%
                IF AM!(I%) - ASHFT! < DELAMIN! THEN GOTO 8801
                IF AM!(I%) - ASHFT! > DELALIM! THEN GOTO 8801
                IF JM!(I%) > JLIMIT! THEN GOTO 8801
                IF AM!(I%) - ASHFT! < JM!(I%) / (SLOPEM! * SFLOW!) + .15 THEN GOTO 8801
                IF AM!(I%) - ASHFT! > JM!(I%) / (SLOPEM! * SFLOW!) + 1.5 THEN GOTO 8801
                JZ!(J%) = JM!(I%)
                AZ!(J%) = AM!(I%) - ASHFT! 'NOW DELTA A'S
                J% = J% + 1
8801 :
        NEXT I%
        NFIT% = J% - 1
        IF NFIT% < 2 THEN
                PRINT "TO LITTLE DATA TO CALCULATE A SLOPE - JQCALC"
                STOP
        END IF
        FOR I% = 1 TO NFIT%
                X!(I%) = LOG(AZ!(I%))
                Y!(I%) = LOG(JZ!(I%))
        NEXT I%
        CALL SLOPE
        BQ# = EXP(BQ#)
'
' CALCULATE THE JIc VALUE USING A SIMPLE ITERATIVE TECHNIQUE
        AL9# = .5 ' INITIAL GUESSES
        JL9! = 200
ITERATE1:
        FL8! = -BQ# * AL9#   MQ# + SLOPEM! * SFLOW! * (AL9# - .2)
        FL9! = -BQ# * MQ# * AL9#   (MQ# - 1) + SLOPEM! * SFLOW!
        AQ# = AL9# - FL8! / FL9!
        JQ! = BQ# * AQ#   MQ#
        IF ABS((JQ! - JL9!) / JQ!) < .01 THEN GOTO GOTJIC
```

```
        AL9# = AQ#
        JL9! = JQ!
        GOTO ITERATE1
GOTJIC:
' LOOP TO GET DEL A MIN (NEWTON RAPHSON)
'

LOOPDELA:
        DELAX! = AQ#
ENTER1:
        FLN! = -BQ# * DELAX!   MQ# + (SFLOW! * SLOPEM!) * (DELAX! - .15)
        FLD! = -MQ# * BQ# * DELAX!   (MQ# - 1) + (SFLOW! * SLOPEM!)
        DELAMIN! = DELAX! - FLN! / FLD!
        IF (DELAMIN! - DELAX!) / DELAMIN! < .01 THEN GOTO LOOP1END
        DELAX! = DELAMIN!
        GOTO ENTER1
LOOP1END:
' LOOP TO GET DEL A LIM (NEWTON RAPHSON)
        DELMXX! = 2!
ENTER2:
        FLN! = -BQ# * DELMXX!   MQ# + (SFLOW! * SLOPEM!) * (DELMXX! - 1.5)
        FLD! = -MQ# * BQ# * DELMXX!   (MQ# - 1) + (SFLOW! * SLOPEM!)
        DELALIM! = DELMXX! - FLN! / FLD!
        IF (DELALIM! - DELMXX!) / DELALIM! < .01 THEN GOTO LOOP2END
        DELMXX! = DELALIM!
        GOTO ENTER2
LOOP2END:
'
' OUTPUT RESULTS
        PRINT NFIT%, " DATA SETS WERE FOUND IN THE EXCLUSION REGION "
        PRINT #2,
        PRINT
        PRINT " THE FIT COEFFICIENTS ARE: "
        PRINT #2, " THE FIT COEFFICIENTS ARE: "
        PRINT
        PRINT #2,
        PRINT USING "& #.###"; " POWER COEFFICIENT (C2) = "; MQ#
        PRINT #2, USING "& #.###"; " POWER COEFFICIENT (C2) = "; MQ#
        PRINT USING "& ####.#"; " AMPLITUDE COEFFICIENT (C1) = "; BQ#
        PRINT #2, USING "& ####.#"; " AMPLITUDE COEFFICIENT (C1) = "; BQ#
        PRINT USING "& #.####"; " FIT COEFFICIENT ( R) = "; RQ#
        PRINT #2, USING "& #.####"; " FIT COEFFICIENT ( R) = "; RQ#
        PRINT
        PRINT #2,
        PRINT USING "& ####.#"; " JQ = "; JQ!; " kJ/m 2"
        PRINT #2, USING "& ####.#"; " JQ = "; JQ!; " kJ/m 2"
        PRINT USING "& #.###"; " CRACK EXTENSION AT JQ = "; AQ#; " mm"
        PRINT #2, USING "& #.###"; " CRACK EXTENSION AT JQ = "; AQ#; " mm"
        PRINT USING "& ###.##"; " DEL A MIN = "; DELAMIN!; " mm"
        PRINT USING "& ###.##"; " DEL A LIM = "; DELALIM!; " mm"
        PRINT #2, USING "& ###.##"; " DEL A MIN = "; DELAMIN!; " mm"
        PRINT #2, USING "& ###.##"; " DEL A LIM = "; DELALIM!; " mm"
        PRINT
        PRINT #2,
        F9% = 0
END SUB

'
        SUB SLOPE
' SUBROUTINE TO CALCULATE LEAST SQUARES BEST FIT STRAIGHT LINE
'
        DIM B1#(3, 3), X1#(3)
        X1#(1) = 1
        FOR I% = 1 TO 3
                FOR J% = 1 TO 3
                        B1#(I%, J%) = 0
                NEXT J%
        NEXT I%
        FOR K% = 1 TO NFIT%
                X1#(2) = X!(K%)
                X1#(3) = Y!(K%)
                FOR I% = 1 TO 3
                FOR J% = I% TO 3
                 B1#(I%, J%) = B1#(I%, J%) + X1#(I%) * X1#(J%)
                NEXT J%
                NEXT I%
        NEXT K%
        Q1# = (B1#(1, 1) * B1#(2, 2) - B1#(1, 2)   2) / (B1#(1, 1) * (B1#(1, 1) - 1))
        Q2# = (B1#(1, 1) * B1#(3, 3) - B1#(1, 3)   2) / (B1#(1, 1) * (B1#(1, 1) - 1))
        MQ# = (B1#(1, 1) * B1#(2, 3) - B1#(1, 2) * B1#(1, 3)) / (B1#(1, 1) * B1#(2, 2) - B1#(1, 2)   2)
        BQ# = (B1#(1, 3) - MQ# * B1#(1, 2)) / B1#(1, 1)
        RQ# = MQ# * SQR(Q1# / Q2#)
END SUB
```

Appendix B: ASTM Fracture Test Standards E 1737 and E 1290

Designation: E 1737 – 96

Standard Test Method for *J*-Integral Characterization of Fracture Toughness[1]

This standard is issued under the fixed designation E 1737; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of fracture toughness as characterized by the *J*-integral. Three toughness properties are identified which vary with the amount of crack extension present at test termination: (*a*) instability without significant prior crack extension (J_c); (*b*) onset of stable crack extension (J_{Ic}); (*c*) stable crack growth resistance curve (*J-R*).[2] A fourth quantity (J_u) not currently interpretable as a toughness property may be measured at fracture instability following stable crack extension. The method applies specifically to geometries that contain notches and flaws that are sharpened with fatigue cracks. The recommended specimens are generally bend-type specimens that contain deep initial cracks. The loading rate is slow and environmentally assisted cracking is assumed to be negligible.

1.1.1 The recommended specimens are the pin-loaded compact (C(T)), the single, edge bend (SE(B)), and the pin-loaded disk-shaped compact (DC(T)) specimen. All specimens have in-plane dimensions of constant proportionality for all sizes.

1.1.2 Specimen dimensions are functions of the ratio of *J*-integral to the material effective yield strength, thus the specimen design details must be based on known or estimates mechanical properties.

1.1.3 The objective of this test method is to set forth a method and to specify limitations for testing prescribed bend-type specimens that will result in *J*-integral fracture toughness values of materials that will be geometry insensitive.

1.1.4 The single specimen elastic compliance method is detailed herein, but other techniques for measuring crack length are permissible if they equal or exceed the accuracy requirements of this test method. For example, a dc electric potential method is described in Annex A5.

1.1.5 A multiple specimen technique for J_{Ic} measurement requiring five or more identically prepared specimens tested to different crack extensions and displacements is presented in Annex A4.

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Load Verification of Testing Machines[3]

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[3]

E 616 Terminology Relating to Fracture Testing[3]

3. Terminology

3.1 Terminology E 616 is applicable to this test method.

3.2 *Definitions:*

3.2.1 *effective thickness* $B_e[L]$—for compliance-based crack extension measurements $B_e = B - (B - B_N)^2/B$.

3.2.2 *effective yield strength,* $\sigma_Y[FL^{-2}]$—an assumed value of uniaxial yield strength that represents the influence of plastic yielding upon fracture test parameters.

NOTE 1—σ is calculated as the average of the 0.2 % offset yield strength σ_{YS}, and the ultimate tensile strength σ_{TS}, for example:

$$\sigma_Y = \frac{\sigma_{YS} + \sigma_{TS}}{2}$$

NOTE 2—In estimating σ_Y, the influence of testing conditions, such as loading rate and temperature, should be considered.

3.2.3 *estimated crack extension,* $\Delta a[L]$—an increase in estimated crack size ($\Delta a = a - a_{oq}$).

3.2.4 *estimated crack size* $a[L]$—the distance from a reference plane to the observed crack front developed from measurements of elastic compliance or other methods. The reference plane depends on the specimen form, and it is normally taken to be either the boundary, or a plane containing either the load line or the centerline of a specimen or plate. The reference plane is defined prior to specimen deformation.

3.2.5 J_c, $J[FL^{-1}]$—a value of J (the crack extension resistance under conditions of crack-tip plane strain) at fracture instability prior to the onset of significant stable crack extension.

3.2.6 J_{Ic}, $J[FL^{-1}]$—a value of J (the crack extension resistance under conditions of crack tip plane strain) near the onset of stable crack extension as specified in this test method.

3.2.7 J_u, $J[FL^{-1}]$—a value of J measured at fracture instability after the onset of significant stable crack extension. It may be size dependent and a function of test specimen geometry.

3.2.8 *J-integral,* $J[FL^{-1}]$—a mathematical expression, a

[1] This test method is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.08 on Elastic-Plastic Fracture Mechanics Technology.

Current edition approved March 10, 1996. Published May 1996.

[2] Information on *R*-curve round-robin data is available from ASTM as a research report. Request RR: E24-1011.

[3] *Annual Book of ASTM Standards,* Vol 03.01.

line or surface integral over a path that encloses the crack front from one crack surface to the other, used to characterize the local stress-strain field around the crack front. See Terminology E 616 for further discussion.

3.2.9 *J-R curve*—a plot of resistance to stable crack extension, Δa or Δa_p.

DISCUSSION—In this test method, the *J-R* curve is a plot of the far-field *J*-integral versus physical crack extension (Δa_p) or estimated crack extension (Δa). It is recognized that the far-field value of *J* may not represent the stress-strain field local to a growing crack.

3.2.10 *net thickness,* $B_N[L]$—distance between the roots of the side grooves in side-grooved specimens.

3.2.11 *original crack size,* $a_o[L]$—the physical crack size at the start of testing.

NOTE 3—In this test method, a_{oq} is the initial crack length estimated by elastic compliance.

3.2.12 *original uncracked ligament,* $b_o[L]$—distance from the original crack front to the back edge of the specimen, that is:

$$b_o = W - a_o$$

3.2.13 *physical crack extension,* $\Delta a_p[L]$—an increase in physical crack size ($\Delta a_p = a_p - a_o$).

3.2.14 *physical crack size,* $a_p[L]$—the distance from a reference plane to the observed crack front. This distance may represent an average of several measurements along the crack front. The reference plane depends on the specimen form, and it is normally taken to be either the boundary, or a plane containing either the load line or the centerline of a specimen or plate. The reference plane is defined prior to specimen deformation.

3.2.15 *precrack load,* $P_M[F]$—the allowable precrack load.

3.2.16 *remaining ligament,* $b[L]$—distance from the physical crack front to the back edge of the specimen, that is:

$$b = W - a_p$$

3.2.17 *specimen span,* $S[L]$—distance between specimen supports for the SE(B) specimen.

3.2.18 *specimen thickness,* $B[L]$—the side to side dimension of the specimen being tested.

3.2.19 *specimen width,* $W[L]$—a physical dimension on a test specimen measured from a reference position such as the front edge in a bend specimen or the load line in the compact specimen to the back edge of the specimen.

4. Summary of Test Method

4.1 This test method involves three-point bend loading or pin loading of fatigue precracked specimens and determination of J as a function of crack growth. Load versus load-line displacement is recorded. The *J*-integral is determined and plotted against estimated or physical crack growth, Δa or Δa_p, within specified limits of crack growth. The resulting data reflect the material's resistance to crack growth.

4.2 For J_c determination, J is evaluated from a load-displacement record which is terminated by fracture instability prior to significant stable crack extension. The value of J_c determined by this test method represents a measure of fracture toughness at instability without significant stable crack extension that is independent of in-plane dimensions. However, there may be a dependence of toughness on thickness which is equivalent to length of crack front.

4.3 For J_{Ic} determination, the J versus crack growth behavior is approximated with a best fit power law relationship. A construction line is drawn, approximating crack tip stretch effects. The construction line is calculated from material flow properties or determined experimentally. Draw an offset line parallel to the construction line but offset by 0.2 mm. The intersection of this line and the power law fit defines J_{Ic}, provided the requirements of this test method are satisfied.

4.4 For *J-R* curve determination, this test method describes a single specimen technique. The *J-R* curve consists of a plot of J versus crack extension, in the region of *J*-controlled growth, and is size independent provided that the requirements of this test method are satisfied. For the procedure described in this test method, crack length and crack extension are determined from elastic compliance measurements. These measurements are taken on a series of unloading/reloading segments spaced along the load-versus-displacement record. Other methods such as dc electric potential can be used to estimate crack length and crack extension.

4.5 An alternative, multi-specimen technique can be used to obtain J_{Ic}. This technique requires five or more identically prepared specimens tested to different crack opening displacements. This technique uses optical measurements of crack extension on the fracture surfaces after the test.

4.6 Supplemental information about the background of this test method and the rationale for many of the technical requirements of this test method are contained in Ref **(1)**.[4]

5. Significance and Use

5.1 The *J*-integral values measured by this test method characterize the toughness of ductile materials that lack sufficient size and thickness to be tested for K_{Ic} in accordance with the requirements of Test Method E 399.

5.1.1 The *J*-integral values can be used as indexes of material toughness for alloy design, materials processing, materials selection and specification, and quality assurance.

5.1.2 The *J*-integral value for most structural metals is independent of testing speed in the quasi-static regime. The value becomes a function of testing speed in the dynamic regime. Cyclic loads or environmental attack under sustained stress, or both, can cause additional contributions to crack extension. Therefore, the application of *J*-integral values in design of service components should be made with full cognizance of service conditions.

5.1.3 *J*-integral values can be used to evaluate materials in terms that can be significant to design, and for evaluation of materials with flaws.

5.1.4 This test method is applicable for a wide range of ductile engineering materials. However, there are high ductility, high toughness materials for which this test method is not applicable. The prescribed procedure may result in unsatisfactory results when applied to materials with extremely high tearing resistance because crack growth due to physical tearing of the material may be virtually indistin-

[4] The boldface numbers in parentheses refer to the references at the end of this test method.

guishable from extensive crack tip blunting.

5.2 The *J-R* curve characterizes, within the limits set forth in this test method, the resistance of metallic materials to slow stable crack growth after initiation from a pre-existing fatigue crack.

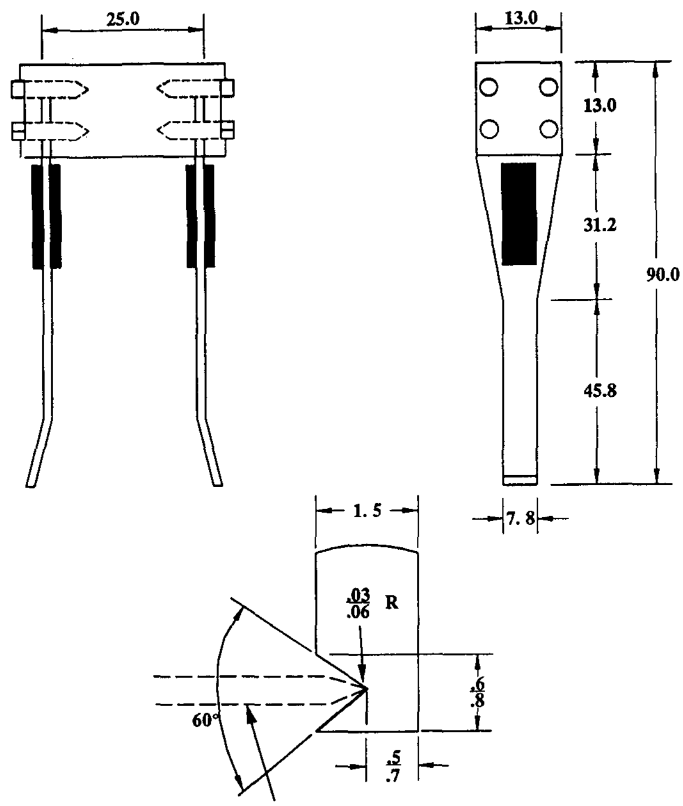
5.2.1 The *J-R* curve can be used to assess the significance of cracks in structural details in the presence of ductile tearing, with awareness of the difference that may exist between laboratory test and field conditions.

5.3 J_{Ic}, as determined by this test method, characterizes the toughness of materials near the onset of stable crack extension from a preexisting fatigue crack.

5.3.1 J_{Ic} and J_c values may be converted to their equivalents in terms of stress-intensity factor, K_I **(2)**, if dominant elastic conditions for the application can be demonstrated. The K_I values from J_{Ic} correspond to the material toughness near the onset of stable crack extension in a dominant linear elastic stress field that contains a preexisting crack. The K_I values from J_c correspond to the material toughness near the onset of unstable crack extension in a dominant linear elastic stress field containing a preexisting crack. The J_{Ic} and J_c values according to this test method cannot be used to obtain K_{Ic} values according to Test Method E 399.

5.4 The value of J_c determined by this test method represents a measure of fracture toughness at instability without significant stable crack extension that is independent of in-plane dimensions. However, there may be a dependence of toughness on thickness, equivalent to a dependence on crack front length.

5.4.1 Values of J_c, may exhibit considerable variability and statistical techniques may be required in their interpretation and application.



NOTE—All dimensions are in millimetres.

FIG. 1 Clip Gage Design for a 8.0-mm (0.3-in.) and More Working Range

6. Apparatus

6.1 Measurements of applied load and load-line displacement are needed to determine the total energy absorbed by the specimen. Load versus load-line displacement may be recorded digitally for processing by computer or autographically with an *x-y* plotter.

6.2 Test fixtures for each specimen type are described in the applicable annex.

6.3 *Displacement Gage:*

6.3.1 Displacement measurements are needed for two purposes: to determine *J* from the measured area under the load-displacement record, and, for the elastic compliance method, to estimate crack extension, Δa, from elastic compliance calculations.

6.3.2 In compact specimens, displacement measurements on the load line are recommended. As a guide, select a displacement gage that has a working range of not more than twice the displacement expected during the test. When the expected displacement is less than 3.75 mm (0.15 in.), the gage recommended in Test Method E 399 may be used. When a greater working range is needed, an enlarged gage such as the one shown in Fig. 1 is recommended. Accuracy shall be within ±1 % of the full working range. In calibration the maximum deviation of the individual data points from a fit to the data shall be less than ±1 %, or ±0.2 % of the working range of the gage when using the elastic compliance method. Knife edges are recommended for friction-free seating of the gage. Maintain parallel alignment of the knife edges within ±1°.

6.3.3 The single edge bend specimen may require two displacement gages. A load-line displacement measurement is required for *J* computation. A crack mouth opening displacement gage may be used to estimate crack size using the elastic compliance technique. The gage shall meet the requirements of 6.3.2. Accuracy of the load-line displacement gage shall be within ±1 % of the full working range. In calibration, the maximum deviation of the individual data points from a fit to the data shall be less than ±1 %, or ±0.2 % of the working range of the gage when using the gage for compliance measurements. Direct methods for load-line displacement measurement are described in Refs **(3—6)**. If a remote transducer is used for load-line displacement measurement, care shall be taken to exclude the elastic displacement of the load train measurement and elastic and inelastic deformations at the load points **(7)**.

6.3.4 For the elastic compliance method, the suggested minimum digital signal resolution for displacement should be one part in 32 000 of the transducer signal range (*V*), and signal stability should be four parts in 32 000 of the transducer signal range (*V*) measured over a 10-min period. Signal noise should be less than two parts in 32 000 of the transducer signal range (*V*).

6.3.5 If an autographic method with expanded scales is used for elastic compliance measurements, displacement signal sensitivity is required which produces approximately

50 mm of pen travel on the displacement scale on each unload/reload sequence. Pen stability is required at the above sensitivity at ±3 mm for a 10-min period.

6.3.6 Gages other than those recommended in 6.3.2 and 6.3.3 are permissible if the required accuracy and precision can be met or exceeded.

6.4 *Load Transducers:*

6.4.1 Testing shall be performed in a testing machine conforming to the requirements of Test Method E 4. Applied load may be measured by any load transducer capable of being recorded continuously. Accuracy of load measurements shall be within ±1 % of the working range. In calibration, the maximum deviation of individual data points from a fit to the data shall be less than ±1 %, or ±0.2 % of the calibrated range of the load transducer when using elastic compliance.

6.4.2 For the elastic compliance method, the suggested minimum digital signal resolution on load should be one part in 4000 of the transducer signal range (V) and the signal stability should be four parts in 4000 of the transducer signal range (V) measured over a 10-min period. Recommended maximum signal noise should be less than two parts in 4000 of the transducer signal range (V).

6.4.3 If an autographic method with expanded scales is used for elastic compliance measurements, the load signal sensitivity which produces at least 100 mm of pen travel on each unloading/reloading sequence is recommended. The required load signal stability at this sensitivity is ±3 mm for a 10-min period.

6.5 Calibration accuracy of displacement transducers shall be verified with due consideration for the temperature and environment of the test. Load calibrations shall be documented periodically in accordance with Practices E 4.

7. Specimen Configurations, Dimensions, and Preparation

7.1 *Specimen Size*—For this test method, the specimen thickness, B, the remaining ligament, b, and the extent of crack growth shall satisfy the requirements of 9.8 and 9.9. In addition, the data shall be qualified by the criteria of 9.7. The initial selection of specimen dimensions can only be based on J values estimated from previous experience. Generally, the greater the ratio of toughness to strength the larger the specimen dimensions required to satisfy the size criteria of this test method.

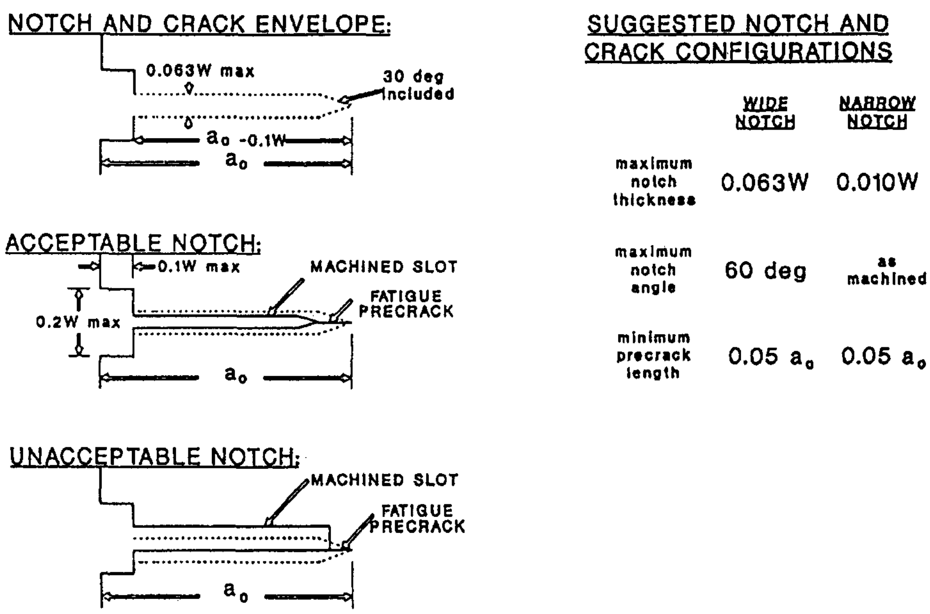
7.2 *Specimen Configurations:*

7.2.1 The standard specimen configurations are shown in annexes: Annex A1, Single Edge Bend Specimen *SE(B)*; Annex A2, Compact Specimen *C(T)*; Annex A3, Disk Shaped Compact Specimen *DC(T)*.

7.2.2 *Standard Specimens*—The initial crack length a_o (starter notch plus fatigue precrack) shall be in the range: $0.45\ W \leq a_o \leq 0.70\ W$. Experience indicates that a value of 0.6 times W is usually optimum for satisfying specimen dimension requirements and test method sensitivity needs. The ratio of width, W, to thickness, B, (W/B) is nominally equal to two.

7.3 The starter notch shall lie within an envelope extending a distance (a_o-0.1W) behind the crack-tip, as shown in Fig. 2. Recommendations for a wide notch and a narrow notch are made in Fig. 2. A wide notch can increase the apparent specimen compliance by 7 % **(8)** causing an error in crack length estimation. To obtain an accurate estimate of crack length from compliance, a narrow notch, such as that produced by electric discharge machining, is suggested. The crack length estimation accuracy of the elastic compliance method can be further improved by precracking beyond the minimum specified in 7.5.2.

7.4 *Side Grooves*—During *J-R* testing, specimens may need side grooves to ensure a straight crack front as specified in 9.7. The total thickness reduction may not exceed 0.25 B. The requirements of 9.7 will usually be met by machining side grooves with an included angle of 45° and a root radius 0.5 ± 0.25 mm (0.02 ± 0.01 in.). Side grooving after precracking will result in nearly straight crack fronts by



NOTE—Crack-starter notch must be centered between top and bottom specimen edges within 0.005 W.

FIG. 2 Envelope of Crack-Starter Notches and Suggested Configurations

removing areas of crack front curvature near the specimen surfaces.

7.5 *Fatigue Precracking:*

7.5.1 All specimens shall be precracked in fatigue at load values based upon the load $P_M[F]$. For *SE(B)* specimens use the following:

$$P_M = \frac{0.5\ \sigma_Y Bb^2}{S}$$

where S = specimen span.

For *C(T)* and *DC(T)* specimens use the following:

$$P_M = \frac{0.4\ \sigma_Y Bb^2}{(2W + a)}$$

The choice of σ_Y shall take into consideration differences in properties at the precracking temperature and the test temperature, in order to minimize yielding the specimen during precracking.

7.5.2 The length of the fatigue pre-crack extension from the machined notch shall not be less than 5 % of the total crack size, a_o, and not less than 1.3 mm (0.05 in.). For the final 50 % of fatigue pre-crack extension or 1.3 mm (0.05 in.), whichever is less, the maximum load shall be no larger than P_M, or a load such that the ratio of the maximum stress intensity applied during fatigue pre-cracking to the elastic modulus (K_{max}/E) is equal to or less than 1.6×10^{-4} $m^{1/2}$ (0.001 $in.^{1/2}$). The accuracy of these maximum load values shall be known within ±5 %. The stress intensity, K_{max}, may be calculated using the formulas for $K_{(i)}$ in the applicable Annex A1 of this test method.

7.5.3 The fatigue pre-cracking is to be done with the material in the same heat-treated condition as that in which it will be fracture tested. No intermediate treatments between fatigue pre-cracking and testing are allowed.

7.5.4 To facilitate fatigue pre-cracking at low stress ratios, the machined notch root radius can be on the order of 0.076 mm (0.003 in.). A chevron form of machined notch, as described in Test Method E 399, may be helpful when control of crack shape is a problem. Alternatively, a reverse loading of a straight-through notch specimen, to a load not to exceed P_M, may result in an acceptable fatigue crack front.

8. Procedure

8.1 *Testing Procedure*—The objective of the procedure described herein is to develop a *J-R* curve, consisting of *J*-integral values at evenly spaced crack extensions, Δa, as shown in Fig. 3. The J_{Ic} can be determined from this resistance curve. If fracture instability occurs prior to the onset of significant ductile crack extension, a J_c can be determined. This procedure describes the single specimen, elastic compliance method. Crosshead or actuator displacement control or displacement gage control shall be used. A multiple specimen test procedure for determination of J_{Ic} is described in Annex A4.

8.1.1 Details of specimen preparation and testing are presented in Annexes A1, A2, or A3, as applicable.

8.2 *Test System Preparation:*

8.2.1 It is recommended that the performance of the load and displacement measuring systems be verified every time the system is brought to test temperature or before beginning a continuous series of tests.

8.2.2 Specimens shall be loaded at a rate such that the time taken to reach the load, P_M, (see 7.6.1) lies between 0.1 and 10.0 min. The rate during unloadings may be as slow as needed to accurately estimate crack length, and shall not exceed the allowable loading rate.

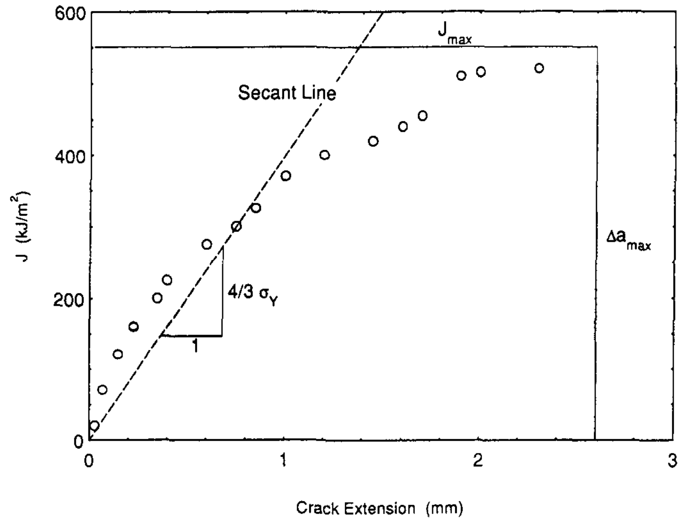


FIG. 3 Typical *J-R* Curve Data

8.2.3 The temperature of the specimen shall be stable and uniform to within ±3°C during the test. The temperature is measured on the specimen surface within a distance of *W*/4 from the crack tip. The determination of an appropriate soaking time shall be the responsibility of those conducting the test.

8.3 *Initial Crack Length Estimation*—For the elastic compliance method, an initial crack length estimate (a_{oq}) shall be determined from compliance measurements repeated at least three times. No individual value shall differ from the mean by more than ±0.002 *W*. The initial crack length determinations from elastic compliance should be carried out in the load range from 0.5 to 1.0 times the maximum final fatigue pre-cracking load.

8.4 *Collection of J-Crack Extension Data:*

8.4.1 The maximum range of unload/reload for crack extension measurement should not exceed the smaller of 0.5 P_M (7.5.1) or 50 % of the current load.

8.4.2 Calculation of Interim *J* and crack extension shall follow the procedures in Annexes A1, A2, or A3, as applicable.

8.4.3 The *J*-integral shall be determined from load, load-line displacement curves. At a given total deflection, the area under the load-displacement curve shall be evaluated with an accuracy of at least ±2 %. Accurate evaluation of *J* from these relationships requires small and uniform crack growth increments consistent with the elastic compliance spacing requirements of 8.4.4 or 8.4.5.

8.4.4 For *J-R* curve determination, crack extension shall be measured in a manner such that the data points are evenly spaced over the prescribed test region. Two *J*-Δa data points are required in the space between the ordinate of the plot and the secant line defined by $J = (4/3)\sigma_Y \Delta a$ (Fig. 3). Eight *J*-Δa data points are required between the secant line and the box defined by the Δa_{max} limit of 9.8.2.2 and J_{max} limit of 9.8.2.1.

8.4.5 If *J-R* curve data from 8.4.4 are to be used to determine J_{Ic}, a minimum of three J versus crack extension data pairs are required between $0.4J_Q$ and J_Q with J_Q as defined by 9.5, and five data pairs are required within the exclusion lines (see 9.9.2 and 9.9.3). To accomplish this, ten or more evenly spaced points over the first 1.5 mm (0.06 in.) of crack extension are recommended.

NOTE 4—Data placement limits previously noted are minimum requirements. Additional data points are recommended to more thoroughly define the *J-R* curve and J_{Ic}.

8.4.6 For many steels, load relaxation may occur prior to conducting compliance measurements causing a time dependent nonlinearity in the unloading slope. This effect may be minimized by holding the specimen at a constant displacement for a time to be determined by the user prior to initiating the unloading.

8.5 *Test Termination:*

8.5.1 If the test is terminated by fracture instability proceed to 8.5.5.

8.5.2 For fully ductile test, after completing the final unloading, the load shall be returned to zero without additional crosshead displacement beyond the then current maximum displacement.

8.5.3 Mark the crack according to one of the following methods. For steels and titanium alloys, heat tinting at about 300°C (570°F) for 30 min works well. For other materials, fatigue cycling can be used. The use of liquid penetrants is not recommended. For both recommended methods, the beginning of stable crack extension is marked by the end of the flat fatigue precracked area. The end of crack extension is marked by the end of heat tint or the beginning of the second flat fatigue area.

8.5.4 The specimen shall be broken to expose the crack, with care taken to minimize additional deformation. It may be helpful to cool ferritic steel specimens enough to ensure brittle behavior. Other materials may also benefit since cooling will reduce deformation.

8.5.5 Along the front of the fatigue crack and the front of the region of slow-stable crack extension, measure the crack size at nine equally spaced points centered on the specimen centerline and extending to 0.005 W from the root of the side groove or surfaces of plane-sided specimens. Calculate the original physical crack size, a_o, and the average physical crack extension, Δa_p, as follows: average the two near-surface measurements, combine the result with the remaining seven crack length measurements, and determine the average. The measuring instrument shall have an accuracy of 0.025 mm (0.001 in.).

8.6 *Alternative Methods:*

8.6.1 Alternative methods of determining crack extension, for example, the electric potential approach of Annex A5, are allowed. These methods shall be used to predict the crack lengths and the results shall meet the qualification requirements given in 9.7.

8.6.2 If displacement measurements are made in a plane other than that containing the load line, the ability to estimate load-line displacement shall be demonstrated using the test material under similar test temperatures and conditions. Estimated load-line displacement values shall be accurate to within ±1 % of the absolute values.

9. Calculation and Interpretation of Results

9.1 *Corrections and Adjustments to Data:*

9.1.1 A correction is applied to the estimated a_i data values to obtain an improved a_{oq}. This correction is intended to obtain the best value of a_{oq} based on the initial set of crack length estimates, a_i, data.

9.1.2 A modified construction line slope, M, can be calculated from a fit to the initial J_i and a_i data, and used for the calculation of J_{Ic}.

9.2 *Adjustment of a_{oq}:*

9.2.1 The value of J_Q is very dependent on the a_{oq} used to calculate the Δa_i quantities. The value obtained for a_{oq} in 8.3.1 might not be the correct value and the following adjustment procedure is required.

9.2.2 Identify all J_i and a_i pairs for which the load at the start of the unloading exceeded P_M and with $a_i \leq a_{min} + 2.5$ mm, where a_{min} is the smallest estimated crack length that meets the P_M requirement. Use this data to calculate a revised a_{oq} from the following equation:

$$a = a_{oq} + \frac{J}{2\sigma_Y} + BJ^2 + CJ^3$$

The coefficients of this equation shall be found using a least squares fit procedure. Example BASIC code to accomplish this fit is presented in Appendix X1.

9.2.3 If the number of data points of 9.2.2 is less than eight or the correlation of this fit is <0.96, the data set is not adequate to evaluate any toughness measures according to this test method.

9.3 If the optically measured crack length, a_o, differs from a_{oq} by more than 0.01 W, the data set is not adequate according to this test method.

9.4 Evaluate the final J_i values using the adjusted a_{oq} of 9.2 and the equations of the applicable ANNEX A1, A2, or A3.

9.5 *Calculation of an Interim J_Q:*

9.5.1 For each a_i value, calculate a corresponding Δa_i as follows:

$$\Delta a_i = a_i - a_{oq}$$

Plot J versus Δa as shown in Fig. 4. Determine a construction line in accordance with the following equation:

$$J = M\sigma_Y\Delta a$$

where the value of M is either taken as 2 or determined from the test data. In some cases the initial slope of the *J-R* curve is steeper than $2\sigma_Y$. For these materials, it is recommended that a J_Q value be determined using $M = 2$ such that an experimental M can then be evaluated and verified according to 9.6. An improved J_Q can then be evaluated. Under no circumstances can a value of M less than 2 be used for J_Q evaluation.

9.5.2 Plot the construction line, then draw an exclusion line parallel to the construction line intersecting the abscissa at 0.15 mm (0.006 in.). Draw a second exclusion line parallel to the construction line intersecting the abscissa at 1.5 mm (0.06 in.). Plot all J-Δa data points that fall inside the area enclosed by these two parallel lines and capped by $J_{limit} = b_o\sigma_Y/15$.

9.5.3 Plot an offset line parallel to the construction and exclusion lines at an offset value of 0.2 mm (0.008 in.).

9.5.4 At least one J-Δa point shall lie between the 0.15-

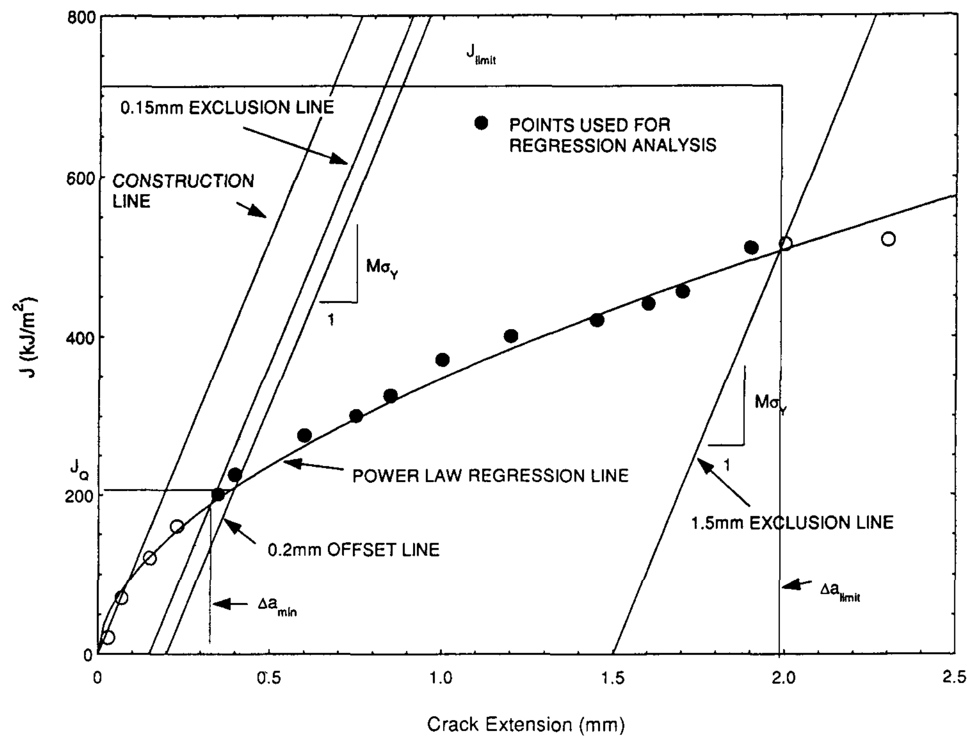


FIG. 4 Definitions for Data Qualification

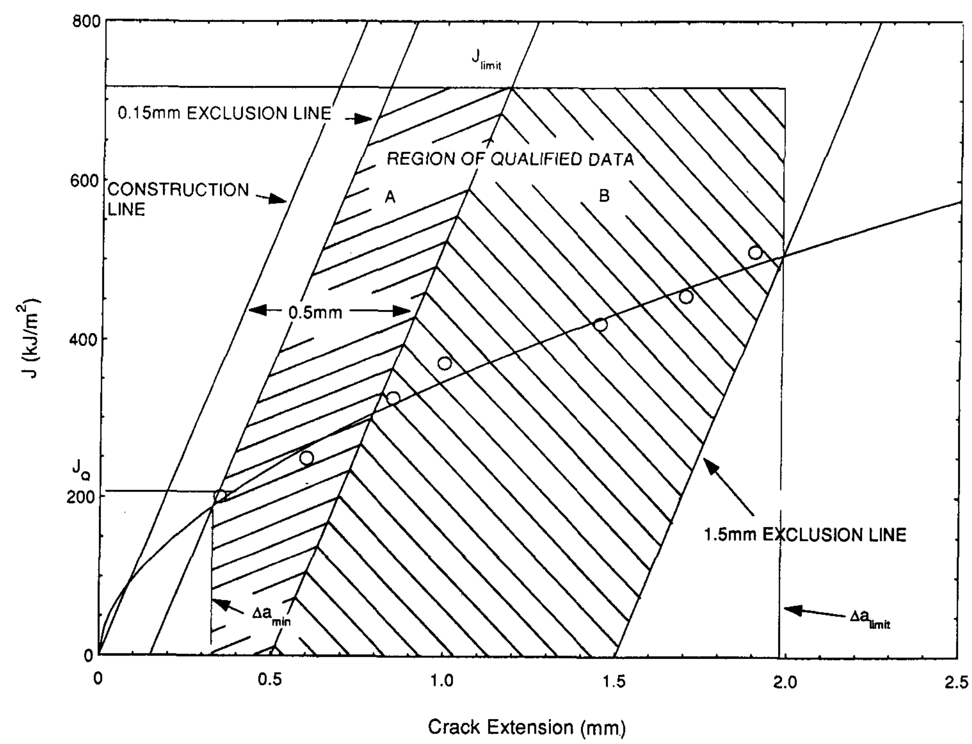


FIG. 5 Definition of Regions of Qualified Data

mm (0.006-in.) exclusion line and a parallel line with an offset of 0.5 mm (0.02 in.) from the construction line as shown in Fig. 5. At least one J-Δa point shall lie between the 0.5-mm offset line and the 1.5-mm (0.06-in.) exclusion line. Acceptable data are shown in Fig. 5. The other J-Δa pairs can be anywhere inside the exclusion zone.

9.5.5 Using the method of least squares determine a linear regression line of the following form:

$$lnJ = lnC_1 + C_2 ln\left(\frac{\Delta a}{k}\right)$$

where $k = 1.0$ mm or 0.0394 in. Use only the data which conform to the requirements stated in the previous sections. Draw the regression line as illustrated in Fig. 4.

9.5.6 The intersection of the regression line of 9.5.5 with the 0.2-mm offset line defines J_Q and Δa_Q. To determine this intersection the following procedure is recommended.

9.5.6.1 As a starting point estimate an interim $J_{Q(1)} = J_{Q(i)}$ value from the data plot of Fig. 4.

9.5.6.2 Evaluate $\Delta a_{(i)}$ from the following:

$$\Delta a_{(i)} = \frac{J_{Q(i)}}{M\sigma_Y} + 0.2 \text{ mm (0.008 in.)}$$

9.5.6.3 Evaluate an interim $J_{Q(i+1)}$ from the power law relationship as follows:

$$J_{Q(i+1)} = C_1 \left(\frac{\Delta a_{(i)}}{k}\right)^{C_2}$$

where $k = 1.0$ mm or 0.0394 in.

9.5.6.4 Increment i and return to 9.5.6.2 and 9.5.6.3 to get $\Delta a_{(i)}$ and interim $J_{Q(i+1)}$ until the interim J_Q values converge to within ±2 %.

9.6 An alternative construction line slope, M, can be calculated by fitting the least squares linear regression line to the initial *J-R* curve data for data in the region $0.2J_Q \leq J_i \leq 0.6J_Q$ as evaluated with $M = 2$. A minimum of six data points are required in the evaluation region to allow an experimental value of M. Only values of $M \geq 2$ are allowed by this test method. A revised J_Q can now be evaluated using this M by returning to 9.2 to 9.4.

9.7 *Qualification of Data*—The data shall satisfy all of the following requirements to be qualified according to this test method. If the data do not pass these requirements no fracture toughness values can be determined according to this test method.

9.7.1 All the test equipment requirements of Section 6 shall be met, along with the specimen tolerance and fatigue pre-cracking requirements of Section 7. The requirements on fixture alignment, test rate, and temperature stability, and accuracy specified in Section 8 and in the related annexes shall also be met.

9.7.2 *Original Crack Size*—None of the nine physical measurements shall differ by more than 5 % from the average defined in 8.5.5.

9.7.3 *Final Crack Size*—None of the nine physical measurements of final physical crack size, a_p, shall differ by more than 5 % from the average defined in 8.5.5. In subsequent tests, the side groove configuration may be modified within the requirements of 7.4 to facilitate meeting this requirement.

9.7.4 *Crack Extension*—None of the nine physical measurements of crack extension shall be less than 50 % of the average Δa_p.

9.7.5 *Crack Extension Prediction*—The crack extension predicted from elastic compliance (or other method) at the last unloading shall be compared with the measured physical crack extension. The difference between these shall not exceed 0.15 Δa_p for crack extensions less than $0.2b_o$, and the difference shall not exceed $0.03b_o$ thereafter.

9.7.6 The a_{oq} shall not differ from a_o by more than $0.01W$.

9.7.7 The number of points in the data set used to calculate a_{oq} shall be ≥8 and the correlation of the least squares fit of 9.2.1 shall be greater than 0.96.

9.7.8 If an experimental value of M is determined, at least six data points are required in the region $0.2J_Q \leq J_i \leq 0.6J_Q$. Only $M \geq 2.0$ can be used in this test method.

9.7.9 The power coefficient C_2 of 9.5.5 shall be less than 1.0.

9.8 *Qualifying the J-R Curve:*

9.8.1 The data shall meet the requirements of 9.7 to qualify as a *J-R* curve according to this test method.

9.8.2 The *J*-integral values and the corresponding crack extensions, calculated with the new a_{oq} value, shall be plotted as shown in Fig. 4. The *J-R* curve shall be defined by the data in a region bounded by the coordinate axes and the J_{max} and Δa_{max} limits specified in 9.8.2.1 and 9.8.2.2. Data spacing shall meet the requirements of 8.4.4.

9.8.2.1 To obtain *J-R* curves that are independent of specimen dimensions, *J* values shall not be used that exceed the smallest J_{max} defined by the following two dimensional limitations:

$$J_{max} = \frac{b_o\sigma_Y}{20}$$

or

$$J_{max} = \frac{B\sigma_Y}{20}$$

NOTE 5—If the available material has insufficient thickness, B, such that the latter of the two J_{max} requirements cannot be satisfied, a credible *J-R* curve can be developed using the remaining ligament, b, limitation only. The resulting *J-R* curve is usable, but is specific to the thickness tested.

9.8.2.2 The maximum crack extension capacity for a specimen is given by:

$$\Delta a_{max} = 0.1b_o.$$

Crack extension values that exceed Δa_{max} shall not be used.

NOTE 6—The status of current technology sets the limits for crack extension. However, measurement of *J-R* curves with crack extension beyond the limits for this test method as set forth in 9.8.2.2 is encouraged. Crack extension prediction accuracy requirements set forth in 9.7.5 shall be adhered to.

9.9 *Qualifying J_Q as J_{Ic}:*

9.9.1 The data shall meet the requirements of 9.7 to qualify J_Q as J_{Ic} according to this test method. Spacing of J versus crack extension data shall be in accordance with the requirements of 8.4.5.

9.9.2 Project the intercepts of the power law curve with the 0.15-mm (0.006-in.) and the 1.5-mm (0.06-in.) exclusion lines vertically down to the abscissa. This indicates Δa_{min} and Δa_{limit}, respectively. Eliminate all data points that fall outside of Δa_{min} and Δa_{limit} as shown in Fig. 5. Also eliminate all data points which lie above the J_{limit} where $J_{limit} = b_o\sigma_Y/15$. The region of qualified data is shown in Fig. 5.

9.9.3 At least five data points shall remain between Δa_{min} and Δa_{limit} and the J_{limit}. Data point spacing shall meet the requirements of 9.5.4. If these data points are different than those used in 9.5, evaluate J_Q, return to 9.5, and obtain a new value of J_Q based only on qualified data.

9.9.4 $J_Q = J_{Ic}$ if:

9.9.4.1 Thickness $B > 25\ J_Q/\sigma_Y$,

9.9.4.2 Initial ligament, $b_o > 25\ J_Q/\sigma_Y$,

9.9.4.3 The slope of the power law regression line, dJ/da, evaluated at Δa_Q is less than σ_Y,

9.10 *Qualifying J_{Qc} as J_c:*

9.10.1 When fracture occurs before significant stable tearing, a size independent single point fracture toughness value, J_c, may be obtained. However, there may be a dependence of toughness on thickness, equivalent to a dependence on crack front length.

9.10.2 The J_{Qc} is calculated at the point of fracture instability using the J formulae in Annexes A1, A2, or A3.

9.10.3 The data shall meet the requirements of 9.7.1 and 9.7.2 to qualify J_{Qc} as J_c according to this test method.

9.10.4 $J_{Qc} = J_c$ if the following conditions are met:

9.10.4.1 B, a_o, $b_o > 200\ J_{Qc}/\sigma_Y$;

9.10.4.2 Crack extension $\Delta a_p < 0.2$ mm (0.008 in.) + $J_{Qc}/M\sigma_Y$.

9.10.4.3 The K_{max} (during the final 50 % of fatigue pre-cracking) $< 0.6(J_{Qc}E)^{1/2}$.

9.11 When fracture instability occurs after significant stable tearing where crack extension $\Delta a_p > 0.2$ mm (0.008 in.) + $J_{Qc}/M\sigma_Y$ and the data are qualified according to 9.7.1 and 9.7.2, a single-point fracture toughness value, $J_u = J_{Qc}$, is obtained. The J_u may be size dependent, a function of test specimen geometry, or both.

10. Report

10.1 Report the following information for each test:

10.1.1 Material yield strength and tensile strength at room temperature,

10.1.2 Test temperature,

10.1.3 Material yield strength and tensile strength at the test temperature and elastic modulus used for calculations,

10.1.4 Crack plane orientation according to Terminology E 616 identification codes.

10.1.5 Specimen thickness, B, and net thickness, B_N.

10.1.6 Specimen width, W.

10.1.7 Specimen initial uncracked ligament size, b_o.

10.1.8 Maximum load used in fatigue pre-cracking for the last increment of crack growth.

10.1.9 Fatigue precracking conditions in terms of maximum stress intensity, K_{max} for the final increment of crack growth.

10.1.10 Original crack size, a_o, from nine-point measurement.

10.1.11 Maximum deviation of a single original crack size measurement from the average value.

10.1.12 Physical crack extension, Δa_p, from nine-point measurement.

10.1.13 Fracture surface and crack front appearance in the stable crack growth regime.

10.1.14 Load displacement record and associated calculations.

10.1.15 Report J_i, a_i, and Δa_i results and a_{oq}, and

10.1.16 For cases of estimated displacement measurement, describe measurements, and any corrections or extrapolations employed.

10.2 *Information Required for J_{Ic} Calculation:*

10.2.1 Report J_{Ic},

10.2.2 Report coefficients of power law regression line, and

10.2.3 Report M.

10.3 *Information Required for J_c or J_u Calculation:*

10.3.1 Report J_c or J_u,

10.3.2 Amount of ductile crack extension measured on specimen fracture surface, and

10.3.3 Report the value of 0.2 mm (0.008 in.) + $J_{Qc}/M\sigma_Y$.

11. Precision and Bias

11.1 *Precision:*

11.1.1 The precision of J versus crack growth is a function of material variability, the precision of the various measurements of linear dimensions of the specimen and testing fixtures, precision of the displacement measurement, precision of the load measurement, as well as the precision of the recording devices used to produce the load-displacement record used in calculating J and crack length. The required load and displacement accuracy, linearity, and digital signal resolution of 6.3 and 6.4 are readily obtainable with modern test equipment. The variation in areas under the load-displacement curve used for J-calculations resulting from these requirements is ±2 %. However, in general the crack length measurement makes a more significant contribution to the variation in the J-R curve although this is difficult to isolate as it is coupled to the analysis procedure and measurement of elastic compliance slopes. These considerations form the basis for the recommended requirements for physical crack straightness of 9.7.2 and 9.7.3, crack extension straightness of 9.7.4, and the final crack length prediction accuracy requirement of 9.7.5. The maximum allowable error in final crack growth prediction is intended to produce a predicted crack growth within ±15 % of the real growth at each measurement point on the J-R curve.

11.1.2 Although it is impossible to separate the contributions from each of the proceding sources of variability, an overall measure of variability in J versus crack extension is available from the results of an interlaboratory test program in which 19 laboratories participated **(9, 10)**. These data, obtained on a homogeneous 5 Ni steel, showed maximum deviation of J values of 10 % for all compact specimens tested, and a maximum deviation of R-curve slope approaching 22 % for all compact specimen results. For compact specimen tests which comprised the majority of the results, estimation of initial and final crack length, with one exception, were within 10 % of the physical post test measurements. Single edge bend results were limited and statistical analysis of six specimens from three laboratories was conducted **(9, 10)**.

11.1.3 Although it is impossible to separate the contributions from each of the preceding sources of variability, an overall measure of variability in J_{Ic} is available from the results of an interlaboratory test program **(11)**.

11.1.4 The precision of J_c is equivalent to any single J measurement, that is, within ±2 %. Since very limited crack extension is allowed before a J_c evaluation, crack extension measurement error does not contribute to measurement error of J_c.

11.2 *Bias*—There is no accepted standard value for J_{Ic}, J_c, or J versus crack extension for any material. In the absence of such a true value, no meaningful statement can be made concerning bias of data.

12. Keywords

12.1 crack initiation; ductile fracture; elastic-plastic fracture toughness; J-integral; resistance curve; stable crack growth

ANNEXES

(Mandatory Information)

A1. SPECIAL REQUIREMENTS FOR TESTING SINGLE-EDGE BEND (SE(B)) SPECIMENS

A1.1 *Specimen:*

A1.1.1 The standard bend specimen is a beam with a fatigue-cracked, single-edge notch loaded in three-point bending with a support span, S, nominally equal to four times the width, W. The general proportions of the specimen configuration are shown in Fig. A1.1.

A1.1.2 Alternative specimens may have $1 \le W/B \le 4$. These specimens shall also have a nominal support span equal to $4W$.

A1.2 *Specimen Preparation:*

A1.2.1 For generally applicable specifications concerning specimen size and preparation see Section 7.

A1.2.2 It is recommended that bend specimens be pre-cracked using three-point bend loading. If the bend specimens are pre-cracked in cantilever bending, the applied load should not exceed 0.5 P_M for the bend specimen as given in 7.5.1.

A1.3 *Apparatus:*

A1.3.1 *Bend Test Fixture*—The general principles of the bend test fixture are illustrated in Fig. A1.2. This fixture is designed to minimize frictional effects by allowing the support rollers to rotate and move apart slightly as the specimen is loaded, thus permitting rolling contact. Thus, the support rollers are allowed limited motion along plane surfaces parallel to the notched side of the specimen, but are initially positively positioned against stops that set the span length and are held in place by low-tension springs (such as rubber bands). Fixtures and rolls shall be made of high hardness (greater than 40 HRC) steels.

A1.3.2 *Displacement Gage*—For generally applicable details concerning the displacement gage see 6.3.

A1.4 *Procedure:*

A1.4.1 *Measurement*—The dimensions B_N, B, and W shall be measured to the nearest 0.050 mm (0.002 in.) or 0.5 %, whichever is larger.

A1.4.2 *Bend Testing*—Set up the bend test fixture so that the line of action of the applied load passes midway between the support roll centers within ±1 % of the distance between the centers. Measure the span to within ±0.5 % of the nominal length. Locate the specimen so that the crack tip is midway between the rolls to within ±1 % of the span, and square the roll axes within ±2°.

A1.4.3 When the load-line displacement measurement is referenced from the loading jig there is potential for introduction of error from two sources, the elastic compression of the fixture as the load increases and indentation of the specimen at the loading points. If a remote transducer is used for load-line displacement measurement, care shall be taken to exclude the elastic displacement of the load train measurement and elastic and inelastic deformations at the load points.

A1.5 *Calculations:*

A1.5.1 Calculations of J-integral are made from load, load-point displacement curves obtained using the procedure outlined in Section 8.

A1.5.2 For the SE(B) specimen—Calculate J as follows:

$$J = J_{el} + J_{pl} \tag{A1.1}$$

where:

J_{el} = elastic component of J, and

J_{pl} = plastic component of J.

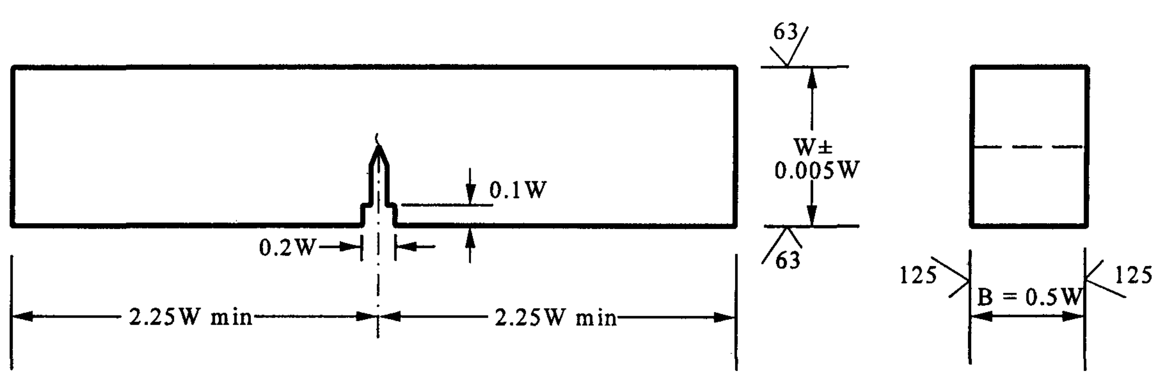
A1.5.3 For the SE(B) specimen at a point corresponding to V_i and P_i on the specimen load versus load-line displacement record as follows:

$$J_{(i)} = \frac{(K_{(i)})^2\,(1 - \nu^2)}{E} + J_{pl(i)} \tag{A1.2}$$

where:

$$K_{(i)} = \left[\frac{P_i S}{(BB_N)^{1/2} W^{3/2}}\right] f(a_i/W) \tag{A1.3}$$

with:



NOTE 1—The two side planes and the two edge planes shall be parallel and perpendicular as applicable to within 0.5°.

NOTE 2—The machined notch shall be perpendicular to specimen length and thickness to within ±2°.

NOTE 3—See Fig. 2.

FIG. A1.1 Recommended SE(B) Specimen

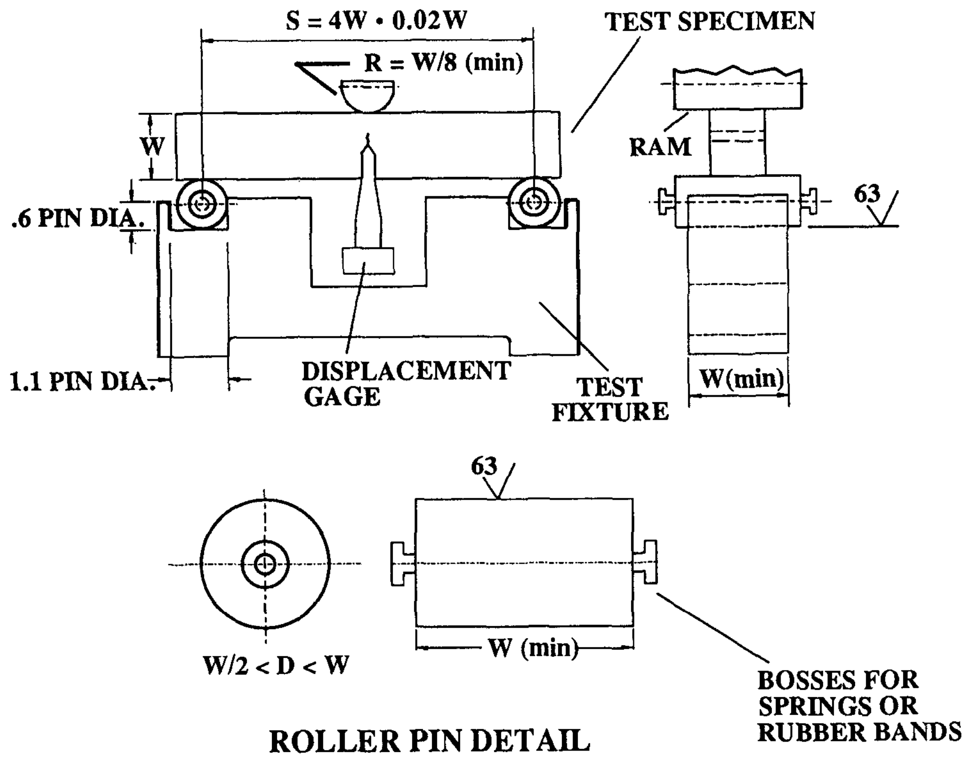


FIG. A1.2 Fixture for SE(B) Specimen Testing

$$f(a_i/W)=\frac{3(a_i/W)^{1/2}\,[1.99-(a_i/W)\,(1-a_i/W)\times(2.15-3.93\,(a_i/W)+2.7\,(a_i/W)^2)]}{2(1+2a_i/W)\,(1-a_i/W)^{3/2}} \quad \text{(A1.4)}$$

and:

$$J_{pl(i)}=\left[J_{pl(i-1)}+\left(\frac{2}{b_{(i-1)}}\right)\left(\frac{A_{pl(i)}-A_{pl(i-1)}}{B_N}\right)\right]\left[1-\frac{a_{(i)}-a_{(i-1)}}{b_{(i-1)}}\right] \quad \text{(A1.5)}$$

In Eq A1.5, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the load versus load-line displacement record between lines of constant displacement at points *i*-1 and *i*, as shown in Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic *J* at point *i* and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the above relationship requires small and uniform crack growth increments consistent with the suggested data spacing of 8.4.4. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)}=A_{pl(i-1)}+[P_{(i)}+P_{(i-1)}]\,[V_{pl(i)}-V_{pl(i-1)}]/2 \quad \text{(A1.6)}$$

where:

$V_{pl(i)}$ = plastic part of the load-line displacement = $V_{(i)} - (P_i C_{LL(i)})$

$C_{LL(i)}$ = slope $(\Delta V/\Delta P)_i$ required to give the current crack length, a_i.

$C_{LL(i)}$ can be determined from knowledge of a_i/W using the following equation:

$$C_{LL(i)}=\frac{1}{E'B_e}\left(\frac{S}{W-a_i}\right)^2\{[1.193-1.98(a_i/W)+4.478\,(a_i/W)^2-4.443\,(a_i/W)^3+1.739\,(a_i/W)^4]\} \quad \text{(A1.7)}$$

A1.5.4 For SE(B) specimens where the span to width ratio is four with crack mouth opening displacements measured at the notched edge, the crack length is:

$$a_i/W=0.999748-3.9504\,U_x+2.9821\,U_x^2-3.21408\,U_x^3+51.51564\,U_x^4-113.031\,U_x^5 \quad \text{(A1.8)}$$

where:

$$U_x=\frac{1}{\left[\frac{B_eWE'C_i}{S/4}\right]^{1/2}+1} \quad \text{(A1.9)}$$

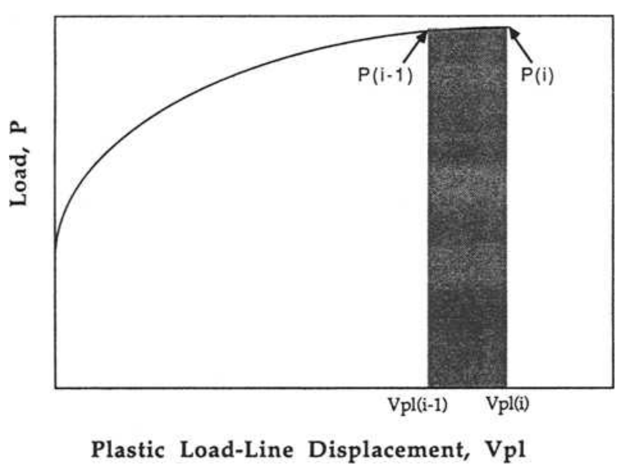


FIG. A1.3 Definition of Plastic Area for Resistance Curve J Calculation

C_i = specimen crack mouth opening elastic compliance $(\Delta V_m/\Delta P)_i$ on an loading/reloading sequence,
V_m = crack mouth opening displacement at notched edge,
ΔV_m = increment of crack mouth opening displacement,
E' = $E/(1 - \nu^2)$.

A1.5.5 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

A2. SPECIAL REQUIREMENTS FOR TESTING COMPACT (C(T)) SPECIMENS

A2.1 *Specimen:*

A2.1.1 The standard compact specimen is a single-edge notched and fatigue-cracked plate loaded in tension. Two specimen geometries which have been used successfully are shown in Fig. A2.1.

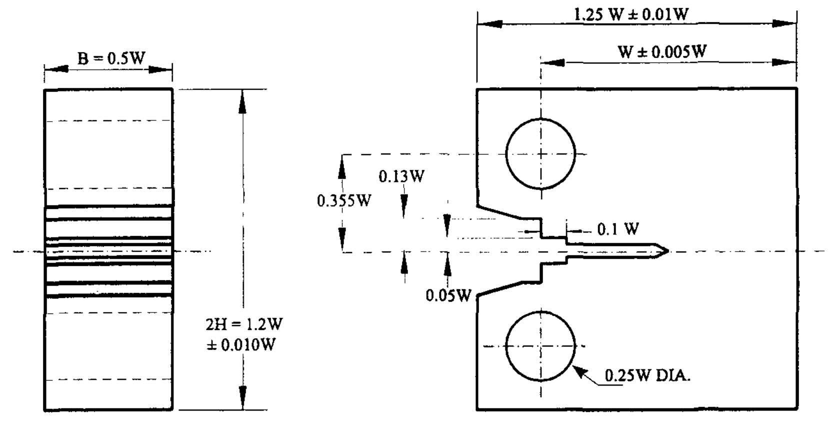
A2.1.2 Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions.

A2.2 *Specimen Preparation*—For generally applicable specifications concerning specimen size and preparation see Section 7.

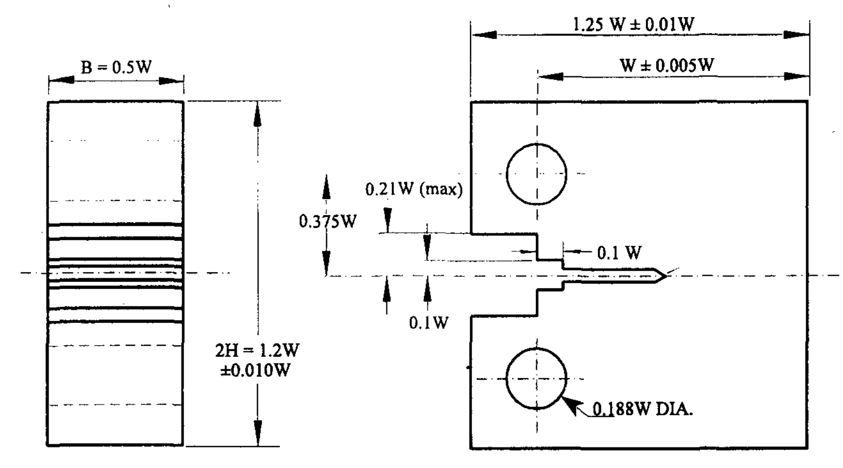
A2.3 *Apparatus:*

A2.3.1 *Tension Testing Clevis:*

A2.3.1.1 A loading clevis suitable for testing compact specimens is shown in Fig. A2.2. Both ends of the specimen



COMPACT TEST SPECIMEN FOR PIN OF 0.24W (+0.000W/-0.005W) DIAMETER



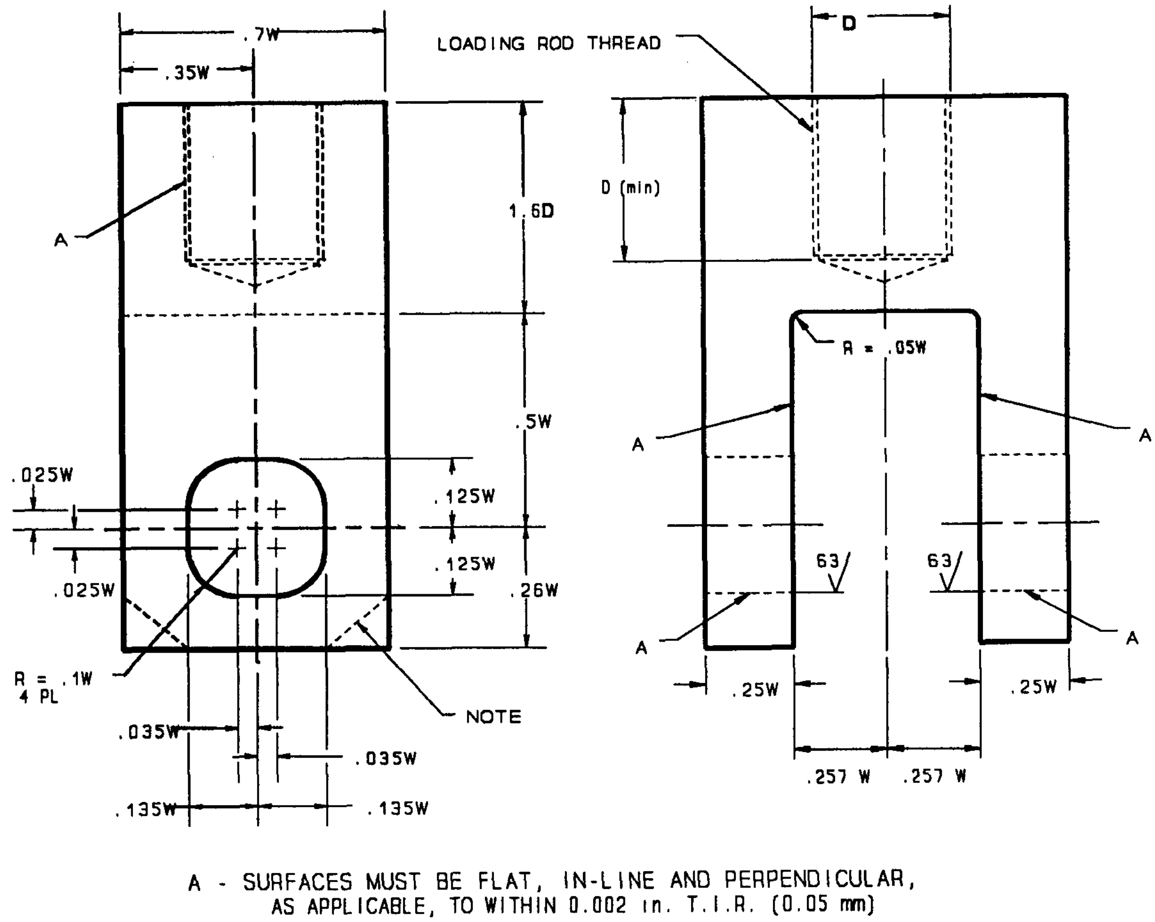
COMPACT TEST SPECIMEN FOR PIN OF 0.1875W(+0.000W/-0.001W)DIAMETER

NOTE 1—A surface shall be perpendicular and parallel as applicable within 0.002 TIR.

NOTE 2—The intersection of the crack starter notch tips on each surface of the specimen shall be equally distant within 0.005 *W* from the centerline of the loading holes.

NOTE 3—See Fig. 2.

FIG. A2.1 Two Compact Specimen Designs That Have Been Used Successfully



NOTE—Corners may be removed as necessary to accommodate the clip page.

FIG. A2.2 Clevis for C(T) Specimen Testing

are held in such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. In order to provide rolling contact between the loading pins and the clevis holes, these holes are provided with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown. Clevises and pins should be fabricated from steels of sufficient strength (greater than 40 HRC) to elastically resist indentation loads.

A2.3.1.2 The critical tolerances and suggested proportions of the clevis and pins are given in Fig. A2.2. These proportions are based on specimens having $W/B = 2$ for $B \geq 12.7$ mm (0.5 in.) and $W/B = 4$ for $B < 12.7$ mm. If a 1930-MPa (280 000-psi) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained. If lower-strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio, then heavier grips will be required. As indicated in Fig. A2.2, the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 9.5 mm (0.375 in.) thick.

A2.3.1.3 Careful attention should be given to achieving good alignment through careful machining of all auxiliary gripping fixtures.

A2.3.2 *Displacement Gage*—For generally applicable details concerning the displacement gage see 6.3.

A2.4 *Procedure:*

A2.4.1 *Measurement*—Measure the dimensions, B_N, B, and W to the nearest 0.05 mm (0.002 in.) or 0.5 %, whichever is larger.

A2.4.2 Loading pin friction and eccentricity of loading can lead to errors in J determinations. Keep the centerline of the upper and lower loading rods coincident within 0.76 mm (0.03 in.) during the test. Center the specimen with respect to the clevis opening within 0.76 mm. Seat the displacement gage in the knife edges firmly by wiggling the gage lightly.

A2.5 *Calculation:*

A2.5.1 Calculations of J-integral are made from load, load-point displacement curves obtained using the procedure outlined in Section 8.

A2.5.2 Calculate J as follows:

$$J = J_{el} + J_{pl} \quad \text{(A2.1)}$$

where:

J_{el} = elastic component of J, and

J_{pl} = plastic component of J.

A2.5.3 At a point corresponding to V_i, P_i on the specimen load versus load-line displacement record as follows:

$$J_{(i)} = \frac{(K_{(i)})^2 (1 - \nu^2)}{E} + J_{pl(i)} \quad \text{(A2.2)}$$

where:

$$K_{(i)} = \left[\frac{P_i}{(BB_N W)^{1/2}}\right] f(a_i/W) \quad (A2.3)$$

with:

$$f(a_i/W) = \frac{[(2 + a_i/W)(0.886 + 4.64(a_i/W) - 13.32(a_i/W)^2 + 14.72(a_i/W)^3 - 5.6(a_i/W)^4)]}{(1 - a_i/W)^{3/2}} \quad (A2.4)$$

and:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{(i-1)}}{b_{(i-1)}}\right)\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right]\left[1 - \gamma_{(i-1)}\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right] \quad (A2.5)$$

where:

$\eta_{(i-1)} = 2.0 + 0.522\, b_{(i-1)}/W$, and

$\gamma_{(i-1)} = 1.0 + 0.76\, b_{(i-1)}/W$.

A2.5.4 In Eq A2.5, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the load versus load-line displacement record between lines of constant displacement at points $i-1$ and i, see Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack-growth-corrected plastic J at point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the relationship in A2.5 requires small and uniform crack growth increments consistent with the data spacing requirements of 8.4.4. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + \frac{[P_{(i)} + P_{(i-1)}][V_{pl(i)} - V_{pl(i-1)}]}{2} \quad (A2.6)$$

where:

$V_{pl(i)}$ = plastic part of the load-line displacement = $V_i - (P_i C_{ci})$, and

C_{ci} = corrected compliance (see A2.5.5) required to give the current crack length, a_i.

For test methods that do not utilize the elastic compliance techniques, C_i can be determined from knowledge of a_i/W using the following equation:

$$C_i = \frac{1}{E'B_e}\left(\frac{W + a_i}{W - a_i}\right)^2 [2.1630 + 12.219(a_i/W) - 20.065(a_i/W)^2 - 0.9925(a_i/W)^3 + 20.609(a_i/W)^4 - 9.9314(a_i/W)^5] \quad (A2.7)$$

A2.5.5 For C(T) specimens, the crack length is given by:

$$a_i/W = 1.000196 - 4.06319\, U_x + 11.242\, U_x^2 - 106.043\, U_x^3 + 464.335\, U_x^4 - 650.677\, U_x^5 \quad (A2.8)$$

where:

$$U_x = \frac{1}{[B_e E' C_{ci}]^{1/2} + 1} \quad (A2.9)$$

where:

$E' = E/(1 - \nu^2)$,

C_{ci} = corrected specimen crack opening compliance on an unloading/reloading sequence,

$$C_{ci} = \frac{C_i}{\left[\frac{H^*}{R}\sin\theta - \cos\theta\right]\left[\frac{D}{R}\sin\theta - \cos\theta\right]} \quad (A2.10)$$

and (Fig. A2.3):

C_i = measured specimen elastic compliance (at the load line),

H^* = initial half-span of the load points (center of pin holes),

R = radius of rotation of the crack centerline, $(W + a)/2$ where a is the updated crack length,

D = one-half of the initial distance between the displacement measurement points,

θ = angle of rotation of a rigid body element about the unbroken midsection line, or

$\theta = \sin^{-1}[(d_m/2 + D)/(D^2 + R^2)^{1/2}] - \tan^{-1}(D/R)$, and

d_m = total measured load-line displacement.

A2.5.6 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

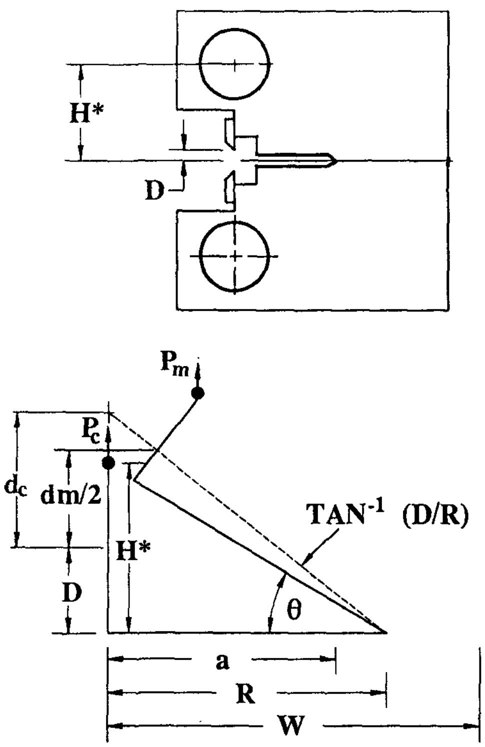


FIG. A2.3 Elastic Compliance Correction for Specimen Rotation

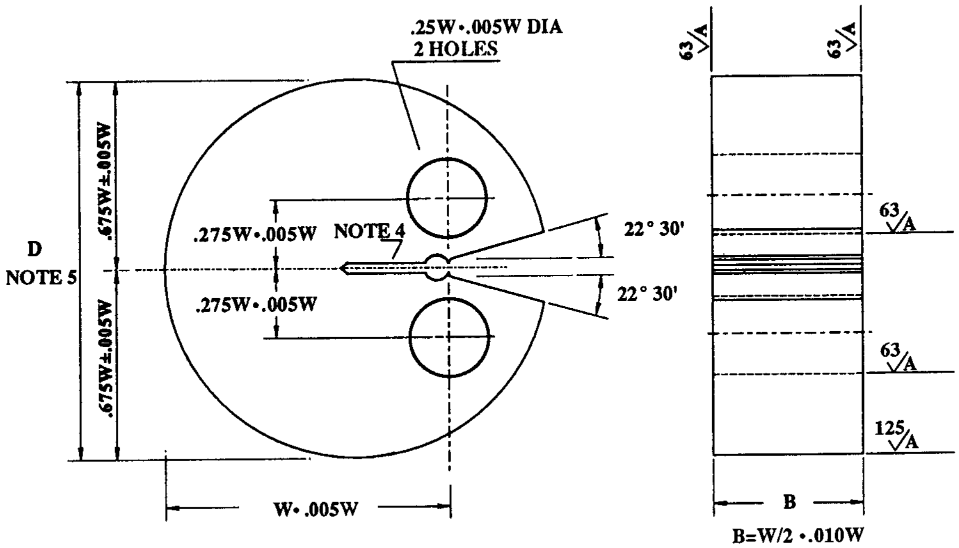
A3. SPECIAL REQUIREMENTS FOR TESTING DISK-SHAPED COMPACT (DC(T)) SPECIMENS

A3.1 *Specimen:*

A3.1.1 The standard disk-shaped compact specimen, DC(T), is a single-edge notched and fatigue-cracked plate loaded in tension **(11)**. A specimen geometry which has been used successfully is shown in Fig. A3.1.

A3.1.2 Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions.

A3.2 *Specimen Preparation:*



NOTE 1—A surface shall be perpendicular and parallel as applicable within 0.002 *W* TIR.

NOTE 2—The intersection of the crack starter notch tips on each surface of the specimen shall be equally distant within 0.005 *W* from the centerline of the loading holes.

NOTE 3—Integral or attached knife edges for clip gage attachment to the crack mouth may be used.

NOTE 4—For starter notch and fatigue crack configuration see Fig. 2.

NOTE 5—Circularity requirements measure radius at eight equally spaced points around the circumference. One of these points shall be the notch plane. Average readings to obtain radius. All values shall be within 5 % of the average.

FIG. A3.1 Disk-Shaped Compact Specimen *DC(T)* Standard Proportions and Tolerances

A3.2.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A3.3 *Apparatus:*

A3.3.1 *Tension Testing Clevis:*

A3.3.1.1 A loading clevis suitable for testing compact specimens is shown in Fig. A2.2. Both ends of the specimen are held in such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. In order to provide rolling contact between the loading pins and the clevis holes, these holes are provided with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown. Clevises and pins should be fabricated from steels of sufficient strength to elastically resist indentation loads (>40 HRC).

A3.3.1.2 The critical tolerance and suggested proportions of the clevis and pins are given in Fig. A2.2. These proportions are based on specimens having $W/B = 2$ for $B \geq$ 12.7 mm (0.5 in.) and $W/B = 4$ for $B <$ 12.7 mm (0.5 in.). If a 1930-MPa (280 000-psi) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained. If lower strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio, then heavier grips will be required. As indicated in Fig. A2.2, the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 9.5 mm (0.375 in.) thick.

A3.3.1.3 Careful attention should be given to achieving good alignment through careful machining of all auxiliary gripping fixtures.

A3.3.2 *Displacement Gage*—For generally applicable details concerning the displacement gage see 6.3.

A3.4 *Procedure:*

A3.4.1 *Measurement*—The analysis assumes the specimen was machined from a circular blank and therefore measurements of circularity as well as width, W, crack length, a, and thicknesses, B and B_N should be made. Measure the dimensions, B_N and B to the nearest 0.05 mm (0.002 in.) or 0.5 %, whichever is larger.

A3.4.1.1 The specimen blank should be checked for circularity before specimen machining. Measure the radius at eight equally spaced points around the circumference of the specimen blank. One of these points should lie in the intended notch plane. Average these readings to obtain the radius, r. If any measurement differs from r by more than 5 %, machine the blank to the required circularity. Otherwise, $D = 2r = 1.35\ W$.

A3.4.1.2 Measure the width, W, and the crack length, a, from the plane of the centerline of the loading holes (the notched edge is a convenient reference line but the distance from the centerline of the holes to the notched edge shall be subtracted to determine W and a). Measure the width, W, to the nearest 0.05 mm (0.002 in.) or 0.5 %, whichever is larger, at not less than three positions near the notch location and record the average value.

A3.5 *Calculation:*

A3.5.1 *Calculation of J*—For the disk compact specimen calculate J as follows:

$$J = J_{el} + J_{pl} \tag{A3.1}$$

where:

J_{el} = elastic component of J, and

J_{pl} = plastic component of J.

For the DC(T) specimen at a point corresponding to a_i, v_i, and P_i on the specimen load versus load-line displacement record as follows:

$$J_{(i)} = \frac{(K_{(i)})^2\,(1 - \nu^2)}{E} + J_{pl(i)} \tag{A3.2}$$

$$K_{(i)} = \left[\frac{P_i}{(BB_N W)^{1/2}}\right] f(a_i/W) \tag{A3.3}$$

where:

$$f(a_i/W) = \frac{(2 + a_i/W)\,(0.76 + 4.8a_i/W - 11.58\,(a_i/W)^2 + 11.43\,(a_i/W)^3 - 4.08\,(a_i/W)^4)}{(1 - a_i/W)^{3/2}} \quad \text{(A3.4)}$$

$$J_{pl(i)} = \left[J_{pl(i)} + \left(\frac{\eta_{i-1}}{b_{i-1}}\right)\frac{(A_{pl(i)} - A_{pl(i-1)})}{B_N}\right]\left[1 - \gamma_{i-1}\frac{(a_i - a_{i-1})}{b_{i-1}}\right] \quad \text{(A3.5)}$$

where:

$\eta_{(i-1)} = 2.0 + 0.522\, b_{(i-1)}/W$, and

$\gamma_{(i-1)} = 1.0 + 0.76\, b_{(i-1)}/W$.

A3.5.2 In Eq A3.5, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the load versus load-line displacement record between lines of constant displacement at points $i-1$ and i, see Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic J at point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the above relationship requires small and uniform crack-growth increments consistent with the data spacing requirements of 8.4.4. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + \frac{(P_i + P_{i-1})\,(V_{pl(i)} - V_{pl(i-1)})}{2} \quad \text{(A3.6)}$$

where:

$V_{pl(i)}$ = plastic part of the load-line displacement = $V_i - (P_i C_{LL(i)})$, and

$C_{LL(i)}$ = compliance, $(\Delta V/\Delta P)_i$ required to give the current crack length, a_i.

For test methods that do not utilize the elastic compliance techniques, C_i can be determined from knowledge of a_i/W using the following equation:

$$C_i = \frac{[1.62 + 17.80\,(a_i/W) - 4.88\,(a_i/W)^2 + 1.27\,(a_i/W)^3]}{E'B_e\,[1 - (a_i/W)]^2} \quad \text{(A3.7)}$$

A3.5.3 *Calculation of Crack Length*—For a single-specimen method using an elastic compliance technique on disk-shaped compact specimens with crack opening displacements measured at the load-line, the crack length is given as follows:

$$a_i/W = 0.998193 - 3.88087\,U_x + 0.187106\,U_x^2 + 20.3714\,U_x^3 - 45.2125\,U_x^4 + 44.5270\,U_x^5 \quad \text{(A3.8)}$$

where:

$$U_x = \frac{1}{[(B_e E' C_{ci})^{1/2} + 1]} \quad \text{(A3.9)}$$

where:

C_{ci} = corrected specimen crack opening compliance $(\Delta v/\Delta P)$ on an unloading/reloading sequence,

$$C_{ci} = \frac{C_i}{\left[\frac{H^*}{R}\sin\theta - \cos\theta\right]\left[\frac{D}{R}\sin\theta - \cos\theta\right]} \quad \text{(A3.10)}$$

where (Fig. A2.3):

C_i = measured specimen elastic compliance (at the load-line),

H^* = initial half-span of the load points (center of the pin holes),

R = radius of rotation of the crack centerline, $(W + a)/2$, where a is the updated crack length,

D = one-half of the initial distance between the displacement measuring points,

θ = angle of rotation of a rigid body element about the unbroken midsection line, or

$$\theta = \sin^{-1}[(d_m/2 + D)/(D^2 + R^2)^{1/2}] - \tan^{-1}(D/R),$$

d_m = total measured load-line displacement.

$E' = E/(1 - \nu^2)$,

$B_e = B - (B - B_N)^2/B$.

A3.5.4 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

A4. SPECIAL REQUIREMENTS FOR MULTISPECIMEN TESTING

A4.1 *Overview*—Multispecimen test methods can be used to evaluate a J_{Ic} toughness parameter in accordance with this test method. In a multispecimen method each specimen is used to develop a single point on the $J - \Delta a_p$ curve and an assemblage of five or more of these points can, by use of the construction of Fig. 5, give a value of J_Q, that is a conditional J_{Ic} value. Because the J values developed are not corrected for crack growth, the resulting *J-R* curve is not qualified according to this test method.

A4.2 *Procedure:*

A4.2.1 All requirements set forth in this test method are applicable for specimen dimensions, specimen preparation, and test apparatus. Only the test procedure and the calculations of J are different for the multispecimen method where all needed crack length measurements are obtained using optical methods from the fracture surface of the broken test sample according to 8.5.5.

A4.2.2 The multiple specimen technique involves loading specimens to selected different displacement levels and marking the amount of crack extension that occurred during loading.

A4.2.3 Load specimens at a rate such that the time taken to reach P_M is between 0.1 and 10.0 min.

A4.2.4 *Number of Specimens*—Several specimens are used to generate the required power law curve. It is suggested that a minimum of six specimens be prepared. All shall be machined to the same dimensions. The initial precrack lengths should be as close as possible. The objective is to replicate the initial portion of the load versus load-line displacement traces as much as possible.

A4.2.5 Take each specimen individually through the following steps:

A4.2.5.1 Load to a selected displacement level that is judged to produce Δa_p in a desired position on the *J-R* curve. A good practice would be to aim for the first significant load drop on the first specimen so that subsequent displacement levels can be better estimated from the first record. Use displacement or clip gage control so that crack growth beyond maximum load can be controlled. Record load and displacement(s) autographically or digitally.

A4.2.5.2 Unload the specimen and mark the crack according to one of the following methods. For steels and titanium alloys, heat tinting at about 300°C (570°F) for 30 min works well. For other materials, fatigue cycling can be used. The use of liquid penetrants is not recommended. For both recommended test methods, the beginning of stable crack extension is marked by the end of the flat fatigue pre-cracked area. The end of crack extension is marked by the end of heat tint or the beginning of the second flat fatigue area.

A4.2.5.3 Break the specimen to expose the crack, with care taken to minimize additional deformation. Cooling ferritic steel specimens enough to ensure brittle behavior may be helpful. Other materials may also benefit since cooling will reduce deformation.

A4.2.5.4 Measure the fatigue and final crack lengths according to 8.5.5.

A4.2.5.5 Calculate $\Delta a_p = a_p - a_o$.

A4.2.5.6 Judge the displacement level needed on the next specimen to obtain a favorable Δa_p position between the parallel exclusion lines (see Fig. 4). Repeat the iteration until at least five data points are favorably positioned to satisfy the conditions of 9.9.3.

A4.3 *Calculation:*

A4.3.1 Calculations of J-integral are made from load, load-point displacement curves obtained using the procedure outlined in Section 8. At a given total deflection, the area under the load-displacement curve is found in square centimetres or square inches accurate to ±2 %. A polar planimeter is commonly used. Alternatively, numerical integration can be used with computer techniques. The measured area is cross-hatched in Fig. A4.1. Areas are then converted to energy units according to the load scale and displacement scale used.

A4.3.2 Calculate J according to the following equation:

$$J = J_{el} + J_{pl} \tag{A4.1}$$

where:

J_{el} = elastic component of J, and

J_{pl} = plastic component of J.

For the SE(B) specimen at a point corresponding to V_i and P_i on the specimen load versus load-line displacement record as follows:

$$J = \frac{K^2 (1 - \nu^2)}{E} + J_{pl} \tag{A4.2}$$

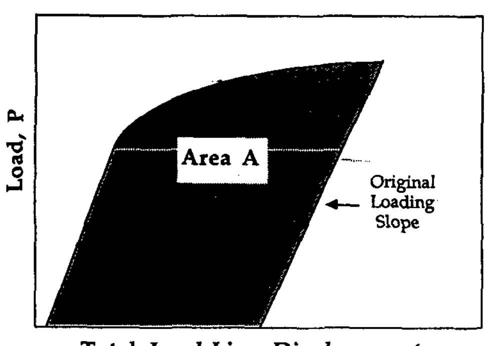


FIG. A4.1 Definition of Area for J Calculation

where:

$$K = \left[\frac{PS}{(BB_N)^{1/2}\, W^{3/2}}\right] f(a_o/W) \tag{A4.3}$$

with:

$$f(a_o/W) = \frac{3(a_o/W)^{1/2}\,[1.99 - (a_o/W)(1 - a_o/W) \times (2.15 - 3.93\,(a_o/W) + 2.7\,(a_o/W)^2)]}{2(1 + 2a_o/W)(1 - a_o/W)^{3/2}} \tag{A4.4}$$

and

$$J_{pl} = \frac{2A_{pl}}{B_N b_o} \tag{A4.5}$$

where:

A_{pl} = area A as shown in Fig. A4.1.

For the C(T) specimen at a point corresponding to V_i, P_i on the specimen load versus load-line displacement record as follows:

$$J = \frac{K^2 (1 - \nu^2)}{E} + J_{pl} \tag{A4.6}$$

where:

$$K = \left[\frac{P}{(BB_N W)^{1/2}}\right] f(a_o/W) \tag{A4.7}$$

for the C(T) specimen:

$$f(a_o/W) = \frac{(2 + a_o/W)(0.886 + 4.64\,(a_o/W) - 13.32\,(a_o/W)^2 + 14.72\,(a_o/W)^3 - 5.6\,(a_o/W)^4)}{(1 - a_o/W)^{3/2}} \tag{A4.8}$$

and for the DC(T) specimen:

$$f(a_o/W) = \frac{(2 + a_o/W)(0.76 + 4.8\,a_o/W - 11.58\,(a_o/W)^2 + 11.43\,(a_o/W)^3 - 4.08\,(a_o/W)^4)}{(1 - a_o/W)^{3/2}} \tag{A4.9}$$

and:

$$J_{pl} = \frac{\eta A_{pl}}{B_N b_o} \tag{A4.10}$$

where:

η = $2 + 0.522\, b_o/W$.

A_{pl} = Area A as shown in Fig. A4.1.

A4.3.3 Plot J versus Δa as shown in Fig. 5. Determine a construction line in accordance with the following equation:

$$J = 2\sigma_Y \Delta a \tag{A4.11}$$

Plot the construction line, then draw an exclusion line parallel to the construction line intersecting the abscissa at 0.15 mm (0.006 in.). Draw a second exclusion line parallel to the construction line intersecting the abscissa at 1.5 mm (0.06 in.). Plot all J-Δa data points that fall inside the area enclosed by these two parallel lines and capped by $J_{limit} = b_o\sigma_Y/15$. Make sure that data spacing meets the requirements of 9.9.3.

A4.3.4 Plot an offset line parallel to the construction and exclusion lines at an offset value of 0.2 mm (0.008 in.).

A4.3.5 Using a method of least squares determine a linear regression line of the following form:

$$\ln J = \ln C_1 + C_2 \ln(\Delta a/k) \tag{A4.12}$$

where k = 1.0 mm or 0.0394 in. Use only the data which conform to the requirements stated in the previous sections. Plot the regression line as illustrated in Fig. 4.

A4.3.6 The intersection of the regression line of A4.3.5

with the offset line of A4.3.4 defines J_Q and Δa_Q. To determine this intersection the following procedure is recommended.

A4.3.6.1 Estimate an interim $J_{Q(1)}$ value from the data plot.

A4.3.6.2 Evaluate $\Delta a_{(1)}$ from:

$$\Delta a_{(1)} = \frac{J_{Q(1)}}{2\sigma_Y} + 0.2 \text{ mm (0.008 in.)} \tag{A4.13}$$

A4.3.6.3 Evaluate an interim $J_{Q(2)}$ from the following power law relationship:

$$J_{Q(2)} = C_1(\Delta a_{(1)}/k)^{C_2} \tag{A4.15}$$

where k = 1.0 mm or 0.0394 in.

A4.3.6.4 Return to A4.3.6.2 and A4.3.6.3 to get $\Delta a_{(i+1)}$ and interim $J_{Q(i+2)}$ until the J_Q values converge to within ±2 %.

A4.4 Qualify this J_Q value as J_{Ic} using the applicable requirements of 9.7, (that is, 9.7.1, 9.7.2, 9.7.3, 9.7.4, 9.7.9), and 9.9.

A5. GUIDELINES FOR DIRECT CURRENT ELECTRIC POTENTIAL DETERMINATION OF CRACK SIZE

A5.1 *Applications*—Electric potential (EP) procedures for crack-size determination are applicable to virtually any electrically conducting material in a wide range of testing environments. The d-c EP technique relies on simple calibrations for standard geometries, and can yield a higher density of points to define a *J-R* curve than is typically achievable using elastic compliance procedures. The procedures discussed herein are those for which two-dimensional models can be used both for the specimen configuration and for the electric potential.

A5.2 *Measurement Principles*—Determining crack size from electric potential measurements relies on the principle that the electric field in a cracked sample with a current flowing through it is a function of the sample geometry, and in particular the crack size. For a constant current flow, the electric potential or voltage difference across the crack plane will increase with increasing crack size due to modification of the electrical field and associated perturbation of the current streamlines. The change in voltage can be related to crack size through analytical or experimental calibration relationships.

A5.3 *Basic Method:*

A5.3.1 A constant current is passed through the sample resulting in a two dimensional electric field which is constant through the thickness at all points. The large scale crack tip plasticity associated with fracture of ductile materials can increase the measured electric potential due to resistivity changes without crack extension. These resistivity changes shall be properly accounted for in order to accurately determine crack extension in ductile materials.

A5.3.2 Changes in the sample or instrumentation may result in proportional changes in the measured voltage. For example, a 1°C change in specimen temperature can result in a significant change in the EP signal due to the change in the material's electric resistivity. Also, some materials exhibit time-dependent conductivity changes while at elevated temperatures. Variations in the gain of amplifiers or calibration of voltmeters may also result in a proportional scaling of the measured voltages. To compensate for these effects, voltage measurements can be normalized using additional voltage measurements taken at a reference location. The reference location may be either on the test sample or on an alternate material sample in the same environment. If the reference measurements are made directly on the test sample, the location shall be chosen so that the reference voltage is not affected by crack size. Since all material and instrument variations are also included in the reference measurements,

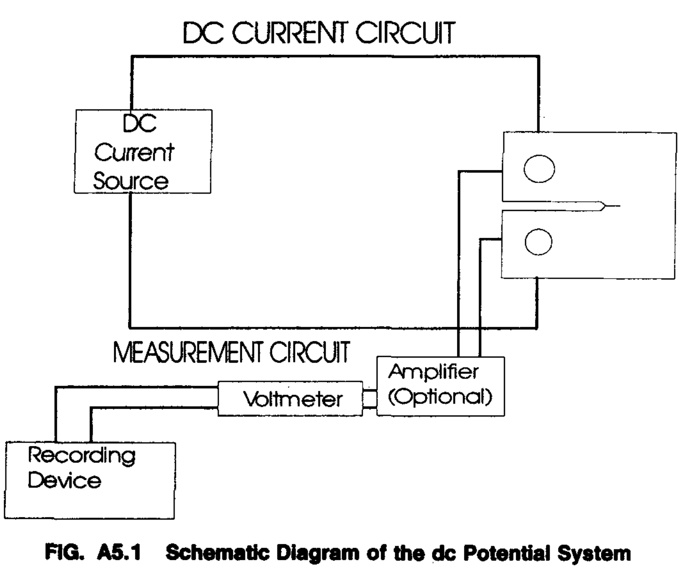


FIG. A5.1 Schematic Diagram of the dc Potential System

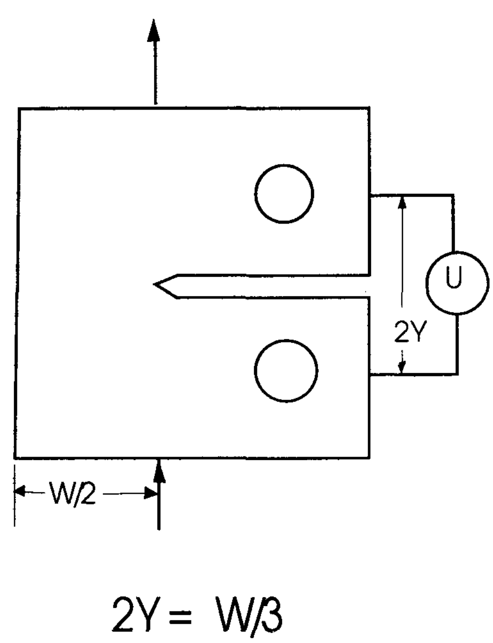


FIG. A5.2 Schematic of C(T) Specimen dc Potential Lead Connections

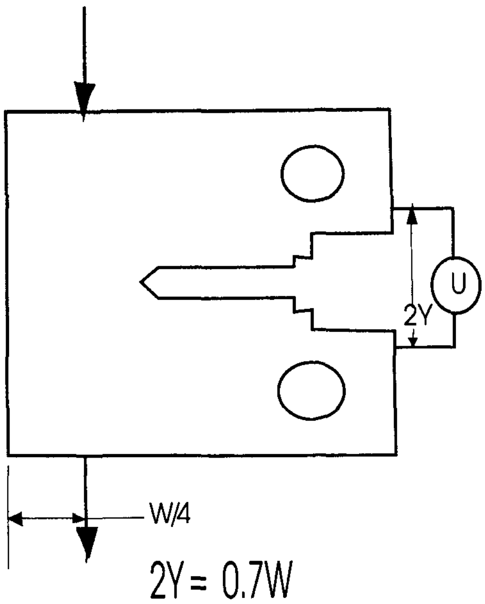


FIG. A5.3 Alternative C(T) Specimen dc Potential Lead Positions

the normalization process should eliminate them. Use of reference voltage measurements can significantly increase crack size resolution for some materials.

A5.3.3 Typical apparatus for the d-c EP technique is shown in Fig. A5.1. The output voltages are typically in the 0.1 to 50.0 mV range for common current magnitudes (5 to 50 *A*), sample dimensions, and materials. Precise measurements (typically ±0.1 %) of these relatively small output voltages shall be made to obtain accurate crack size values. To obtain sufficient voltage resolution usually requires special care in eliminating electrical noise and drift.

A5.3.4 The d-c method is susceptible to thermoelectric effects which produce d-c potentials in addition to those due to the sample electrical field. These thermoelectric voltages can be a substantial fraction of the total measured voltage. Since the thermoelectric effect is present even without the input current, it is possible to account for it by subtracting voltage measurements taken with the current off from the measurements made with the current on. An alternative method corrects for the thermoelectric effect by taking voltage measurements while reversing the direction of current flow. Corrected EP measurements are then equal to one half of the difference of the measured potential readings taken at each current polarity.

A5.4 *Current Generating Equipment*—A constant current shall be maintained by the power supply with sufficient short- and long-term stability. The required stability is a function of the resolution of the voltage measurement equipment (see A5.5) and the desired crack size resolution. For optimum conditions, the relative stability of the power supply should be equal to the effective resolution of the voltage measurement system; that is, if the voltage measurement system can effectively resolve one part in 1000 of the output voltage from the sample (including electric noise, inherent inaccuracies such as nonlinearity, etc.), then the power supply should be stable to one part in 1000.

A5.5 *Voltage Measurement Equipment*—Voltage measurements shall be made with any equipment that has sufficient resolution, accuracy, and stability characteristics. The dc method requires equipment capable of measuring small changes in dc voltage (for example, 0.05 to 0.5 µv) with relatively low dc signal to noise ratios. Although there are a variety of ways to implement the voltage measurement system, three commonly used systems include amplifier/autographic recorder, amplifier/microcomputer analog to digital converter, and digital voltmeter/microcomputer. Autographic recorders are commonly available with suitable sensitivity and can be used to record the output voltage directly from the sample. A preamplifier can be used to boost the direct voltage output from the sample before recording. Another common technique uses a preamplifier to boost the direct output from the sample to a level that can be digitized using a conventional analog to digital converter and microcomputer. A third method makes use of a digital voltmeter with a digital output capability. The advantage of this type of system is that all of the sensitive analog circuits are contained within a single instrument.

A5.6 *Crack Length Versus Electric Potential Relationships:*

A5.6.1 Closed form solutions for the relationship between electric potential versus crack size have been analytically derived for the SE(B) and C(T). These are described in A5.7.

A5.6.2 It is also possible to empirically develop relationships for virtually any type of sample geometry used in *J-R* curve testing. Such empirical relationships can be advantageous in instances when sample geometries are complex, or wire placement has been altered. Analytical or empirical relationships should be experimentally verified using alternative measurements at various crack sizes in the range of interest (optical surface measurements, compliance measurements, or post-test fracture surface measurements). Such measurements should be reported and may be used for correcting crack lengths estimated from closed form equations.

A5.6.3 Voltage wire placements are usually a compromise between good sensitivity to crack size changes and immunity to errors caused by minor variations in lead location from sample to sample. Near crack tip lead locations yield better sensitivity to changes in crack size or to crack initiation. The difficulty with this type of arrangement is that the electrical field is, in general, highly nonuniform in the near tip region. Thus, minor variations in lead placement from one sample to the next may produce significant differences in measured voltage for the same crack size. In most cases those positions which give greatest sensitivity to crack size changes also have the greatest sensitivity to variations in lead wire positioning.

A5.6.4 Current input wire locations also represent a compromise between uniformity and sensitivity. Placement of the current inputs near the crack tip region focuses the current streamlines there resulting in increased sensitivity to crack initiation. Placement of the current leads midway across the remaining ligament tends to provide a more uniform current field for crack growth.

A5.7 *Specimen Geometries:*

A5.7.1 Specimen geometries for J_{Ic}/*J-R* curve testing covered in this annex are the compact tension, C(T), and single-edge notched bend, SE(B). The equations listed in the following sections are derived under dc conditions using either closed form or experimental calibrations.

A5.7.2 *C(T) Geometry Voltage Versus Crack Size Relationship:*

A5.7.2.1 A closed form expression that applies approximately for the C(T) geometry is as follows:

$$\frac{a}{W} = \frac{2}{\pi} cos^{-1} \left[\frac{cosh\left(\frac{\pi y}{2W}\right)}{cosh\left[\left(\frac{U}{U_0}\right) cosh^{-1} \left[\frac{cosh\left(\frac{\pi y}{2W}\right)}{cos\left(\frac{\pi a_0}{2W}\right)}\right]\right]} \right] \quad (A5.1)$$

where:

U = electric potential signal,
U_o = initial electric potential signal,
a = crack length,
a_o = initial crack length,
W = specimen width, and
y = $W/6$ (see Fig. A5.2).

A5.7.2.2 An experimental calibration for the *C(T)* specimen has been developed based on data from Ref **(13)** which involved current inputs at the $W/4$ position as shown in Fig. A1.3. A fifth-order polynomial fit to the data over the range from a/W = 0.45 to a/W = 0.8 yields the following expression:

$$\frac{a}{W} = \left[0.2864\left(\frac{U}{U_o} - 0.5\right)\right]^{0.3506} \quad (A5.2)$$

A5.7.3 *SE(B) Geometry Voltage Versus Crack Size Relationship:*

A5.7.3.1 The closed form expression provided in A5.7.2 has been found to apply to SE(B) specimens for the case where the current input leads are at the $W/2$ location as shown in Fig. A5.4.

A5.7.3.2 An experimental calibration developed for the SE(B) specimen has been developed based on data from Ref **(13)** which involved current inputs at the $W/4$ position as shown in Fig. A5.3. A fifth-order polynomial fit to the data over the range from a/W = 0.45 to a/W = 0.8 yields the following expression:

$$\frac{a}{W} = \left[0.4512\left(\frac{U}{U_o} - 0.5\right)\right]^{0.4688} \quad (A5.3)$$

NOTE 7—Regardless of which EP versus crack-size expression is used, the use of a reference probe is encouraged (see A5.3). This reference probe should be located on the test specimen (or another specimen at the identical test conditions) in a region unaffected by crack growth. When employing such a reference probe, the EP measurements made for crack-size determination (U in Eq A5.1, A5.2, and A5.3) are divided by the ratio U_{ref}/U_{ref0}:

where:

U_{ref} = reference probe voltage measured at the same time as the EP crack voltage is measured, and
U_{ref0} = initial reference probe voltage.

A5.8 *Effects of Plasticity on Electric Potential:*

A5.8.1 The analytical/experimental calibrations described in A5.7 do not account for the effects of plasticity on the measured potential. It is therefore necessary to separate changes in the potential due to plasticity from those due to crack extension. Within the requirements of this test method, it is assumed that all of the significant plasticity in the fracture specimen occurs prior to crack initiation. The electric potential signal change prior to the attainment of crack initiation as defined in 9.6 is therefore ignored and the remainder of the EP signal change is used to establish the *J-R* curve. It has been found that a plot of EP versus crack mouth-opening displacement will generally remain linear until the onset of crack extension. Such a plot (Fig. A5.6) can be useful in determining the amount of the electric potential signal to attribute to plasticity versus crack extension.

A5.9 *Determination of Crack Length:*

A5.9.1 Construct a plot of electric potential measured during the test as a function of crack-opening displacement, v, as shown in Fig. A5.6. Determine the best-fit of the equation $U = F \times v + G$ to the data over the range from 0.1 to 0.5 P_{max} using the method of least-squares. Plot the equation, $U = F \times v + 1.05(G)$. The intersection of this line with the data shall define the point v_B, U_B. When using Eq A5.1 to calculate crack length, $U_B = U_o$. If Eq A5.2 or A5.3 is used to calculate the crack length, the value U_o must first be calculated from the following expressions:

for the C(T) specimen using Eq A5.2, calculate U_o from the following equation:

$$U_o = \frac{U_B}{3.4916\left(\frac{a_o}{W}\right)^{2.851} + 0.5} \quad (A5.4)$$

and for the SE(B) specimen using Eq A5.3, calculate U_o from the following equation:

$$U_o = \frac{U_B}{2.216\left(\frac{a_o}{W}\right)^{2.133} + 0.5} \quad (A5.5)$$

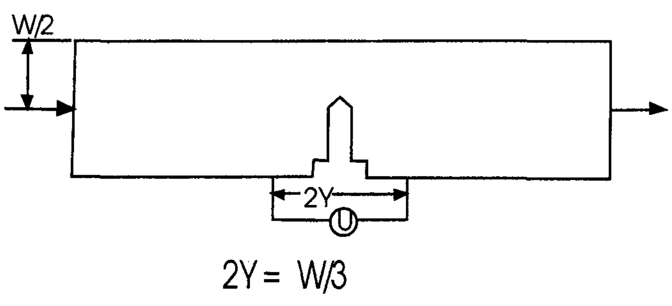


FIG. A5.4 Schematic of SE(B) dc Potential Lead Connections

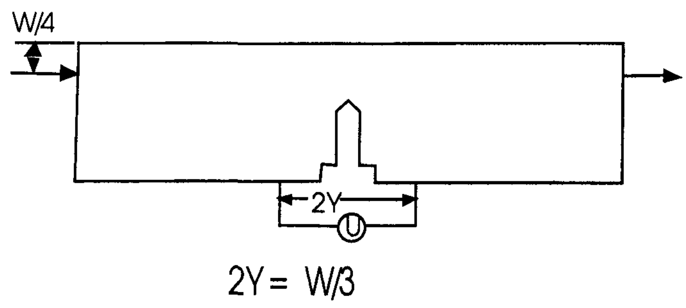


FIG. A5.5 Alternative SE(B) dc Potential Lead Connections

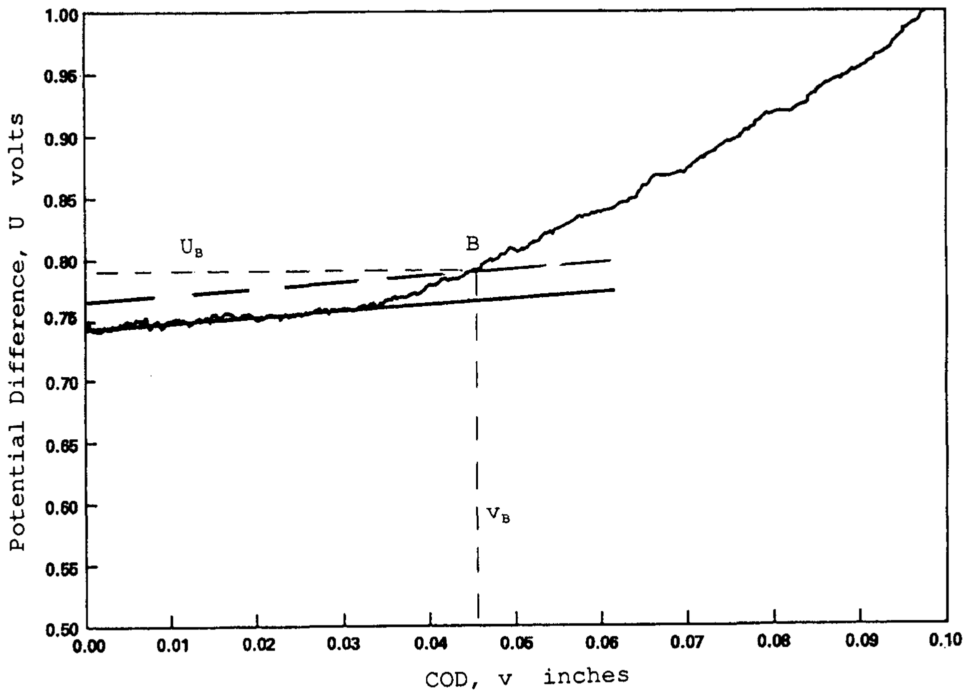


FIG. A5.6 Potential Rise Versus Crack Opening Displacement for a Structural Steel (10)

A5.9.2 For each data point in the test record prior to the intersection Point *B* defined by $v = v_B$, as shown in A5.9.1, calculate crack extension from the relationship $\Delta a = J/(2\sigma_Y)$. For all data after this point, calculate the crack length from the appropriate equation, for example, A5.1, A5.2, or A5.3, using the value of U_o determined in A5.9.1 and an initial crack length equal to $a_o + \Delta a_B$, where $\Delta a_B = J_B/(2\sigma_Y)$ calculated at Point *B*.

A5.9.3 The predicted crack length at the end of the test shall be within $0.05\Delta a/W$ of the final physical crack size determined in 8.5.4.

A5.10 *Gripping Considerations*—The electric potential method of crack size determination relies on a current of constant magnitude passing through the sample when the potential voltage is measured. During such potential measurements it is essential that very little of the applied current be shunted in a parallel circuit through the test machine. For most commercially available test machines and grip assemblies the resistance through the test frame is considerably greater than that of the test sample. In some situations an alternative path for the applied current may exist through the test frame. In such cases, additional steps to provide isolation between the specimen and load frame may be necessary. Users of the potential method should ensure that the electric resistance measured between the grips (with no specimen in place) is several orders of magnitude higher than the resistance of the specimen between the current input locations. The specimen resistance should be determined for the range of crack sizes encountered during the test. A resistance ratio (test frame resistance divided by the specimen resistance) of 10^4 or greater is sufficient for most practical applications. Isolation of the specimen from the load frame is particularly important when using power supplies with non-isolated (ground-referenced) outputs. Use of this type of power supply may require isolating both ends of the test specimen from the test frame to avoid ground loop problems.

A5.11 *Wire Selection and Attachment*—Careful selection and attachment of current input and voltage measurement wires can avoid many problems associated with the electric potential method. This is particularly important in elevated temperature environments where the strength, melting point, and oxidation resistance of the wires must be taken into account.

A5.11.1 *Current Input Wires*—Selection of current input wire should be based on current carrying ability, and ease of attachment (weldability, connector compatibility). Wires must be of sufficient gage to carry the required current under test conditions and may be mechanically fastened or welded to the sample or gripping apparatus.

A5.11.2 *Voltage Measurement Wires*—Voltage wires should be as fine as possible to allow precise location on the sample and minimize stress of the wire during loading which could cause detachment. Ideally, the voltage sensing wires should be resistance-welded to the sample to ensure a reliable, consistent joint. Lead wires may be fastened using mechanical fasteners for materials which exhibit poor welding characteristics (for example certain aluminum alloys) provided that the size of the fastener is accounted for when determining location of voltage sensing leads.

A5.12 *Resolution of Electric Potential Systems*—The effective resolution of EP measurements depends on a number of factors including voltmeter resolution or amplifier gain, or both, current magnitude, sample geometry, voltage measurement and current input wire locations, and electric conductivity of the sample material. Here, effective resolution is defined as the smallest change in crack size which can be distinguished in actual test operation, not simply the best resolution of the recording equipment. For common laboratory-sized samples, a direct current in the range from 5 to 50A and voltage resolution of approximately ±0.1 μV or ±0.1 % of U_o will yield a resolution in crack size of better than 0.1 % of the sample width. For highly conductive materials (for example, aluminum, copper) or lower current levels, or both, the resolution would decrease, while for materials with a lower conductivity (that is, titanium, nickel) resolutions of better than 0.01 % of the sample width have been achieved. For a given specimen geometry, material, and instrumentation, crack-size resolution shall be analyzed and reported.

NOTE 8—To illustrate the magnitude of voltages measured on a standard specimen type, 1*T* C(T) samples of 25-mm (1-in.) width, 20 % side-grooved, with an initial a/W ratio of 0.65, input current of 60 A at the $W/4$ position, and potential outputs on the front face (Fig. A5.3) produce the following results:

Material	Approximate EP at 60 A
Aluminum (5456)	0.4 mV
Steel (A106)	0.7 mV
Stainless steel (304)	3.0 mV

A5.13 *Techniques to Reduce Voltage Measurement Scatter:*

A5.13.1 Because of the low-level signals which must be measured with the d-c current method, a number of procedures should be followed to improve voltage measurement precision.

A5.13.2 *Induced EMF*—Voltage-measurement lead wires should be as short as possible and should be twisted to reduce stray voltages induced by changing magnetic fields. Holding the wires rigid also helps reduce the stray voltages that can be generated by moving the wires through any static magnetic fields that may exist near the test frame. In addition, routing the voltage measurement leads away from motors, transformers, or other devices which produce strong magnetic fields is recommended.

A5.13.3 *Electrical Grounding*—Proper grounding of all devices (current source, voltmeters, and so forth) should be made, avoiding ground loops.

A5.13.4 *Thermal Effects*—For d-c systems thermal EMF measurement and correction is critically important. A minimum number of connections should be used and maintained at a constant temperature to minimize thermoelectric effects. All measuring devices (amplifiers/preamplifiers, voltmeters, analog-to-digital converters) and the sample itself should be maintained at a constant temperature. Enclosures to ensure constant temperatures throughout the test may prove beneficial. Some voltmeters for d-c systems have built-in automatic correction for internal thermoelectric effects. These units may be of benefit in cases where it is not possible to control the laboratory environment.

A5.13.5 *Selection of Input Current Magnitude*—The choice of current magnitude is an important parameter: too low a value may not produce measurable output voltages; too high a value may cause excessive specimen heating or arcing. To minimize these problems, current densities should be kept to the minimum value which can be used to produce the required crack-size resolution. The maximum current that can be used with a particular sample can be determined by monitoring the sample temperature while increasing the current in steps, allowing sufficient time for the sample to thermally stabilize. Particular care should be exercised when testing in vacuum, as convection currents are not available to help maintain the sample at ambient temperature.

A5.13.6 *D-C Current Stabilization Period*—Allow a sufficient stabilization period after turning the d-c electric potential current either ON or OFF before making a voltage measurement. Most solid-state power sources can stabilize the output current within a period of 1 or 2 s for a step change in output, however this should be verified for each particular sample and experimental setup.

NOTE 9: *Precautions*—Care must be taken to demonstrate that the applied current does not affect crack tip damage processes and crack growth characteristics. Large-scale crack tip plasticity can increase measured electrical potentials due to resistivity increases without crack extension. These changes must be accounted for by methods such as those outlined previously (A5.8) for accurate determinations of crack length from d-c EP.

APPENDIX

(Nonmandatory Information)

X1. RECOMMENDED DATA FITTING TECHNIQUE

X1.1 To fit the equation of 9.2.1 to the RDAT J_i, a_i data using the method of least squares, the following equation must be set up and solved for a_{oq}, B, and C:

$$\begin{Bmatrix} \Sigma a_i - \dfrac{\Sigma J_i}{2\sigma_Y} \\ \Sigma a_i J_i^2 - \dfrac{\Sigma J_i^3}{2\sigma_Y} \\ \Sigma a_i J_i^3 - \dfrac{\Sigma J_i^4}{2\sigma_Y} \end{Bmatrix} = \begin{bmatrix} RDAT & \Sigma J_i^2 & \Sigma J_i^3 \\ \Sigma J_i^2 & \Sigma J_i^4 & \Sigma J_i^5 \\ \Sigma J_i^3 & \Sigma J_i^5 & \Sigma J_i^6 \end{bmatrix} \begin{Bmatrix} a_{oq} \\ B \\ C \end{Bmatrix}$$

X1.2 This equation can be set up and solved using a standard spreadsheet. The Microsoft QuickBASIC program which follows can also be used to accomplish this process.

```
SUB JFIT
'
' SUBROUTINE TO SET UP FUNCTION FOR Aoq EVALUATION
'
' USES EQUATION a = Aoq + J/(2*SFLOW) + B J ^ 2 + C J ^ 3
'
' WRITTEN BY J. A. Joyce USNA, Annapolis, 1993
'
' INPUT IS RDAT% PAIRS OF a AND J IN VECTOR ARRAYS AM! AND
JM!
'
' NEED IN MAIN PROGRAM A COMMON SHARED RDAT%, AM!(),
JM!(),
'  XN!(), FF!(), AN!(), SFLOW!
'
' INITIALIZATION
FOR I% = 1 TO 3
  FOR J% = 1 TO 4
  AN!(I%,J%) = 0.
  NEXT J%
NEXT I%
' DO SUMMATIONS FOR LEAST SQUARES
AN!(1,1) = RDAT%
JISUM! = 0.
FOR I% = 1 TO RDAT%
  JISUM! = JISUM! + JM!(I%)
  AN!(1,2) = AN!(1,2) + JM!(I%) ^ 2
  AN!(2,2) = AN!(2,2) + JM!(I%) ^ 4
  AN!(1,3) = AN!(1,3) + JM!(I%) ^ 3
  AN!(2,3) = AN!(2,3) + JM!(I%) ^ 5
  AN!(3,3) = AN!(3,3) + JM!(I%) ^ 6
  AN!(1,4) = AN!(1,4) + AM!(I%)
  AN!(2,4) = AN!(2,4) + AM!(I%)*JM!(I%) ^ 2
  AN!(3,4) = AN!(3,4) + AM!(I%)*JM!(I%) ^ 3
NEXT I%
AN!(2,1) = AN!(1,2)
AN!(3,1) = AN!(1,3)
AN!(3,2) = AN!(2,3)
AN!(1,4) = AN!(1,4) - JISUM!/(2*SFLOW!)
AN!(2,4) = AN!(2,4) - AN!(1,3)/(2*SFLOW!)
AN!(3,4) = AN!(3,4) - AN!(2,2)/(2*SFLOW!)
' NOW SOLVE THESE EQUATIONS USING GAUSS ELIMINATION
' FOR XN!
CALL GAUSS
PRINT "COEFFICIENTS OF INITIALIZATION ARRAY ARE:"
PRINT XN!(1),.XN!(2), XN!(3)
'
' CHECK THE FIT
FOR I% = 1 TO RDAT%
  FF!(I%) =
XN!(1)+JM!(I%)/(2*SFLOW!)+XN!(2)*JM!(I%) ^ 2+XN!(3)*JM!(I%) ^ 3
'  PRINT JM!(I%), AM!(I%), FF!(I%)
NEXT I%
' CALCULATION OF THE CORRELATION OF THE FIT
YM! = 0.
FOR I% = 1 TO RDAT%
  YM! = YM! + AM!(I%)/RDAT%
NEXT I%
SY2! = 0.
SYX2! = 0.
FOR I% = 1 TO RDAT%
  SY2! = SY2! + (AM!(I%) - YM!) ^ 2/(RDAT%-1)
  SYX2! = SYX2! + (AM!(I%) - FF!(I%)) ^ 2/(RDAT%-2)
NEXT I%
RFIT! = SQR(1.0 - SYX2!/SY2!)
PRINT "CORRELATION OF FIT = ";RFIT!
PRINT #2,"CORRELATION OF FIT = ";RFIT!
END SUB
SUB GAUSS
' INPUT DATA IS IN AN!(3,4) - OUTPUT IS XN!(3)
' SUBROUTINE IN BASIC TO DO A GAUSS ELIMINATION SOLUTION
' SET NOW FOR 3X3 MATRIX
' OUTPUT IS A VECTOR XN
N% = 3
M% = N% + 1
L% = N% - 1
' START REDUCTION TO TRIANGULAR FORM
FOR K% = 1 TO L%
  K1% = K% + 1
  JJ% = K%
  BG! = ABS(AN!(K%,K%))
' REM START OF SEARCH FOR LARGEST PIVOT ELEMENT
FOR I% = K1% TO N%
  AB! = ABS(AN!(I%,K%))
  IF BG! > AB! THEN BG! = AB!: JJ% = I%
NEXT I%
IF JJ% = K% GOTO REDUCE
' INTERCHANGES ROWS TO GET MAX PIVOT ELEMENT
FOR J% = K% TO M%
  TE! = AN!(JJ%,J%)
  AN!(JJ%,J%) = AN!(K%,J%)
  AN!(K%,J%) = TE!
NEXT J%
'
'  DETERMINES REDUCED ELEMENTS OF TRIANGULAR SET
' REDUCE:
FOR I% = K1% TO N%
  Q! = AN!(I%, K%)/AN!(K%, K%)
  FOR J% = K1% TO M%
    AN!(I%, J%) = AN!(I%, J%) - Q!*AN!(K%, J%)
  NEXT J%
NEXT I%
FOR I% = K1% TO N%
  AN!(I%,K%) = 0.
NEXT I%
NEXT K%
' BACK SUBSTITUTION FOR THE SOLUTIONS
XN!(N%) = AN!(N%,M%)/AN!(N%, N%)
FOR NN% = 1 TO L%
  SU! = 0.
  I% = N% - NN%
  I1% = I% + 1
  FOR J% = I1% TO N%
    SU! = SU! + AN!(I%, J%) * XN!(J%)
  NEXT J%
  XN!(I%) = (AN!(I%, M%) - SU!)/AN!(I%,I%)
NEXT NN%
END SUB
```

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Designation: E 1290 – 93

Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement[1]

This standard is issued under the fixed designation E 1290; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of critical crack-tip opening displacement (CTOD) values at one or more of several crack extension events. These CTOD values can be used as measures of fracture toughness for metallic materials, and are especially appropriate to materials that exhibit a change from ductile to brittle behavior with decreasing temperature. This test method applies specifically to notched specimens sharpened by fatigue cracking. The recommended specimens are three-point bend [SE(B)] or compact [C(T)] specimens. The loading rate is slow and influences of environment (other than temperature) are not covered. The specimens are tested under crosshead or clip gage displacement controlled loading.

1.1.1 The recommended specimen thickness, B, is that of the material in thicknesses intended for an application. Superficial surface machining may be used when desired.

1.1.2 For the recommended three-point bend specimens [SE(B)], width, W, is either equal to, or twice, the specimen thickness, B, depending upon the application of the test. (See 4.3 for applications of the recommended specimens.) For SE(B) specimens the recommended initial normalized crack size is $0.45 \leqq a_o/W \leqq 0.55$. The span-to-width ratio (S/W) is specified as 4.

1.1.3 For the recommended compact specimen [C(T)] the initial normalized crack size is $0.45 \leqq a_o/W \leqq 0.55$. The half-height-to-width ratio (H/W) equals 0.6 and the width to thickness ratio is within the range $2 \leqq W/B \leqq 4$.

1.2 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Force Verification of Testing Machines[2]

E 8 Test Methods for Tension Testing of Metallic Materials[2]

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[2]

E 616 Terminology Relating to Fracture Testing[2]

E 813 Test Method for J_{Ic}, A Measure of Fracture Toughness[2]

E 1152 Test Method for Determining J-R Curves[2]

3. Terminology

3.1 Terminology E 616 is applicable to this test method.

3.2 *Definitions:*

3.2.1 *crack tip opening displacement, (CTOD),* $\delta[L]$—the crack displacement due to elastic and plastic deformation at variously defined locations near the original (prior to an application of load) crack tip.

Discussion—In this test method, CTOD is the displacement of the crack surfaces normal to the original (unloaded) crack plane at the tip of the fatigue precrack, a_o.

In CTOD testing, δ_c [L] is the value of CTOD at the onset of unstable brittle crack extension (see 3.2.13) or pop-in (see 3.2.7) when $\Delta a_p < 0.2$ mm (0.008 in.). The load P_c and the clip gage displacement v_c, for δ_c are indicated in Fig. 1.

In CTOD testing, δ_u [L] is the value of CTOD at the onset of unstable brittle crack extension (see 3.2.13) or pop-in (see 3.2.7) when the event is preceded by $\Delta a_p > 0.2$ mm (0.008 in.). The load P_u and the clip gage displacement v_u, for δ_u are indicated in Fig. 1.

In CTOD testing, δ_m [L] is the value of CTOD at the first attainment of a maximum load plateau for fully plastic behavior. The load P_m and the clip gage displacement v_m, for δ_m are indicated in Fig. 1.

3.2.2 *effective yield strength,* σ_Y $[FL^{-2}]$—an assumed value of uniaxial yield strength that represents the influence of plastic yielding upon fracture test parameters.

Discussion—The calculation of σ_Y is the average of the 0.2 % offset yield strength (σ_{YS}), and the ultimate tensile strength (σ_{TS}), that is $(\sigma_{YS} + \sigma_{TS})/2$. Both σ_{YS} and σ_{TS} are determined in accordance with Test Methods E 8.

3.2.3 *original crack size,* a_o $[L]$—see Terminology E 616.

3.2.4 *original uncracked ligament,* b_o $[L]$—the distance from the original crack front to the back surface of the specimen at the start of testing, $b_o = W - a_o$.

3.2.5 *physical crack extension,* Δa_p $[L]$—an increase in physical crack size, $\Delta a_p = a_p - a_o$.

3.2.6 *physical crack size,* a_p $[L]$—see Terminology E 616.

Discussion—In CTOD testing, $a_p = a_o + \Delta a_p$.

3.2.7 *pop-in*—a discontinuity in the load versus clip gage displacement record. The record of a pop-in shows a sudden increase in displacement and, generally, a decrease in load. Subsequently, the displacement and load increase to above their respective values at pop-in.

3.2.8 *slow stable crack extension* $[L]$—a displacement controlled crack extension beyond the stretch zone width (see 3.2.12). The extension stops when the applied displacement is held constant.

3.2.9 *specimen span,* S $[L]$—the distance between spec-

[1] This test method is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.08 on Elastic-Plastic Fracture Mechanics Technology.

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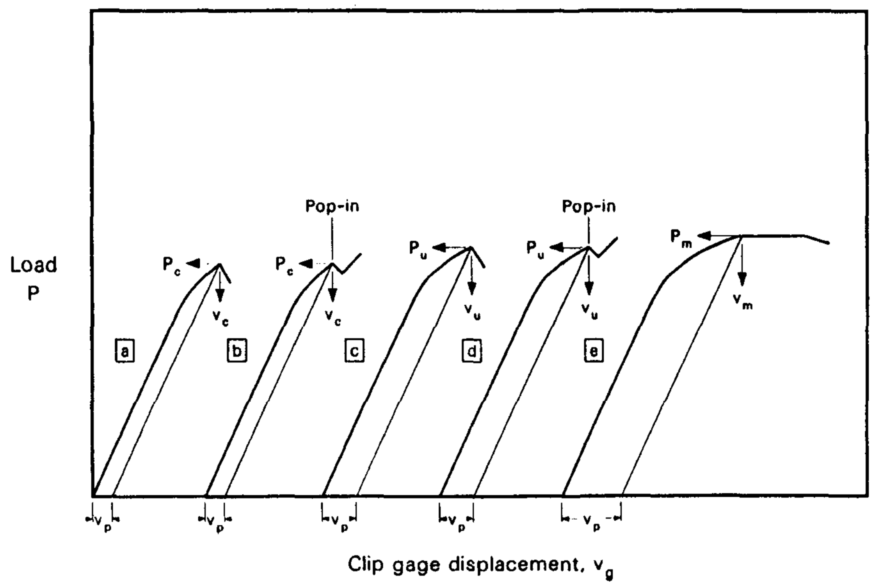
[2] *Annual Book of ASTM Standards*, Vol 03.01.



NOTE 1—Construction lines drawn parallel to the elastic loading slope to give v_p, the plastic component of total displacement, v_g.
NOTE 2—In curves b and d, the behavior after pop-in is a function of machine/specimen compliance, instrument response, etc.

FIG. 1 Types of Load Versus Clip Gage Displacement Records

imen supports in a bend specimen.

3.2.10 *specimen thickness, B*[*L*]—see Terminology E 616.

3.2.11 *specimen width, W* [*L*]—see Terminology E 616.

3.2.12 *stretch zone width, SZW* [*L*]—the length of crack extension that occurs during crack-tip blunting, for example, prior to the onset of unstable brittle crack extension, pop-in, or slow stable crack extension. The SZW is in the same plane as the original (unloaded) fatigue precrack and refers to an extension beyond the original crack size.

3.2.13 *unstable brittle crack extension* [*L*]—an abrupt crack extension that occurs with or without prior stable crack extension in a standard test specimen under crosshead or clip gage displacement control.

4. Summary of Test Method

4.1 The objective of the test is to determine the value of CTOD at one or more of several crack extension events. The values of CTOD may correspond to: δ_c, the onset of unstable brittle crack extension with no significant prior slow stable crack extension (see 3.2.1); δ_u, the onset of unstable brittle crack extension following prior slow stable crack extension; δ_m, at the first attainment of a maximum load plateau for fully plastic behavior.

4.2 The test method involves crosshead or clip gage displacement controlled three-point bend loading or pin loading of fatigue precracked specimens. Load versus clip gage crack opening displacement is recorded, for example, Fig. 1. The loads and displacements corresponding to the specific events in the crack initiation and extension process are used to determine the corresponding CTOD values. For values of δ_c, δ_u and δ_m, the corresponding load and clip gage displacements are obtained directly from the test records.

4.3 The rectangular section bend specimen and the compact specimen are intended to maximize constraint and these are generally recommended for those through-thickness crack types and orientations for which such geometries are feasible. For the evaluation of surface cracks in structural applications for example, orientations T-S or L-S (Terminology E 616), the square section bend specimen is recommended. Also for certain situations in curved geometry source material or welded joints, the square section bend specimen may be preferred. Square section bend specimens may be necessary in order to sample an acceptable volume of a discrete microstructure.

5. Significance and Use

5.1 The CTOD values determined by this test method may be used to characterize the toughness of materials that: (a) are too ductile or lack sufficient size to be tested for K_{Ic} in accordance with the requirements of Test Method E 399, or (b) show a propensity for unstable crack extension that would invalidate tests in accordance with the requirements of Test Method E 813.

5.2 The different values of CTOD determined by this test method characterize the resistance of a material to crack initiation and early crack extension at a given temperature.

5.3 The values of CTOD may be affected by specimen dimensions. It has been shown that values of CTOD determined on SE(B) specimens using the square section geometry may not be the same as those using the rectangular section geometry, and may differ from those obtained with C(T) specimens (see 4.3).

5.4 The values of CTOD determined by this test method may serve the following purposes:

5.4.1 In research and development, CTOD testing can show the effects of certain parameters on the fracture toughness of metallic materials significant to service performance. These parameters include material composition, thermo-mechanical processing, welding, and thermal stress relief.

5.4.2 For specifications of acceptance and manufacturing quality control of base materials, weld metals, and weld heat affected zones.

5.4.3 For inspection and flaw assessment criteria, when used in conjunction with fracture mechanics analyses.

6. Apparatus

6.1 This procedure involves measurement of applied load, P, and clip gage crack opening displacement, v. Load versus displacement is autographically recorded on an x-y plotter for visual display, or converted to digital form for accumulation in a computer information storage facility and subsequent processing. Testing is performed under crosshead or clip gage displacement control in a compression or tension testing machine, or both, that conforms to the requirements of Practices E 4.

6.2 *Fixturing for Three-Point Bend Specimens*—A recommended SE(B) specimen fixture is shown in Fig. 2. Friction effects between the support rollers and specimen are reduced by allowing the rollers to rotate during the test. The use of high hardness steel of the order of 40 HRC or more is recommended for the fixture and rollers to prevent indentation of the platen surfaces.

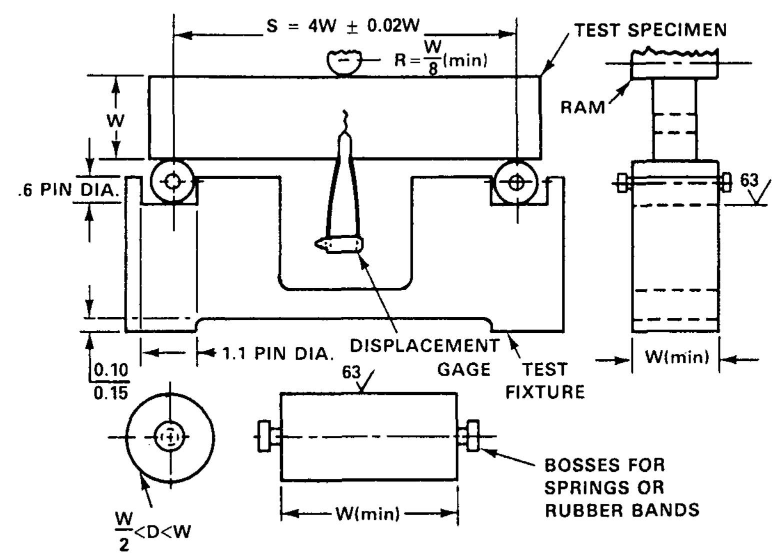
6.3 *Tension Testing Clevis*—A loading clevis suitable for testing C(T) specimens is shown in Fig. 3. Each leg of the specimen is held by such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. To provide rolling contact between the loading pins and the clevis holes, these holes are produced with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown. Clevises and pins should be fabricated from steels of sufficient strength and hardness (greater than 40 HRC) to elastically resist indentation loads. The critical tolerances and suggested proportions of the clevis and pins are given in Fig. 3. These proportions are based on specimens having $W/B = 2$ for $B > 12.7$ mm (0.5 in.) and $W/B = 4$ for $B \leqq 12.7$ mm (0.5 in.). If a 1930 MPa (280 000 psi) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained. If lower strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio, then heavier grips will be required. As indicated in Fig. 3, the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 9.5 mm (0.375 in.) thick. Attention should be given to achieving good alignment through careful machining of all auxiliary gripping fixtures.

6.4 *Displacement Measuring Devices:*

6.4.1 Displacement measuring gages are used to measure opening displacements on SE(B) specimens at either knife edges a distance z beyond the crack mouth, Fig. 4a, or at the crack mouth ($z = 0$) in the case of integral knife edges, Fig. 4b. For C(T) specimens, where the opening displacement is not measured on the load line, the difference between the load line and the displacement measuring point shall constitute the dimension z (see 9.2). Alternatively, when the opening displacements on C(T) specimens are made on or within ±0.002 W of the load line, it may be assumed that $z = 0$.

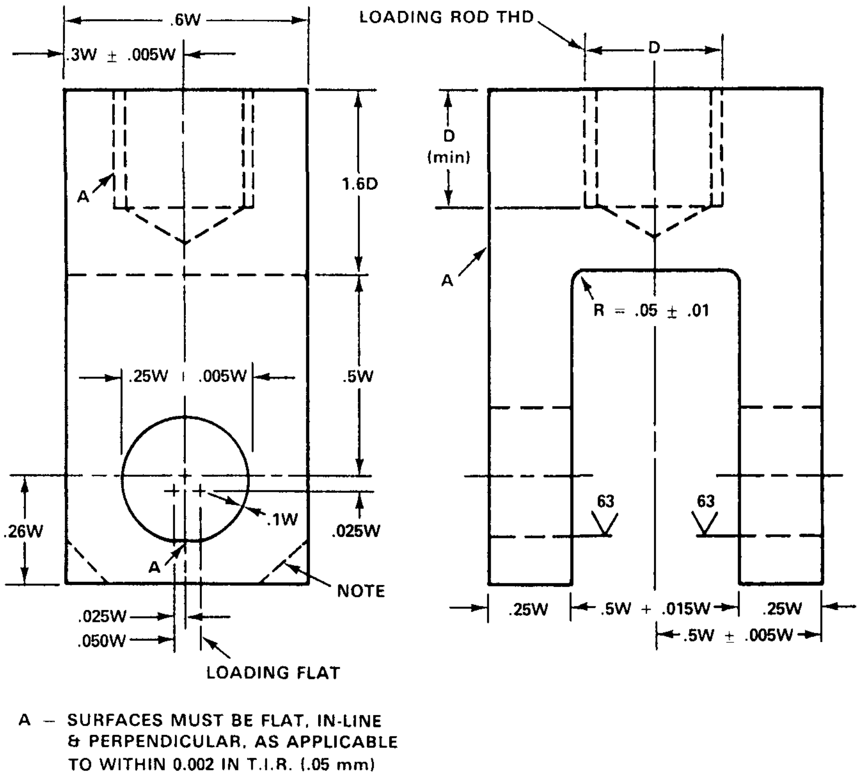
6.4.2 The clip gage recommended in Test Method E 399 may be used in cases where the total expected displacement is 2.5 mm (0.1 in.) or less. Sensitivity and linearity requirements specified in Test Method E 399, shall be met over the full working range of the gage. In addition, the gage is to be calibrated to within ±1 % of the working range.

6.4.3 For cases where a linear working range of up to 8 mm (0.3 in.) or more is needed, an enlarged gage such as that shown in Fig. 5 can be used. Both linearity and accuracy of



NOTE 1—Roller pins and specimen contact surface of loading ram must be parallel to each other within 0.002W.
NOTE 2— 0.10 in. = 2.54 mm; 0.15 in. = 3.81 mm.

FIG. 2 SE(B) Test Fixture Design



NOTE—Corners of the clevis may be removed as necessary to accommodate the clip gage.

FIG. 3 Clevis for C(T) Specimen Testing

the equipment or system used shall be demonstrated to be within ±1 % of the working range of the equipment.

6.4.4 The seating between the clip gage and knife edges shall be firm and free from friction drag.

6.5 *Load Measurement*—The sensitivity of the load sensing device shall be sufficient to avoid distortion caused by over amplification and the device shall have a linearity identical to that for the displacement signal. The combination of force sensing device and recording system shall permit the force P to be determined from the test record within an accuracy of ±1 %.

7. Specimen Configurations, Dimensions, and Preparation

7.1 The SE(B) specimens, shown in Figs. 6 and 7, are tested with a span to width ratio, S/W, of 4. Therefore, it is suggested that overall specimen length should be at least 4.5 W.

7.1.1 The standard bend specimens shall be of thickness, B, at least equal to that employed in the specific structural application of interest, or the original product form thickness. The specimen should be one of the types shown in Figs. 6 and 7.

7.1.2 The recommended original crack size, a_o, of the SE(B) specimen shall be within the range 0.45 $W \leqq a_o \leqq 0.55$ W.

7.1.3 In order to machine fatigue crack-starter notches to depths greater than 2.5 mm (0.1 in.), a stepped width notch is an allowed exception. This is acceptable, provided that: (a) the stepped width notch falls completely within the envelope shown in Fig. 8, and, (b) the length of the fatigue precrack extension from the machined notch tip satisfies the requirement of 7.3.2. Separate or integral knife edges for accommodating clip gages are shown in Fig. 4.

7.2 The recommended C(T) specimen designs are shown in Fig. 9. These are similar to the configurations recommended in Test Methods E 813 and E 1152. The designs are suitable for use with flat bottom clevises of Test Method E 399 design (see Fig. 3). A cut-out section on the front face provides room to attach razor blade edges on the load line of the specimen. The sharp edges of the blades shall be square with respect to specimen surfaces and parallel within 0.5°. A specially prepared spacer block can be used to achieve these requirements.

7.2.1 The C(T) specimen shall be of thickness, B, at least equal to that employed in the specific structural application of interest, or the original product form thickness.

7.2.2 The C(T) specimen half-height to width ratio H/W is 0.6, and the width W to thickness B ratio shall be within the range $2 \leqq W/B \leqq 4$.

7.2.3 The original crack length, a_o, of the compact specimen shall be within the range 0.45 $W \leqq a_o \leqq 0.55$ W.

7.3 *Fatigue Precracking:*

7.3.1 All specimens shall be precracked in fatigue at load values no greater than the load P_f calculated in accordance with the following equations.

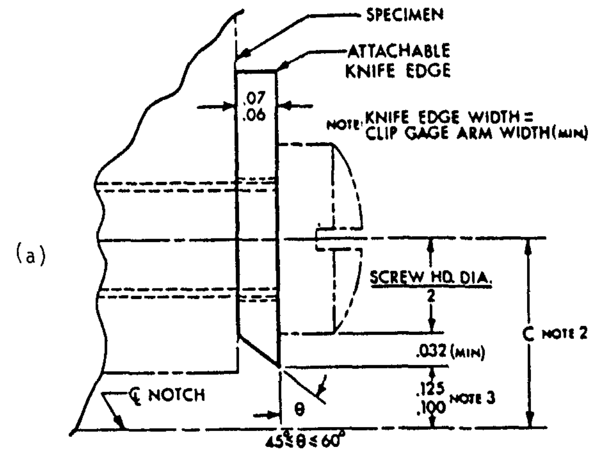
For SE(B) specimens use:

$$P_f = 0.5(Bb_o^2\sigma_Y/S)$$

For C(T) specimens use:

$$P_f = 0.4\ Bb_o^2\sigma_Y/(2W + a_o)$$

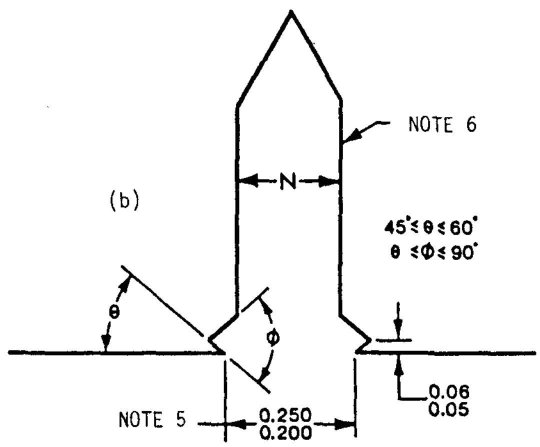
7.3.2 The length of the fatigue precrack extension from



NOTE 1—Dimensions are in inches.
NOTE 2—Effective gage length = 2C + Screw Thread Diameter ≤ $W/2$. (This will always be greater than the gage length specified in Test Method E 399, A1.1.)
NOTE 3—Dimension shown corresponds to clip gage spacer block dimension in Test Method E 399, Annex A1.

Metric Equivalents

in.	0.032	0.06	0.07	0.100	0.125
mm	0.81	1.5	1.8	2.54	3.18

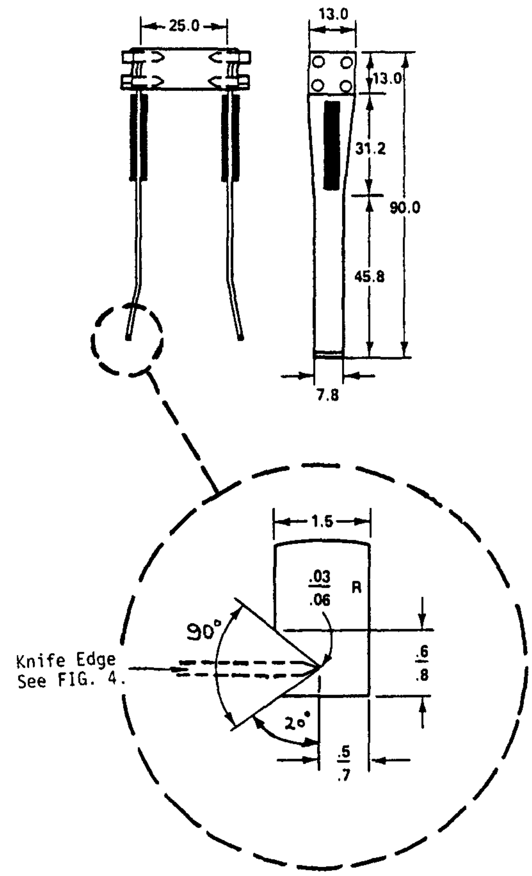


NOTE 4—Dimensions in inches.
NOTE 5—Gage length shown corresponds to clip gage spacer block dimensions shown in Test Method E 399, Annex A1, but other gage lengths may be used provided they are appropriate to the specimen.
NOTE 6—For starter notch configurations see Fig. 8.

Metric Equivalents

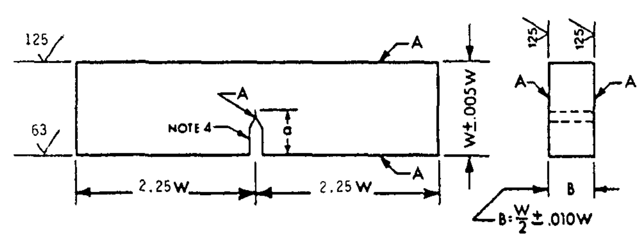
in.	0.050	0.060	0.200	0.250
mm	1.3	1.5	5.1	6.4

FIG. 4 Knife Edges for Location of Clip Gages



NOTE—All dimensions in mm.

FIG. 5 Clip Gage Design for 8 mm (0.3 in.) and More Working Range (See 6.4.3.)

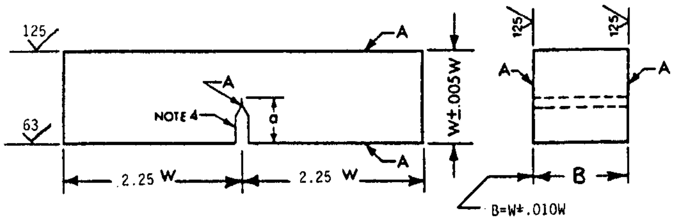


NOTE 1—A surfaces shall be perpendicular and parallel as applicable within 0.001 W TIR.
NOTE 2—Crack starter notch shall be perpendicular to specimen surfaces to within ±2°.
NOTE 3—Integral or attachable knife edges for clip gage attachment may be used (see Fig. 4).
NOTE 4—For starter notch and fatigue crack configurations see Fig. 8.

FIG. 6 Proportional Dimensions and Tolerances for Rectangular Section SE(B) Specimens

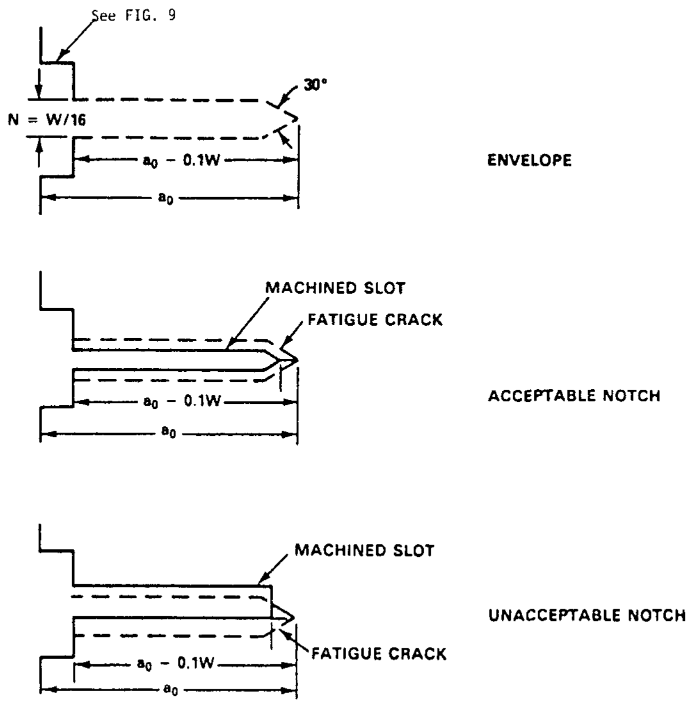
the machined notch shall not be less than 5 % of the total crack length, a_o, and not less than 1.3 mm (0.05 in.). For the final 50 % of fatigue precrack extension or 1.3 mm (0.05 in.), whichever is less, the maximum load shall be no larger than: (a) P_f, or, (b) a load such that the ratio of stress intensity factor range to Young's modulus ($\Delta K/E$) is equal to or less than 0.005 mm$^{1/2}$ (0.001 in.$^{1/2}$), whichever is less. The accuracy of these maximum load values shall be known within ±5 %. The ratio of minimum precracking load to maximum precracking load shall not exceed 0.10. The stress intensity range ΔK may be calculated using the formulae in 9.2.

7.3.3 Normally, the fatigue precracking should be done at room temperature with the material in the condition (metallurgical and thermal-mechanical processing) in which it will be tested. Intermediate treatments between fatigue precracking and testing are only allowed when such treatments



NOTE 1—*A* surfaces shall be perpendicular and parallel as applicable within 0.001 *W* TIR.
NOTE 2—Crack starter notch shall be perpendicular to specimen surfaces to within ±2°.
NOTE 3—Integral or attachable knife edges for clip gage attachment may be used (see Fig. 4).
NOTE 4—For starter notch and fatigue crack configurations see Fig. 8.

FIG. 7 Proportional Dimensions and Tolerances for Square Section SE(B) Specimens



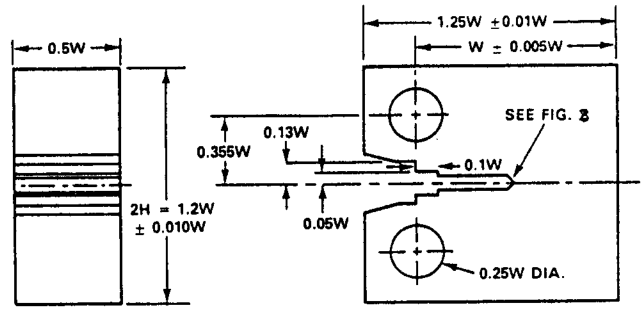
NOTE 1—*N* must not exceed *W*/16.
NOTE 2—The intersection of the crack starter surfaces with the two specimen faces shall be equidistant from the top and bottom edges of the specimen within 0.005 *W*.

FIG. 8 Envelope of Crack-Starter Notches

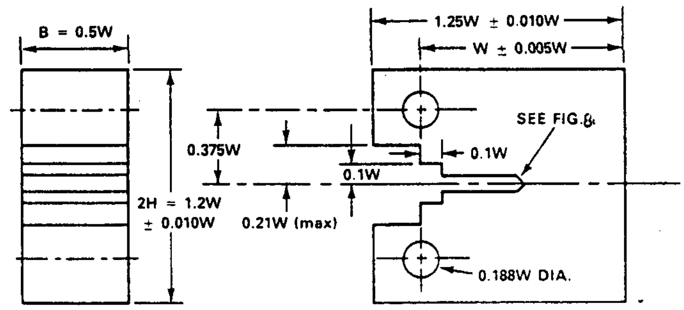
are used to simulate a specific structural application of interest.

7.3.4 To promote early fatigue crack initiation, and promote planar crack growth, a notch tip radius of 0.08 mm (0.003 in.) or less should be used. Additionally, there may be an advantage in using a Chevron notch (see appropriate figure in Test Method E 399), or by statically preloading the specimen. In the latter case, the specimen is loaded in such a way that the straight-through notch tip is compressed in a direction normal to the intended crack plane, but without allowing the applied load to exceed P_f.

7.3.5 The fatigue crack shall fall within the limiting envelope as shown in Fig. 8.



C(T) Specimen for pin of 0.24*W* (+0.000 *W*/−0.005*W*) diameter



C(T) Specimen for pin of 0.1875*W* (+0.000*W*/−0.001*W*) diameter

FIG. 9 Alternative C(T) Specimen Designs

8. Procedure

8.1 The objective of the procedure described herein is to identify the critical CTOD values that can be used as measures of the fracture toughness of materials. These values are derived from measurements of load and clip gage displacement, as described in Section 9.

8.2 After completion of the test, proceed as follows:

8.2.1 Heat tint or fatigue crack the specimen to mark the amount of slow stable crack extension. If fatigue crack marking is used, this should be done using a maximum cyclic load less than the previously applied monotonic load with the minimum cyclic load equal to 70 % of the maximum cyclic load. The maximum cyclic load should be of sufficient magnitude to prevent damage to the fracture surfaces by crack closure.

8.2.2 Break the specimen open to expose the crack, taking care to minimize additional deformation. Cooling ferritic steels enough to ensure brittle behavior may be helpful.

8.2.3 Measure the original crack length, a_o, and physical crack length after slow stable crack extension, a_p, in accordance with 8.9.4.

8.3 *Testing Rate*—Load the specimen such that the rate of increase of stress intensity factor to the load P_f is within the range from 0.55 to 2.75 MPa m$^{1/2}$/s (30 000 to 150 000 psi in.$^{1/2}$/min). Carry out the test under either crosshead or clip gage displacement control (see 6.1 and 10.1.4).

8.4 *Specimen Test Temperature*—Control the specimen test temperature to an accuracy of ±2°C (±3°F). It is recommended that tests be made in situ in suitable low or high temperature media, as appropriate. In a liquid medium, hold the specimen at least 30 s/mm (12 min/in.) after the specimen surface has reached the test temperature and prior to testing. When using a gaseous medium, use a soaking time significantly longer than 30 s/mm (12 min/in.) of thickness. The determination of an appropriate soaking time in a gaseous medium shall be the responsibility of those conducting the test.

8.5 *SE(B) Testing*—Install the bend fixture so that the line of action of the applied load passes mid-way between the support roller centers within 0.5 % of the distance between these centers. Position the specimens with the notch centerline mid-way between the rollers to within 0.5 % of the span, and position square to the roller axes within 2°.

8.6 *C(T) Testing*—To minimize errors from loading pin friction and eccentricity of loading from misalignment, the axes of the loading rods should be kept coincident within 0.8 mm (0.03 in.) during the test. Center the specimen with respect to the clevis opening within 0.8 mm (0.03 in.).

8.7 *Clip Gage Seating*—Seat the displacement gage in the knife or razor edges firmly, by lightly rocking the gage.

8.8 *Recording:*

8.8.1 The test records shall consist of autographic plots or digital records, or both, of the output of the load sensing device versus the output from the clip gage.

8.8.2 *Test Record*—The linear elastic portion of the load versus deflection test record shall exhibit a slope between 0.7 and 1.5. Maximum load can be estimated from 2.5 P_f, where P_f is as specified for SE(B) and C(T) specimens in 7.3.1.

8.9 *Measurements*—All specimen dimensions shall be within the tolerances shown in Figs. 6, 7, and 9.

8.9.1 *Thickness*—Measure the specimen thickness, B, before testing, accurate to the nearest 0.05 mm (0.002 in.) or 0.5 %B, whichever is larger, at three locations along the uncracked ligament of the specimen. Record the average B.

8.9.2 *SE(B) Specimen Width*—Prior to testing, measure the width, W, adjacent to the notch on both sides accurate to the nearest 0.05 mm (0.002 in.) or 0.1 %W, whichever is larger. Record average W.

8.9.3 *C(T) Specimen Width*—Prior to testing, measure the width, W, from the load line to the back edge of the specimen on both sides of the notch, accurate to the nearest 0.05 mm (0.002 in.) or 0.1 %W, whichever is larger. Record average W.

8.9.4 *Crack Length*—After completion of the test (and, if necessary, breaking open the specimen after heating tinting or fatigue cracking in accordance with 8.2), examine the fracture surface. Along the front of the fatigue crack, and along the front of any slow stable crack extension, including the SZW, measure the crack length at nine equally spaced points across the specimen thickness, centered about the specimen centerline and extending to 0.005W from the specimen surfaces. Calculate the original (fatigue) crack length, a_o, and the final physical crack length, a_p (which includes the tear length and SZW), as follows: average the two near-surface measurements, add this result to the remaining seven crack length measurements, and average this total length by dividing by eight (see 9.4 for crack geometry validity criteria). The individual crack length measurements should be accurate to within the nearest 0.03 mm (0.001 in.).

9. Analysis of Experimental Data

9.1 *Assessment of Load/Clip Gage Displacement Records*—The applied load-displacement record obtained from a fracture test on a notched specimen will usually be one of the five types shown in Fig. 1.

9.1.1 In the case of a smooth continuous record in which the applied load rises with increasing displacement up to the onset of unstable brittle crack extension or pop-in, and where no significant slow stable crack growth has occurred (see 3.2 and Figs. 1a and 1b), the critical CTOD, δ_c shall be determined from the load and plastic component of clip gage displacement, v_p, corresponding to the points P_c and v_c. If failure occurs close to the linear range, apply the procedure of Test Method E 399 to test whether a valid K_{Ic} measurement can be made.

9.1.2 In the event that significant slow stable crack extension (see 3.2) precedes either unstable brittle crack extension or pop-in, or a maximum load plateau occurs, the load-displacement curves will be of the types shown in Figs. 1c, 1d, and 1e, respectively. These figures illustrate the values of v and P to be used in the calculation of δ_u or δ_m, whichever is appropriate.

9.1.3 If the pop-in is attributed to an arrested unstable brittle crack extension in the plane of the fatigue precrack, the result must be considered as a characteristic of the material tested.

NOTE 1—Splits and delaminations can result in pop-ins with no arrested brittle crack extension in the plane of the fatigue precrack.

For this method, such pop-in crack extension can be assessed by a specific change in compliance, and also a post-test examination of the specimen fracture surfaces. When the post-test examination shows that the maximum pop-in crack extension has exceeded 0.04 b_o, calculate values of δ_c or δ_u corresponding to the loads P_c or P_u and displacements of v_c or v_u, respectively (for example, point B in Fig. 10a), in accordance with 9.2. When the post-test examination of the fracture surface shows no clear evidence that the maximum pop-in crack extension has exceeded 0.04 b_o, the following procedure may be used to assess the significance of small pop-ins (see 3.2 and Figs. 1b and 1d). Referring to Fig. 10:

9.1.3.1 Draw the tangent OA and a parallel line BC through the maximum load point associated with the particular pop-in under consideration.

9.1.3.2 Draw the line BD parallel to the load axis.

9.1.3.3 Mark the point E at 0.95BD.

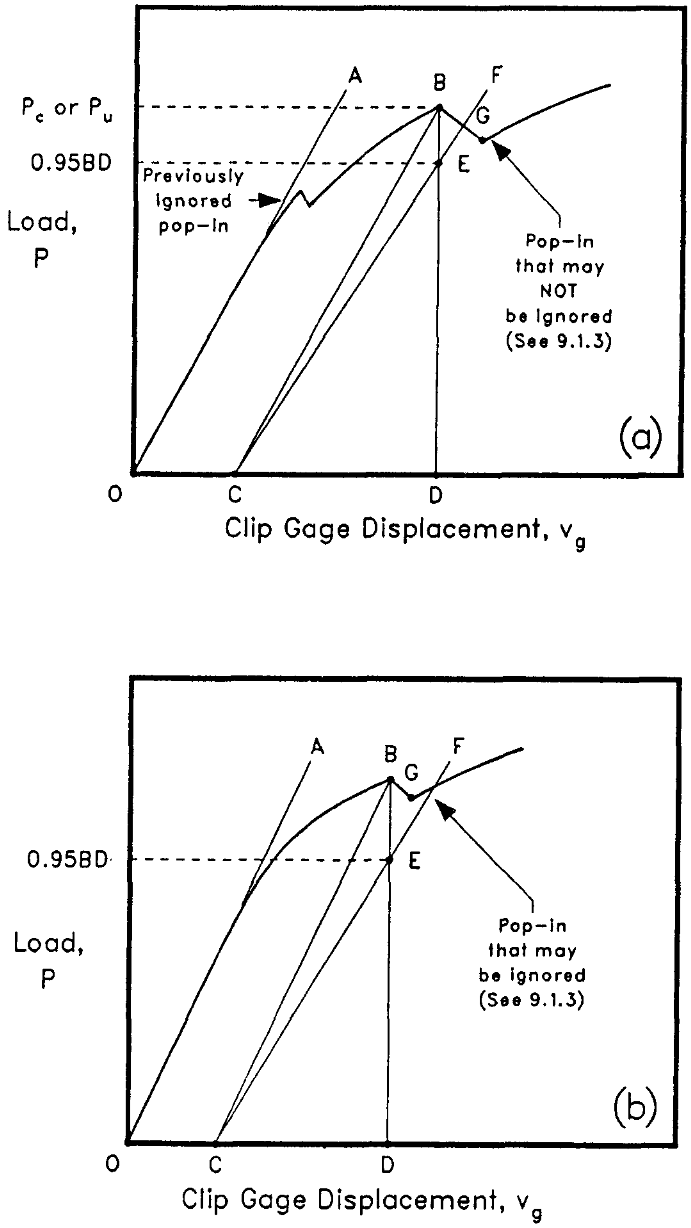
9.1.3.4 Draw the line CEF.

9.1.3.5 Mark the point G corresponding to the load and displacement at pop-in crack arrest.

9.1.3.6 When the point G is outside the angle BCF, calculate values of δ_c or δ_u corresponding to the loads P_c or P_u and displacements v_c or v_u, respectively (for example, point B in Fig. 10a), in accordance with 9.2.

9.1.3.7 When the point G is within the angle BCF, the pop-in may be ignored (Fig. 10b).

NOTE 2—Although an individual pop-in may be ignored on the basis of these criteria, this does not necessarily mean that the lower bound of fracture toughness has been measured. For instance, in an inhomogeneous material such as a weld, a small pop-in may be recorded because of fortuitous positioning of the fatigue precrack tip. Thus, a



NOTE—Slope of line CF is exaggerated for clarity.

FIG. 10 Significance of Pop-In

slightly different fatigue precrack position may give a larger pop-in, which could not be ignored. In such circumstances the specimens should be sectioned after testing, and examined metallographically to ensure that the crack tips have sampled the weld or base metal region of interest (see Ref. (**1**)).[3]

9.2 *Methods for Calculation of δ_c, δ_u, or δ_m*—Having obtained the required value of the clip gage displacement, it is necessary to convert this to the relevant CTOD using the following relationship for SE(B) specimens and C(T) specimens having $0.45 \leq a_o/W \leq 0.55$ (see 1.1.2 and 7.1.2). To calculate δ_c, δ_u or δ_m:

$$\delta = K^2(1 - \nu^2)/2\sigma_{YS}E + r_p(W - a_o)v_p/[r_p(W - a_o) + a_o + z]$$

[3] The boldface numbers in parentheses refer to the list of references at the end of this test method.

where:
$K = YP/[BW^{1/2}]$, and
Y is determined as follows:
(a) SE(B) Specimen having $S = 4W$:

$$Y = \frac{6(a_o/W)^{1/2}(1.99 - a_o/W[1 - a_o/W] \cdot [2.15 - 3.93a_o/W + 2.7(a_o/W)^2])}{(1 + 2a_o/W)(1 - a_o/W)^{3/2}}$$

(b) C(T) Specimen:

$$Y = \frac{(2 + a_o/W)(0.886 + 4.64a_o/W - 13.32(a_o/W)^2 + 14.72(a_o/W)^3 - 5.6(a_o/W)^4)}{(1 - a_o/W)^{3/2}}$$

Values of Y for the SE(B) and C(T) specimens are summarized in Tables 1 and 2, respectively.

P = load corresponding to P_c, P_u or P_m. See Fig. 1,
ν = Poisson's ratio,
σ_{YS} = yield or 0.2 % offset yield strength at the temperature of interest,
E = Young's modulus at the temperature of interest,
v_p = plastic component of clip gage opening displacement corresponding to v_c, v_u or v_m. See Fig. 1,
z = distance of knife edge measurement point from front face (notched surface) on SE(B) specimen, or from load line in C(T) specimen (see 6.4.1), and
r_p = plastic rotation factor = 0.4 $(1 + \alpha)$.

(c) for SE(B) specimen:
$\alpha = 0.1$, and
$r_p = 0.44$.

(d) for C(T) specimens:

$$\alpha = 2\sqrt{[(a_o/b_o)^2 + a_o/b_o + 1/2]} - 2(a_o/b_o + 1/2)$$

and

$$r_p = 0.47 \text{ for } 0.45 \leq a_o/W \leq 0.50, \text{ or}$$
$$r_p = 0.46 \text{ for } 0.50 < a_o/W \leq 0.55$$

9.3 *Discontinued Test*—If the test is terminated by some fault in the testing system, or the load-displacement recording exceeds the range of the clip gage or recording chart, report δ as being greater than that concomitant with the last load recorded. In the latter case, report the maximum load as greater than the load recorded at chart run-out.

9.4 *Qualifying CTOD Values:*

9.4.1 The critical CTOD values, for example, δ_c and δ_u, are valid if:

9.4.1.1 These values of CTOD are equal to or less than the measurement capacity of the specimen, which corresponds to δ_m.

9.4.1.2 The difference between the maximum and minimum of all 9 crack length measurements of the fatigue crack does not exceed 0.10 the original (fatigue) crack length a_o,

9.4.1.3 No part of the fatigue crack front is closer to the machined notch than the lesser of 0.025 W or 1.3 mm (0.05 in.),

9.4.1.4 The plane of the fatigue crack surface does not exceed an angle of 10° from the plane of the notch, and

9.4.1.5 The fatigue crack front is not multi-planar or branched.

10. Report

10.1 Report the following information for each test:

TABLE 1 Stress Intensity Coefficients (Y) for SE(B) Specimens Having $S/W = 4$

a/W	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.45	9.142	9.169	9.196	9.223	9.250	9.278	9.305	9.333	9.361	9.389
0.46	9.417	9.445	9.473	9.502	9.530	9.559	9.588	9.617	9.646	9.675
0.47	9.704	9.734	9.763	9.793	9.823	9.853	9.883	9.913	9.944	9.974
0.48	10.01	10.04	10.07	10.10	10.13	10.16	10.19	10.22	10.26	10.29
0.49	10.32	10.35	10.38	10.42	10.45	10.48	10.52	10.55	10.58	10.62
0.50	10.65	10.68	10.72	10.75	10.79	10.82	10.86	10.89	10.93	10.96
0.51	11.00	11.03	11.07	11.10	11.14	11.18	11.21	11.25	11.29	11.32
0.52	11.36	11.40	11.43	11.47	11.51	11.55	11.59	11.63	11.66	11.70
0.53	11.74	11.78	11.82	11.86	11.90	11.94	11.98	12.02	12.06	12.10
0.54	12.15	12.19	12.23	12.27	12.31	12.35	12.40	12.44	12.48	12.53
0.55	12.57									

NOTE—For rectangular and square section specimens see Figs. 6 and 7.

TABLE 2 Stress Intensity Coefficients (Y) for C(T) Specimens

a/W	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
0.45	8.340	8.363	8.387	8.410	8.434	8.458	8.482	8.506	8.531	8.555
0.46	8.579	8.604	8.629	8.654	8.678	8.704	8.729	8.754	8.779	8.805
0.47	8.830	8.856	8.882	8.908	8.934	8.960	8.987	9.013	9.040	9.066
0.48	9.093	9.120	9.147	9.175	9.202	9.230	9.257	9.285	9.313	9.341
0.49	9.369	9.398	9.426	9.455	9.483	9.512	9.541	9.571	9.600	9.629
0.50	9.659	9.689	9.719	9.749	9.779	9.810	9.840	9.871	9.902	9.933
0.51	9.964	10.00	10.03	10.06	10.09	10.12	10.16	10.19	10.22	10.25
0.52	10.29	10.32	10.35	10.39	10.42	10.45	10.49	10.52	10.56	10.59
0.53	10.63	10.66	10.70	10.73	10.77	10.80	10.84	10.87	10.91	10.95
0.54	10.98	11.02	11.06	11.10	11.13	11.17	11.21	11.25	11.29	11.33
0.55	11.36									

10.1.1 The specimen configuration.

10.1.2 The crack plane orientation in accordance with appropriate figures in Terminology E 616.

10.1.3 Specimen test temperature, °C (°F), and environment.

10.1.4 The crosshead displacement rate for testing systems in which the rate of change of crosshead displacement can be set, mm/min (in./min).

10.1.5 The time to reach the load P_f, min.

10.1.6 Material yield strength and tensile strength at room temperature.

10.1.7 Material yield strength and tensile strength at the temperature corresponding to the CTOD test conditions.

10.1.8 CTOD, δ_c, δ_u, or δ_m, mm (in.), as appropriate, to an accuracy of two significant figures.

10.1.9 Specimen thickness B, mm (in.).

10.1.10 Specimen width W, mm (in.).

10.1.11 SE(B) specimen load span S, mm (in.).

10.1.12 Specimen initial uncracked ligament size b_o, mm (in.).

10.1.13 Distance of clip gage away from SE(B) surface or from C(T) load line, z, mm (in.).

10.1.14 Crack length a_o, mm (in.), and, if applicable, Δa_p, mm (in.).

10.1.15 Load-displacement record.

10.1.15.1 The appropriate plastic component v_p of the clip gage opening displacement v_c, v_u, or v_m, mm (in.).

10.1.15.2 The appropriate applied force P_c, P_u, or P_m, N (lbf).

10.1.16 Fatigue precracking parameters and observations.

10.1.16.1 Range of stress intensity factor, ΔK, for the final portion of precrack growth, MPa$\sqrt{m}$ (ksi$\sqrt{in.}$).

10.1.16.2 The temperature of the specimen during precracking, °C (°F).

10.1.16.3 The load ratio, $R = P_{min}/P_{max}$.

10.1.16.4 Details of any pop-in that may have been ignored in accordance with the assessment procedure in 9.1.3.

11. Precision and Bias

11.1 *Precision:*

11.1.1 This practice contains four indices of fracture toughness, each of which derives variability from unique sources. Materials tested at upper shelf temperatures are characterized by δ_m for the onset of a maximum load plateau. The CTOD at maximum load, δ_m, can be sensitive to the quality of the autographic equipment used, especially the responsiveness to small changes in load or displacement, or both. The selection of the point of first onset of a maximum load plateau can be somewhat subjective and is a significant problem with very ductile materials that show extensive displacement approaching the maximum load.

11.1.2 The CTOD toughness of ferritic materials tested in the transition temperature range is characterized in this method by δ_c or δ_u. Subtle differences in constraint from geometry differences can promote inconsistency. Also in the mid-transition, data inconsistency, even among specimens of identical dimensions, is commonly encountered. This method recommends testing practices and specimen geometries that affect reasonable control over variability in CTOD outcome. Laboratories should replicate tests in order to assess the effects of variability on CTOD values.

11.1.3 An interlaboratory test program involving eleven laboratories was conducted to assess: (a) the measurement precision of the estimation of specific values of CTOD, and (b) the correlation between rectangular section SE(B) and C(T) specimens. CTOD fracture toughness was estimated for two materials at: (a) initiation of stable crack extension, (b) initiation of unstable crack extension, or (c) the onset of a maximum load plateau. The participants used either single-specimen unloading compliance, electric potential drop, or multiple-specimen heat tinting to estimate the CTOD at initiation of crack extension.[4]

11.2 *Bias:*

11.2.1 Bias suggests a consistent difference from a standard value or set of standard values. There are no "standard" CTOD values for any material. However, bias due to geometry variations can be expected in CTOD values for a particular material. In particular, specimen size and/or remaining ligament size are known to affect the CTOD transition temperature behavior in ferritic steels. Thicker specimens of a given material are expected to have a higher transition temperature. Also, for upper shelf behavior, the value of δ_m can be expected to be larger in specimens of larger plan view size or in specimens of larger remaining ligament size.

11.2.2 Differences in CTOD values for a given specimen thickness and test temperature have been observed between SE(B) and C(T) specimens. However, the present test method attempts to minimize such differences.

11.2.3 Finally, it should be noted that the plastic rotation factor r_p is not a constant factor. The parameter r_p is a complex function of specimen configuration and size, applied loading and material. The values of r_p used in this test method are slightly larger than those in other CTOD test methods **(2, 3)**. The values in this test method are based on an examination of published experimental data (see Refs **4–6**), and rigid plastic slip line field analyses **(7, 8)**.

[4] Data on the round robin results are on file at ASTM Headquarters. Request RR: E-24-1013.

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