Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials

1. Scope

1.1 This test method covers the determination of the plane-strain fracture toughness \( K_Ic \) of metallic materials by testing a variety of fatigue-cracked specimens having a thickness of 0.067 in. (1.7 mm) or greater. The details of the actual specimen and test configurations are shown in sections A1 through A7 and A9.

1.2 Plane-strain fracture toughness tests of thinner materials are sufficiently brittle (see 7.1) can be made with other types of geometries (3). There is no standard test method for testing such materials.

1.3 Measured values of plane-strain fracture toughness used in inch-pound units are to be regarded as standard.

1.4 This test method is divided into two main parts. The first part gives general information concerning the recommendations and requirements for \( K_Ic \) testing. The second part is composed of annexes that give the displacement-gage design, fatigue-cracking procedures, and special requirements for various specimen configurations covered by this method. In addition, an annex is provided for the specific procedures to be followed in rapid-load plane-strain fracture toughness tests. General information and requirements annex to all specimen types are listed as follows:

1.5 Special requirements for the various specimen configurations appear in the following order:

2. Referenced Documents

2.1 ASTM Standards:

- E 399 - 90 (Reapproved 1997)
- E 8 - Test Methods for Tension Testing of Metallic Materials

Annex A1

Special Requirements for Rapid-Load \( K_Ic \) Tests

1.5 Special requirements for the various specimen configurations appear in the following order:

- Annex A3
- Annex A4
- Annex A2
- Annex A5
- Annex A4
- Annex A6
- Annex A5

1.6 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.
3. Terminology

3.1 Definitions— Terminology E 616 is applicable to this test method.

3.1.1 Stress-intensity factor, K, KI, KG, KII, KIII (Ft-1/2)—the magnitude of the ideal-crack-tip stress field (a stress-field singularity) for a particular mode in a homogeneous, linear-elastic body.

3.1.1.1 Discussion—Values of K for modes I, II, and III are given by:

\[ K_I = \lim_{\rho \to 0} \frac{1}{\rho} \sqrt{2\pi} \sigma_{\tau,\rho}, \]

\[ K_{II} = \lim_{\rho \to 0} \frac{1}{\rho} \sqrt{2\pi} \tau_{\rho,\rho}, \]

\[ K_{III} = \lim_{\rho \to 0} \frac{1}{\rho} \sqrt{2\pi} \tau_{\rho,\tau}, \]

where \( \rho \) is a distance directly forward from the crack tip to a location where the significant stress is calculated.

3.1.1.2 Discussion—In this test method, mode I is assumed.

3.1.2 Plane-strain fracture toughness—the crack-extension resistance under conditions of crack-tip plane strain.

3.1.2.1 Discussion—For example, at mode I for slow rates of loading and negligible plastic-zone adjustment, plane-strain fracture toughness is the value of stress-intensity factor designated \( K_I (\text{Ft}^{-1/2}) \) as measured using the operational procedure (and satisfying all of the validity requirements) specified in this test method, which provides for the measurement of crack-extension resistance at the start of crack extension and provides operational definitions of crack-tip sharpness, start of crack extension, and crack-tip plane strain.

3.1.2.2 Discussion—See also definitions of crack-extension resistance, crack-tip plane strain, and mode.

3.1.2.3 Discussion—In this test method, mode I is assumed.

3.1.3 Crack plane orientation—an identification of the plane and direction of a fracture in relation to product geometry. This identification is designated by a hypnotized code with the first letter(s) representing the direction normal to the crack plane and the second letter(s) designating the expected direction of crack propagation.

3.1.3.1 Discussion—The fracture toughness of a material usually depends on the orientation and direction of propagation of the crack in relation to the anisotropy of the material, which depends, in turn, on the principal directions of mechanical working or grain flow. The orientation of the crack plane should be identified wherever possible in accordance with the following systems (11). In addition, the product form should be identified (for example, straight-rolled plate, cross-rolled plate, panicake forging, etc.).

3.1.3.2 Discussion—For rectangular sections, the reference directions are identified as in Figs. 1 and 2, which gives examples for a rolled plate. The same system would be useful for sheet, extrusions, and forgings with nonsymmetrical grain flow.

4. Summary of Test Method

4.1 This test method involves testing of notched or unnotched specimens that have been precracked in fatigue by loading in tension and bending, or by thermal cycling, or by loading in fatigue, across the notch at the specimen edge in the direction normal to the axis of the specimen. The load corresponding to a 2% apparent increment of crack extension is established by a specified deviation from the linear portion of the load. The \( K_I \) value is calculated from this load by equations that have been established on the basis of elastic stress analysis of specimen of the type described in this method. The validity of the determination of \( K_I \) value by this test method depends upon the establishment of a uniform condition of the crack tip. Although the crack tip is not sharp, the crack is sharp enough to propagate at a relatively low rate.

4.2 The specimen size required for testing purposes is determined by the strength of the material; therefore a range of proportional specimens is provided.

5. Significance and Use

5.1 The property \( K_I \) determined by this test method

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FIG. 1 Crack Plane Orientation Code for Rectangular Sections

FIG. 2 Crack Plane Orientation Code for Rectangular Sections where Specimens are Tilted with Respect to the Reference Directions

develops the resistance of a material to fracture in a
real environment in the presence of a sharp crack under
realistic constraint, such that the state of stress near the
crack front approaches tensile plane strain, and the crack-
by-crack plastic region is small compared with the crack size
and crack plane directions. A $K_{IC}$ value is related
by fracture toughness testing to a lower limiting value of fracture
strength. This value may be used to estimate the relation
between failure stress and notch size for a material in service
under the conditions of high constraint described above
and expected. Background information concerning the
use of this method in terms of linear elastic fracture mechanics may be found in Refs (1) and (2).

The $K_{IC}$ value of a given material is a function of
notch geometry and environment. Furthermore, cyclic loads can
lead to crack extension at $K_{IC}$ values less than the $K_{IC}$ value.
A crack can extend under cyclic or sustained load without
nucleation by the presence of an aggressive environment. There-

FIG. 3 Crack Plane Orientation Code for Bar and Hollow Cylinder

fore, application of $K_{IC}$ in the design of service components
should be made with awareness to the difference that may
exist between the laboratory tests and field conditions.

5.1.2 Plane-strain crack toughness testing is unusual in
that there can be no advance assurance that a valid $K_{IC}$ will
be determined in a particular test. Therefore it is essential
that all of the criteria concerning validity of results be
carefully considered as described herein.

5.1.3 Clearly it will not be possible to determine $K_{IC}$, if any
dimension of the available stock of a material is insufficient
to provide a specimen of the required size. In such a case the
specimen strength ratio determined by this method will often
have useful significance. However, this ratio, unlike $K_{IC}$, is
not a concept of linear elastic fracture mechanics, but can be
a useful comparative measure of the toughness of materials

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when the specimens are of the same form and size, and that size is insufficient to provide a valid determination, but sufficient that the maximum load results from pronounced crack propagation rather than plastic instability.

5.1.3.1.1 The strength ratio for center-cracked plate specimens tested in uniaxial tension may be determined by Test Method E 338.

5.2 This test method can serve the following purposes:

5.2.1 In research and development to establish, in quantitative terms, significant to service performance, the effects of metallurgical variables such as composition or heat treatment, or of fabricating operations such as welding or forming, on the fracture toughness of new or existing materials.

5.2.2 In service evaluation, to establish the suitability of a material for a specific application for which the stress conditions are prescribed and for which maximum flaw sizes can be established with confidence.

5.2.3 For specifications of acceptance and manufacturing quality control, but only when there is a sound basis for specification of minimum values, and then only if the dimensions of the product are sufficient to provide specimens of the size required for valid determination. The specification of the values in relation to a particular application should signify that a fracture control study has been conducted on the component in relation to the expected history of loading and environment, and in relation to the sensitivity and reliability of the crack detection procedures that are to be applied prior to service and subsequently during the anticipated life.

6. Apparatus

6.1 Loading—Specimens should be loaded in a testing machine that has provision for automatic recording of the load applied to the specimen.

6.2 Fixtures—Fixtures suitable for loading the specimen configurations covered by this method are shown in the appropriate annex. These fixtures are so designed to minimize the frictional contributions to the measured load.

6.3 Displacement Gauge—The displacement gauge output shall indicate the relative displacement of two gauge points located gage positions spanning the crack starter notch mouth. Exact and positive positioning of the gage on the specimen is essential, yet the gage must be released without damage when the specimen breaks. A recommended design for a self-supporting, releasable gage is shown in Fig. 4 and described in Annex A1. The strain gage bridge arrangement is also shown in Fig. 4.

6.3.1 The specimen must be provided with a pair of accurately machined knife edges that support the gage area and serve as the displacement reference points. These knife edges can be machined integral with the specimen as shown in Fig. 4 and Fig. 5 or they may be separate pieces fixed to the specimen. A suggested design for such attachable knife edges is shown in Fig. 6. This design is based on a knife edge spacing of 0.2 in. (5.1 mm). The effective gage length is established by the points of contact between the knife and hole threads. For the design shown, the major diameter of the screw has been used in setting this gage length. A No 2 screw will permit the use of attachable knife edges in specimens having \( W > 1 \) in. (25 mm).

6.3.2 Each gage shall be checked for linearity using an extensometer calibrator or other suitable device. The repetitability of the calibrator at each displacement interval should be within \( <0.00005 \) in. (0.00013 mm). Readings shall be taken at equally spaced intervals over the working range of the gage (see Annex A1). This calibration procedure should be performed three times, removing and

FIG. 4 Double-Cantilever Clip-To-Displacement Gage Showing Mounting by Means of Integral Knife Edges (Gage Design Details are Given in Annex A1)
7. Specimen Size, Configurations, and Preparation

7.1 Specimen Size

7.1.1 In order for a result to be considered valid according to this method it is required that both the specimen thickness, \( B \), and the crack length, \( a \), exceed \( 2.5 (K_I / \sigma_y)^{1/2} \) where \( \sigma_y \) is the 0.2% offset yield strength of the material for the temperature and loading rate of the test (1, 5, 6).

7.1.2 The initial selection of a size of specimen from which valid values of \( K_I \) will be obtained may be based on an estimated Value of \( K_I \) for the material. It is recommended that the value of \( K_I \) be overestimated, so that a conservatively large specimen will be employed for the initial tests. After a valid \( K_I \) result is obtained with the conservative-size initial specimen, the specimen size may be reduced to an appropriate size [a and \( B \geq 2.5 (K_I / \sigma_y)^{1/2} \)] for subsequent testing.

7.1.3 Alternatively, the ratio of yield strength to Young's modulus can be used for selecting a specimen size that will be adequate for all but the toughest materials.

When it has been established that \( 2.5 (K_I / \sigma_y)^{1/2} \) is substantially less than the minimum recommended thickness given in the preceding table, then a correspondingly smaller specimen can be used. On the other hand, if the form of the available material is such that it is not possible to obtain a specimen with both crack length and thickness greater than \( 2.5 (K_I / \sigma_y)^{1/2} \), then it is not possible to make a valid \( K_I \) measurement according to this method.

7.2 Specimen Configurations—The configurations of the various specimens are shown in the following annexes: Annex A3, Bend Specimen SE; Annex A4, Compact Specimen C (T); Annex A5, Arc-Shaped Tension Specimen A (T); Annex A6, Disk-Shaped Compact Specimen DC (T); and Annex A9, Arc-Shaped Bend Specimen A(B).

7.2.1 Standard Specimens—The crack length, \( a \) (crack starter notch plus fatigue crack) is nominally equal to the thickness, \( B \), and is between 0.45 and 0.55 times the width, \( W \). The ratio \( W/B \) is nominally equal to two.

7.2.2 Alternative Specimens—In certain cases it may be desirable to use specimens having \( W/B \) ratios other than two. Alternative proportions for bend specimens are \( 1 \leq W/B \leq 4 \). For the other specimen configurations, alternative specimens may have \( 2 \leq W/B \leq 4 \). These alternative specimens shall have the same crack length-to-width ratio as the standard specimens. It should be appreciated that \( K_I \) values, obtained using alternative specimen proportions may not agree with those obtained using the standard specimens (15).

7.3 Specimen Preparation—The dimensional tolerances and surface finishes shown on the specimen drawings given
in Annexes A3 to A6 and A9 shall be followed in specimen preparation.

7.3.1 Fatigue Crack Starter Notch—Three forms of fatigue crack starter notches are shown in Fig. 7. To facilitate fatigue-cracking at low stress intensity levels, the root radius for a straight-through slot terminating in a V-notch should be 0.003 in. (0.08 mm) or less. If a chevron form of notch is used, the root radius may be 0.010 in. (0.25 mm) or less. In the case of a slot tipped with a hole it will be necessary to provide a sharp stress raiser at the end of the hole. Care should be taken to ensure that this stress raiser is so located that the crack plane orientation requirements (2.4.2) can be met.

7.3.2 Fatigue Cracking—Fatigue cracking shall be conducted in accordance with the procedures outlined in Annex A2. Fatigue cycling shall be continued until the fatigue crack will satisfy the requirements stated in the following two sections.

7.3.2.1 The crack length (total length of the crack starter configuration plus the fatigue crack) shall be between 0.45 and 0.55 W.

7.3.2.2 For a straight-through crack starter terminating in a V-notch (see Fig. 7), the length of the fatigue crack on each surface of the specimen shall not be less than 2.5% of W or 0.005 in. (1.3 mm) min, and for a crack starter tipped with a drilled hole (see Fig. 7), the fatigue crack extension from the stress raiser tipping the hole shall not be less than 0.5 of 0.050 in. on both surfaces of the specimen, where D is the diameter of the hole, (1.3 mm), min. For a chevron notch crack starter (see Fig. 7), the fatigue crack shall emerge from the chevron on both surfaces of the specimen.

8. General Procedure

8.1 Number of Tests—It is recommended that at least three replicate tests be made for each material condition.

8.2 Specimen Measurement—Specimen dimensions shall conform to the tolerances shown in the appropriate annex. Three fundamental measurements are necessary for the calculation of the stress intensity factor, namely, the thickness, B, the crack length, a, and the width, W.

8.2.1 Measure the thickness, B, to the nearest 0.001 in. (0.025 mm) or to 0.1%, whichever is larger, at not less than three equally spaced positions along the line of intended crack extension from the fatigue crack tip to the unnotched side of the specimen. The average of these three measurements should be recorded as B.

8.2.2 Measure the crack length, a, after fracture to the nearest 0.5 % at the following three positions: at the center of the crack front, and midway between the center of the crack front, and the end of the crack front on each surface of the specimen.
specimen. Use the average of these three measurements as the crack length to calculate \( K_c \). The following requirements shall apply to the fatigue crack front: (1) The difference between any of the three crack length measurements shall not exceed 10% of the average. (2) For a chevron notch starter (see Fig. 7), the fatigue crack shall emerge from the specimen on both surfaces of the specimen, neither surface crack length shall differ from the average length by more than 10%, and the difference between these two surface measurements shall not exceed 10% of the average crack length. (3) For a straight-through starter notch (see Fig. 7) no part of the crack front shall be closer to the machined starter notch than 2.5\( \mu \text{m} \) or 0.050 in. (1.3 mm) minimum, nor shall the surface crack length measurements differ from the average crack length by more than 15%, and the differences between these two measurements shall not exceed 10% of the average crack length.

8.3 Measure the width, \( W \), as described in the annex appropriate to the specimen type being tested.

8.4 The plane of the crack shall be parallel to both the specimen width and thickness direction with \( \pm 10^\circ \) (7).

8.5 Loading Rate—For conventional (static) testing load a specimen at a rate such that the rate of increase of stress intensity is within the range from 30,000 to 150,000 psi in.\(^{-1/2}\) min\(^{-1}\) (0.55 to 2.75 MPa m\(^{1/2}\) s\(^{-1}\)). The loading rates corresponding to these stress intensity rates are given in the appropriate annex for the specimen being tested. For rapid-loading testing the loading rates are given in Annex A7.

8.6 Test Record—Make a test record consisting of an acoustic plot of the output of the load-sensing transducer versus the output of the displacement gage. The initial slope of the linear portion shall be between 0.7 and 1.5. It is conventional to plot the load along the vertical axis, as in an ordinary tension test record. Select a combination of load-sensing transducer and autographic recorder so that the load, \( P_c \), net 9.1), can be determined from the test record with an accuracy of ±1%. With any given equipment, the accuracy at readout will be greater the larger the scale of the test record.

8.7 Continue the test until the specimen can sustain no further increase in load. In some cases the range of the chart will not be sufficient to include all of the test record up to maximum load, \( P_{max} \). In any case, read the maximum load from the dial of the testing machine (or other suitable recorder) and record it on the chart.

9. Calculation and Interpretation of Results

9.1 Interpretation of Test Record and Calculation of \( K_c \)—in order to establish that a valid \( K_c \) has been determined, it is necessary first to calculate a conditional result, \( K_{c0} \), which involves a construction on the test record, and then to determine whether this result is consistent with the size and \( \delta \) strength of the specimen according to 7.1. The procedure is as follows:

9.1.1 Draw the initial line \( OP \), shown in Fig. 7 through the origin of the test record with slope \( (P_{0.5})/\delta = 0.95 \) \((P_{0.5})/\delta \) in the slope of the tangent \( CD \) to the initial part of the record (Note 6). The load \( P_{0.5} \) is then defined as follows: if the load at every point on the record which precedes P is lower than \( P_{0.5} \), then \( P = P_{0.5} \) (Fig. 8 Type II). If, however, there is a maximum load preceding \( P_{0.5} \) which exceeds it, then this maximum load is \( P_{max} \) (Fig. 8 Types II and III).

9.1.2 Calculate the ratio \( P_{max}/P_{0.5} \), where \( P_{max} \) is the maximum load the specimen was able to sustain (see 8.4). If this ratio does not exceed 1.10, proceed to calculate \( K_{c0} \) as described in the annex appropriate to the specimen being tested. If \( P_{max}/P_{0.5} \) does exceed 1.10, then the test is not a valid \( K_c \) test because it is then possible that \( K_c \) bears no relation to \( K_c \). In this case proceed to calculate the specimen strength ratio.

9.1.3 Calculate 2.5 \((K_{c0}/\delta^{1/2})\) where \( \delta^{1/2} \) is the 0.2% offset yield strength in tension (see Test Methods E 8). If this quantity is less than both the specimen thickness and the crack length, then \( K_{c0} \) is equal to \( K_c \). Otherwise, the test is not a valid \( K_c \) test. Expressions for calculations of \( K_{c0} \) are given in the annex appropriate to the specimen being tested.

9.1.4 If the test result fails to meet the requirements in 9.1.2 or in 9.1.3, or both, it is necessary to use a larger specimen to determine \( K_c \). The dimensions of the larger specimen can be estimated on the basis of \( K_c \) but generally will be at least 1.5 times those of the specimen that failed to yield a valid \( K_c \) value.

9.1.5 Calculate the specimen-strength ratio \( K_{c0} \), according to the annex appropriate to the specimen being tested.

9.2 Fracture Appearance—The appearance of the fracture is valuable supplementary information and shall be noted for each specimen. Common types of fracture appearance are shown in Fig. 9. For fractures of Types (a) or (b), measure the average width, \( b \), of the central flat fracture area, and note and record the proportion of oblique fracture per unit flat area thickness \( (b)/B \). Make this measurement at a location midway between the crack tip and the unnotched edge of the specimen. Report fracture Type of (c) as full oblique fractures.

10. Report

10.1 The specimen configuration code as shown with the specimen drawing in the appropriate annex shall be reported. In addition, this code shall be followed with loading code \( (T \) for tension and \( B \) for bending) and the code for crack plane orientation (see Section 5). These latter two codes should appear in separate parentheses. For example, a test result obtained using the compact specimen (see Annex A4) might be designated as follows: C(T)T5-T. The first letter indicates compact specimen. The second letter indicates the loading test tension and the first of the last two letters indicates that the normal to the crack plane is in the direction of principal deformation and the second of these letters indicates the intended direction of crack propagation is in the direction of least deformation.

10.2 In addition, the following information should be reported for each specimen tested:

10.2.1 The form of the product tested: for example, forging, plate, casting, etc.

10.2.2 Thickness, \( B \).
10.2.3 Width (depth), W.

10.2.3.1 Offset of the loading holes, X, for the arc-shaped tension specimen.

10.2.3.2 Outer and inner radii, r2 and r1, for arc-shaped specimens.

10.2.4 Fatigue precracking conditions in terms of:

10.2.4.1 Maximum stress intensity, \( K_{\text{max}} \), and number of cycles for terminal fatigue crack extension over a length at least 2.5% of the overall length of notch plus crack, and

10.2.4.2 The stress intensity range for terminal crack extension.

10.2.5 Crack length measurements:

10.2.5.1 At center of crack front;

10.2.5.2 Midway between the center and the end of the crack front on each side, and at each surface.

10.2.6 Test temperature.

10.2.7 Relative humidity as determined by Test Method E 337.

10.2.8 Loading rate in terms of \( K_i \) (change in stress intensity factor per unit time) (2).

10.2.9 Load-displacement record and associated calculations.

10.2.10 Fracture appearance.

10.2.11 Yield strength (offset = 0.2%) as determined by Methods E 8.

10.2.12 \( R_{\text{ch}} \) or \( R_{\text{ch}} \) followed by the parenthetical statement "invalid according to section(s) . . . . . . of ASTM Test Method E 399."

10.2.13 \( R_X \) where \( x \) refers to the specimen configuration as given in the appropriate annex.

10.2.14 \( P_{\text{max}}/P_{\text{op}} \)

FIG. 9 Common Types of Fracture Appearance

10.3 It is desirable to list the information required in 10.1 and 10.2 in the form of a table. A suggested form for such a table is given in Fig. 10.
FIG. 10  Suggested Form of Table for Reporting Information Listed in 10.1 and 10.2

TABLE 1  Estimates of Precision for Ken Measurements for Three Specimen Types

<table>
<thead>
<tr>
<th>Specimen Types</th>
<th>2019-1810</th>
<th>18N steel</th>
<th>4340</th>
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<tr>
<td>934 Units</td>
<td>233</td>
<td>140</td>
<td>1419</td>
</tr>
<tr>
<td><strong>Park</strong></td>
<td>50.6</td>
<td>48.2</td>
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<td><strong>Hayes</strong></td>
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<td>2.04</td>
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<td><strong>Manga</strong></td>
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<td>2.41</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Bend Specimens

Grand mean, X\(\bar{X}\) = 35.6 (22.4) 50.2 (45.9) 58.2 (53.0) 67.3 (79.4)

Standard deviation, S\(\bar{X}\) = 1.24 (1.13) 1.40 (1.27) 1.96 (1.64) 1.96 (1.79)

Compact Specimens

Aircraft specimens

Grand mean, X\(\bar{X}\) = 35.6 (22.4) 50.2 (45.9) 58.2 (53.0) 67.3 (79.4)

Standard deviation, S\(\bar{X}\) = 1.24 (1.13) 1.40 (1.27) 1.96 (1.64) 1.96 (1.79)

Aircraft specimens

X\(\bar{X}\) = 35.6 (22.4) 50.2 (45.9) 58.2 (53.0) 67.3 (79.4)

Standard deviation, S\(\bar{X}\) = 1.24 (1.13) 1.40 (1.27) 1.96 (1.64) 1.96 (1.79)

* Units of grand mean and standard deviation are [mm] (s.e.)*

The standard deviation has been pooled for all laboratories testing a given alloy. For data on which this table was based, see Refs (8, 9) for the bend specimen, Ref (8) for the compact specimen, and Ref (18) for the aircraft specimen.
structure. Thus the contribution of material variability to the measurements of $K_i$ was minimized. It should be understood that the measures of precision listed in Table 1 apply to alloys which do not exhibit strong transitional fracture behavior with changes in temperature or strain rate. When temperature and strain rate variations induce large changes in toughness, increased scatter in $K_i$ measurements may be noted. For example, within or below the transition range of a structural steel, the initial advance from the fatigue crack will be controlled by the abrupt fracture of local elements at the crack tip, accompanied by rapid transfer of load to adjacent regions which may then exhibit cleavage fracture. Under these circumstances, a specimen size effect may be observed in which both the mean and the standard deviation of $K_i$ values tend to increase with decreasing specimen size.

11.3 Bias—There is no accepted "standard" value for the plane strain fracture toughness of any material. In the absence of such a true value, any statement concerning bias is not meaningful.

**ANNEXES**

*(Mandatory Information)*

**A1. DESIGN FOR DOUBBLE-CANTILEVER DISPLACEMENT GAGE**

A1.1 The gage consists of two cantilever beams and a spacer block which are clamped together with a single nut and bolt, as shown in Fig. A.1. Electrical-resistance strain gages are cemented to the tension and compression surfaces of each beam, and are connected as a Wheatstone bridge incorporating a suitable balancing resistor. The material for the gage beams should have a high ratio of yield strength to elastic modulus, and titanium alloy 13V-11Cr-2Al in the solution treated condition has been found very satisfactory for this purpose. If a material of different modulus is substituted, the spring constant of the assembly will change correspondingly, but the other characteristics will not be.

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**Note:** Dimensions are in inches.

<table>
<thead>
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<th><strong>Metric Equivalents</strong></th>
<th><strong>in.</strong></th>
<th><strong>mm</strong></th>
<th><strong>In.</strong></th>
<th><strong>mm</strong></th>
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<td>41.28</td>
<td>1047.8</td>
</tr>
</tbody>
</table>

**FIG. A.1.1** Beams for Double-Cantilever Displacement Gage

422
A2. FATIGUE PRECRACKING OF $K_I$

FRAC TURE TOUGHNESS SPECIMENS

most engineering materials since the fatigue cracking process can be closely controlled when careful attention is given to the known contributory factors. However, there are some materials that are too brittle to be fatigue cracked since they fracture as soon as the fatigue crack initiates; these are outside the scope of the present test method. The purpose of this annex is to provide guidance on the production of satisfactory fatigue precracks, and to state the associated requirements for a valid $K_I$ test.
A.2.1.2 A fatigue precrack is produced by cyclically loading the notched specimen with a ratio of minimum to maximum stress between ~1 and +0.1 for a number of cycles usually between about 10^3 and 10^6 depending on specimen size, notch preparation, and stress intensity level. The maximum stress intensity in the terminal (2.5 %) stage of fatigue crack growth must not exceed 60 % of the \( K_{\text{J}} \) value of the material. Some fraction of the total number of cycles required to produce the fatigue precrack is consumed in initiation of the crack at the notch root; the remainder accounts for growth of the crack to the required length. If the total number of cycles is excessive, the reason is usually that the number of cycles required for initiation is excessive rather than that the subsequent rate of crack growth is low. There are several ways of promoting early crack initiation: (1) by providing a very sharp notch tip; (2) by using a chevron notch (Fig. 33); (3) by statically preloading the specimen in such a way that the notch tip is compressed in a direction normal to the intended crack plane but without allowing the nominal compressive stress to exceed the yield strength of the material; (4) by using a negative fatigue load ratio.

A.2.2 Equipment

A.2.2.1 The equipment for fatigue cracking shall be such that the stress distribution is uniform through the specimen thickness; otherwise the crack will not grow uniformly. The stress distribution shall also be symmetrical about the plane of the prospective crack; otherwise the crack will deviate unduly from that plane and the test result will be significantly affected (7).

The K calibration for the specimen, as loaded by the equipment, shall be known with an error of not more than 5 %. The K calibration is the relation of the stress intensity factor \( K \) to either the load or to some prescribed displacement and the specimen dimensions (1). The stresses recommended in the test method (see appropriate annex) are also suitable for fatigue cracking, and K calibrations for specimens loaded through these fixtures are given in the annexes of this test method. If different fixtures are used, the appropriate K calibration should be determined experimentally with these fixtures (7). The advantage of experimental K calibration, as compared with numerical methods of analysis, is that accurate modeling of the boundary conditions with the actual fixtures is assured. It is important to bear in mind that if the fatigue cycle involves reversal of load, the K calibration can be very sensitive to the distribution of clamping forces necessary to grip the specimen.

A.2.3 Specimen Requirements

A.2.3.1 The fatigue precracking shall be conducted with the specimen fully heat treated to the condition in which it is to be tested.

A.2.3.2 The combination of starter notch and fatigue precrack must conform to the requirements shown in Fig. 7. The nominal crack length is equal to 0.5 % of the total length of the starter notch slot plus fatigue crack. To facilitate fatigue precracking at a low level of stress intensity, the notch root radius of a straight-notch should be no more than -0.003 in. (0.08 mm). If a chevron notch is used (Fig. 7), the notch root radius can be as much as 0.01 in. (0.25 mm) because of the compound stress concentration at the point of the chevron. Early crack initiation can also be promoted by precompression of the notch tip region, as stated in A.2.1.2.

A.2.3.3 It is advisable to mark two pencil lines on each side of the specimen normal to the anticipated paths of the surface traces of the fatigue crack. The line most distant from the notch tip should indicate the minimum required length of fatigue crack, and the other the terminal part of that length equal to not less than 2.5 % of the overall length of notch plus fatigue crack, that is 0.0125 in. During the final stage of fatigue crack extension, for at least this distance, the ratio of maximum stress intensity of the fatigue cycle to the Young's modulus of the material, \( K_{\text{J}}/E \), shall not exceed 0.002 in. \( K_{\text{J}}/E \). Furthermore, the \( K_{\text{J}}/E \) must not exceed 60 % of the \( K_{\text{J}} \) value determined in the subsequent test if \( K_{\text{J}} \) is to qualify as a valid \( K_{\text{J}} \) result.

A.2.4 Precracking Procedure

A.2.4.1 Fatigue precracking can be conducted under either load control or displacement control provided that the appropriate K calibration is known with requisite accuracy for the specimen and fixture (A.2.2.1). If the load cycle is maintained constant, the maximum K and the K range will increase with crack length, if the displacement cycle is maintained constant, the reverse will happen. The initial value of the maximum fatigue load or displacement should be calculated from the K calibration and the specimen and notch dimensions. It is suggested that this load be selected so that the maximum stress intensity factor in the initial portion of the fatigue cycle does not exceed 80 % of the estimated \( K_{\text{J}} \) value of the material. Higher K values result in undesirable high crack growth rates. The minimum is then selected so that the stress ratio is between ~1 and +0.1. The more negative the stress ratio, the faster the fatigue precrack will be completed, but this advantage is offset by the need for more elaborate fixtures than are required when the stress ratio is positive.

A.2.4.2 The specimen shall be accurately located in the loading fixture and secured as required so that the boundary conditions correspond to the applicable K calibration. Fatigue cycling is then begun, usually with a sinusoidal waveform and near to the highest practical frequency. There is no known marked frequency effect on fatigue precrack formation up to at least 100 Hz in the absence of adverse environments. The specimen should be carefully monitored until crack initiation is observed on one side. If crack initiation is not observed on the other side before appreciable growth is observed on the first, then fatigue cycling should be stopped to try to determine the cause and remedy for the unsymmetrical behavior. Sometimes, simply turning the specimen around in relation to the fixture will solve the problem. When the most advanced crack trace has almost reached the first scribed line corresponding to 97.5 % of the final crack length, the maximum load or displacement, as appropriate, shall be reduced so that the terminal value \( K_{\text{J}}/E \) is unlikely to exceed 60 % of the estimated minimum value of \( K_{\text{J}} \), of the material, and also the terminal value of \( K_{\text{J}}/E \) will not exceed 0.002 in. \( K_{\text{J}}/E \). To minimize the load the stress ratio is then adjusted so that the stress ratio is between ~1 and +0.1. Fatigue cycling is then continued until the surface traces on both sides of the specimen indicate that...
A.3. SPECIAL REQUIREMENTS FOR THE TESTING OF BEND SPECIMENS

A.3.1 Specimen

A.3.1.1 The standard bend specimen is a single edge-notched and fatigue cracked beam loaded in three-point bending with a support span, S, nominally equal to four times the beam width, W. The general proportions of this specimen configuration are shown in Fig. A.3.1.

A.3.1.2 Alternative specimens may have S ≤ W/2 or S = 4W. The second specimen shall also have a nominal support span equal to 4W.

A.3.2 Specimen Preparation

A.3.2.1 For generally applicable specifications concerning specimen size and preparation see Section 7.

A.3.2.2 It is desirable to fatigue crack the bend specimen in the same fixtures in which it will be tested so that the K calibration is accurately known. However, bend specimens are sometimes cracked in cantilever bending because this method permits ease of reversed loading. If the K calibration in three-point bending is used in cantilever bending, the bending moments for a given K value will be underestimated. While fatigue cracking in cantilever bending can yield satisfactory results, it should be emphasized that the crack tip area field can be distorted and the fatigue crack orientation changed by excessive clamping forces.

A.3.3 Apparatus

A.3.3.1 Bend Test Fixture—The general principles of the bend test fixture are illustrated in Fig. A.3.2. 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 axially positively positioned against stops that set the span length and are held in place by low-tension springs (such as fiber bands).

A.3.3.2 Displacement Gate—For generally applicable details concerning the displacement gate see 6.3. For the bend test the displacements will be essentially independent
ture Tt and testing at a different temperature Tt, Kmax must not exceed 0.6 (σy/√σs)Kc where σy and σs are the yield strengths at the respective temperatures Tt and Tc.

of the gauge length up to a gauge length of W/2.

A.3.4 Procedure

A.3.4.1 Measurements—For a bend specimen measure the width (depth), W, and the crack length, a, from the notched side of the specimen to the opposite side and to the crack front, respectively.

A.3.4.1.1 For general requirements concerning specimen measurement see 8.2.

A.3.4.2 Bend Specimen Testing—Set up the test fixture so that the line of action of the applied load shall pass midway between the support roll centers within 1% of the distance between these centers (for example, within 0.04 in. (1.0 mm) for a 4-in. (100-mm) span). Measure the span to within 0.5% of nominal length. Locate the specimen with the crack tip midway between the rolls to within 1% of the span, and square to the roll axes within 2°. Seat the displacement gate on the knife edges to maintain registry between knife edges and gate grooves. In the case of attachable knife edges, seat the gate before the knife edge positioning screws are tightened.

A.3.4.2.1 Load the specimen at a rate such that the rate of increase of stress intensity is within the range 50 to 150 ksi-in.1/2/min (0.55 to 2.75 MPa·m1/2/s), corresponding to a loading rate for the standard (B = 0.5 W) 1-in. (25.4-mm) thick specimen between 4000 and 20 000 lb/min (0.30 to 1.5 kN/s).

A.3.4.3 For details concerning recording of the test record see 8.4.

A.3.5 Calculations

A.3.5.1 Interpretation of Test Record—For general requirements and procedures in interpretation of the test record see 9.1.

A.3.5.2 Validity Requirements—For a description of the validity requirements in terms of limitations on Pmax/P0 and the specimen size requirements, see 9.1.2 through 9.1.3.

A.3.5.3 Calculation of Kc—For the bend specimen calculate Kc in units of ksi-in.1/2 (MPa·m1/2) as follows (Note A.13.3)

\[ K_c = \left( \frac{P_{max}}{B W^{1/2}} \right) f_a / (u/W) \]

FIG. A.3.1 Bend Specimen SE (B)—Standard Proportions and Tolerances
FIG. A.3.2 Bend Test Futures Design

where:

\[ \frac{3(a/W)^2}{4}(1.19 - \frac{a}{W})^2 \times (2.13 - 1.93a/W + 2.3a^2/W^2) \]
\[ \times (2 + 2a/W)(1 - a/W) \]

\[ f(a/W) = \frac{2}{1 + \frac{2a}{W}} \]

where:

- \( P_0 \) = load as determined in 9.1.1, kbf (kN),
- \( B \) = specimen thickness as determined in 8.2.1, in. (cm),
- \( S \) = span as determined in A.3.4.2, in. (cm),
- \( W \) = specimen depth (width) as determined in A.3.4.1, in. (cm),
- \( a \) = crack length as determined in 8.2.2, in. (cm).

Note A3.1—This expression is considered to be accurate within ±5.5% over the entire range of \( a/W \) from 0 to 1 for an \( S/W = 4 \) (12).

To facilitate calculation of \( K_{p0} \), values of \( f(a/W) \) are tabulated in the following table for specific values of \( a/W \).

<table>
<thead>
<tr>
<th>( a/W )</th>
<th>( f(a/W) )</th>
<th>( a/W )</th>
<th>( f(a/W) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.450</td>
<td>2.29</td>
<td>0.000</td>
<td>3.66</td>
</tr>
<tr>
<td>0.453</td>
<td>2.32</td>
<td>0.005</td>
<td>3.70</td>
</tr>
<tr>
<td>0.460</td>
<td>2.35</td>
<td>0.010</td>
<td>2.75</td>
</tr>
<tr>
<td>0.463</td>
<td>2.39</td>
<td>0.015</td>
<td>2.79</td>
</tr>
<tr>
<td>0.470</td>
<td>2.43</td>
<td>0.020</td>
<td>2.84</td>
</tr>
<tr>
<td>0.475</td>
<td>2.46</td>
<td>0.025</td>
<td>2.87</td>
</tr>
<tr>
<td>0.480</td>
<td>2.50</td>
<td>0.030</td>
<td>2.94</td>
</tr>
<tr>
<td>0.483</td>
<td>2.54</td>
<td>0.035</td>
<td>2.99</td>
</tr>
<tr>
<td>0.490</td>
<td>2.58</td>
<td>0.040</td>
<td>3.04</td>
</tr>
<tr>
<td>0.495</td>
<td>2.62</td>
<td>0.045</td>
<td>3.09</td>
</tr>
<tr>
<td>0.500</td>
<td>2.66</td>
<td>0.050</td>
<td>3.14</td>
</tr>
</tbody>
</table>

A3.3.4 Calculation of \( R_{p0} \)—For the bend specimen calculate the specimen strength ratio (which is dimensionless and has the same value in any consistent system of units):

\[ R_{p0} = \frac{\delta_{p0}}{f_{c}^*} \]

where:

- \( \delta_{p0} \) = maximum load that the specimen was able to sustain,
- \( B \) = thickness of specimen as determined in 8.2.1,
- \( W \) = width (depth) of specimen, as determined in A.3.4.1,
- \( a \) = crack length as determined in 8.2.2, and
- \( f_{c}^* \) = yield strength in tension (offset = 0.2%) (see Test Methods E 8).

A3.3.5 Calculation of Crack Mouth Opening Compliance Using Crack Length Measurement—For bend specimen calculate the crack mouth opening compliance, \( V_{cmo}\), in units of m/N (in./lb) as follows (see Note A3.2):

\[ V_{cmo} = \frac{1}{S}(E/W) \cdot \delta_{p0}/W \]

where:

- \( \delta_{p0} = 6\alpha_{p0}/W(0.76 - 2.78(a/W)) + 3.8(\alpha_{p0}/W)^2 - 2.04(\alpha_{p0}/W)^3 + 0.66/(1 - a/W)^2 \), ft

where:

- \( V_{cmo} \) = crack mouth opening displacement, m (in.),
- \( P \) = applied load, kbf (kN),
- \( E' \) = Effective Young's Modulus (= E for plane stress; \( E \) (1 - \( r^2 \)) for plane strain, Pa (psi)).
- \( r \) = Poisson's Ratio; and
- \( S, B, W \), and \( a \) are as defined in A3.5.3.

Note A3.2—This expression is considered to be accurate to within \( ±1.0\% \) for any \( a/W \) (23). This expression is valid only for crack mouth opening compliance.
A3.5.6 Calculation of Crack Lengths Using Crack Mouth Opening Compliance Measurements—For bend specimens, calculate the normalized crack length as follows (see Note A3.3):

\[ a/W = 0.9997 - 3.95U + 2.982U^2 - 3.214U^3 + 31.52U^4 - 113.0U^5 \]

where:

\[ U = 1 / (1 + ((E'V_N/PAW/S))^a) \]

Note A3.3—This expression for the equation in A3.5.5 within ±0.01% of \( W \) for 0.3 ≤ \( \alpha/W \) ≤ 0.9 (M4). This expression is valid only for crack mouth displacements measured at the location of the integral knife edges shown in Fig. 3. If attachable knife edges are used, they must be removed or inset to provide the same measurement point location.

A4. SPECIAL REQUIREMENTS FOR THE TESTING OF COMPACT SPECIMENS

A4.1 Specimen

A4.1.1 The standard compact specimen is a single-edge-notched and fatigue cracked plate loaded in tension. The general proportions of this specimen configuration are given in Fig. A4.1.

A4.1.2 Alternative specimens may have 2 ≤ \( W/B \) ≤ 4 but with no change in other proportions.

A4.2 Specimen Preparation

A4.2.1 For generally applicable specifications concerning specimen size and preparation see Section 7.

A4.3 Apparatus

A4.3.1 Tensile Testing Clevis—A loading clevis suitable for testing compact specimens is shown in Fig. A4.2. 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 (4). Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown.

A4.4.3.1.1 The critical tolerances and suggested proportions of the clevis and pins are given in Fig. A4.2. These proportions are based on specimens having \( W/B = 2 \) for \( B > 0.5 \) in. (12.7 mm) and \( W/B = 4 \) for \( B < 0.5 \) in. (12.7 mm). If a 280 000-psi (1930-MPa) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained for testing the specimen sizes and \( 
\frac{\sigma_0}{E} \) ratios given in 7.1.3. If lower-strength grip material is used, or if substantially larger specimens are required at a given \( 
\frac{\sigma_0}{E} \) ratio than those shown in 7.1.3, then heavier grips will be required. As indicated in Fig. A4.2 the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 0.375 in. (9.5 mm) thick.

A4.4.3.1.2 Careful attention should be given to achieving as good alignment as possible through careful machining of all auxiliary gripping fixtures.

A4.4.3.2 Displacement Gage—For generally applicable details concerning the displacement gage see 6.3. For the compact specimen the displacements will be essentially independent of the gage length up to 1.2 \( W \).

A4.4.4 Procedure

A4.4.4.1 Measurement—For a compact specimen 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 must be subtracted to determine \( H \) and \( a \)). Measure the width, \( W \), to the nearest 0.001 in. (0.025 mm) or 0.1%, whichever is larger, at not less than five positions near the notch location, and record the average value.

A4.4.4.1.1 For general requirements concerning specimen measurement see 8.2.

A4.4.4.2 Compact Specimen Testing—When assembling the loading train (clevises and their attachments to the test machine) care should be taken to minimize eccentricity of loading due to misalignments external to the clevises. To obtain satisfactory alignment keep the centerline of the upper and lower loading rods coincident within 0.03 in. (0.76 mm) during the test and center the specimen with respect to the clevis opening within 0.03 in. (0.76 mm).

A4.4.4.2.1 Load the compact specimen at such a rate that the rate of increase of stress intensity is within the range 300 to 150 ksi-in.\(^{1/2}\)/min (0.53 to 2.75 MPa-m\(^{1/2}\)/s) corresponding to a loading rate for a standard \( (W/B) = 2 \) in.-thick specimen between 4500 and 22 500 lb/min (0.34 to 1.1 KN/s).
4.4.2.2 For details concerning recording of the test results see 4.4.

4.5 Calculations

4.5.1 For general requirements and procedures in interpretation of the test record see 9.1.

4.5.2 Description of the validity requirements in terms of limitations on Ptrue/Po and the specimen size requirements see 9.1.2 through 9.1.3.

4.5.3 Calculations of K true —For the compact specimen determine K true in units of ksi-in.\(^{1/2}\) (MPa-m\(^{1/2}\)) from the following expression (Note A4.1)

\[ K_t = \frac{P_{true}}{B^{1/2}W^{3/2}f_c(a/W)} \]

where:
- \( (2 + 4/E)Y0.886 + 4.64/aW \)
- \( f_c(a/W) = 13.32a^2/B^2 + 14.72a/B^2 - 5.6a/B \)

Note:
- \( a \) is load determined in 9.1.1, kbf (KN).
- \( f_c \) is specimen thickness as determined in 8.2.1, in. (cm).
- \( a \) is specimen width, as determined in A4.4.1, in. (cm), and
- \( W \) is crack length as determined in 8.2.2 and A4.4.1, in. (cm).

Note A4.1—This expression is considered to be accurate within \( \pm 5\% \) over the range of \( a/W \) from 0.2 to 1 (1:5).

4.5.3.1 To facilitate calculation of \( K_{true} \), values of \( f_c(a/W) \) are tabulated below for specific values of \( a/W \).

### Table: Values of \( f_c(a/W) \) for compact specimens

<table>
<thead>
<tr>
<th>( a/W )</th>
<th>( f_c(a/W) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.450</td>
<td>0.500</td>
</tr>
<tr>
<td>0.455</td>
<td>0.505</td>
</tr>
<tr>
<td>0.460</td>
<td>0.510</td>
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<td>0.545</td>
</tr>
<tr>
<td>0.500</td>
<td>0.550</td>
</tr>
</tbody>
</table>

4.5.4 Calculation of \( R_o \)—For the compact specimen calculate the specimen strength ratio which is dimensionless and has the same value in any consistent system of units:

\[ R_o = \frac{2\pi(a+\delta)(a+\delta)\sigma}{B^{1/2}W^{3/2}f_{true}} \]

Note:
- \( \delta \) is maximum load that the specimen was able to sustain.
- \( a \) is thickness of specimen as determined in 8.2.1.
- \( \delta \) is width of the specimen as determined in A4.4.1.

A5. SPECIAL REQUIREMENTS FOR THE TESTING OF THE ARC-SHAPED TENSION SPECIMEN

A5.1 Specimen

A5.1.1 The arc-shaped tension specimen is a single edge-notched and fatigue cracked ring specimen loaded in tension.

A5.1.2 General proportions of two designs of the specimens are given in Fig. A5.1. The value of the radius ratio \( r_1/r_2 \) is not critical, so that specimens can be taken from any cylindrical geometries. However, it should be noted that specimens with \( r_1/r_2 = 0 \) (that is, from a solid cylinder) do not make the best possible use of the test material because the definition of \( W \) was chosen to accommodate hollow cylinders. The disk-shaped specimen should be used for tests on solid cylinders (see Annex A6).
A5.1.2. The arc-shaped tension specimen is intended to measure the fracture toughness so that the normal to the crack plane is in the circumferential direction and the direction of crack propagation is in the radial direction. This is the C-R orientation as defined in 5.1.3. For other orientations, a bend (Annex A3) or a compact (Annex A4) specimen should be used.

A5.1.3. The specimen with $X/W = 0.5$ (Fig. A5.1a) represents a half ring segment. The specimens with $X/W = 0$ (Fig. A5.1b) represent the smallest specimen of this configuration that can be cut from a ring.

A5.1.4. Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions. The use of alternative specimen proportions can be advantageous because in many cases it is possible to test ring segments with no machining of the inner and outer radii, that is, with no change in $W$.

A5.2 Specimen Preparation

A5.2.1. For generally applicable specifications concerning specimen size and preparation see Section 7.

A5.3 Apparatus

A5.3.1. Tension Testing Clevis—A loading clevis suitable for testing arc-shaped tension specimens is shown in Fig. A5.2. 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 surface (4). Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown.

A5.3.1.1. The critical tolerances and suggested proportions of the clevis and pins are given in A5.2. These proportions are based on specimens having $W/B = 2$ for $B \geq 0.5$ in. (12.7 mm) and $W/B = 4$ for $B \leq 0.5$ in. (12.7 mm). If 280,000 psi (1930 MPa) yield strength material is used for the clevis and pins, adequate strength will be obtained for testing the specimen sizes and $W/B$ ratio given in 7.1.3. If lower-strength grip material is used, or if substantially larger specimens are required at a given $W/B$ ratio than those shown in 7.1.3, then heavier gauges will be required. As indicated in Fig. A5.2, the clevis corners may be cut off sufficiently to accommodate seating of the clip gauge specimens less than 0.375 in. (9.5 mm) thick.

A5.3.1.2. Careful attention should be given to achieving a good alignment as possible through careful machining of auxiliary gripping fixtures.

A5.3.2. Displacement Gage—For generally applicable details concerning the displacement gage see 6.3.

A5.3.2.1. An alternative means of measuring the displacement is allowed for the specimen with $X/W = 0.5$. Center-punch-type indentations are provided on the inner surface of the specimen at mid-thickness and in the plate at the center line of the loading holes as shown in Fig. A5.4. The load-point displacement of the specimen is measured these points using a displacement gage fitted with points and meeting the requirements described in 6.4.1.

A5.3.2.2. The displacements will be essentially independent of the gage length for the arc-shaped specimen provided the gage length is equal to or less than $W/2$.

A5.4 Procedure

A5.4.1. Measurement—Before testing an arc-shaped specimen, measure $(r_1 - r_2)$ to the nearest 0.001 in. (0.025 mm).
FIG. A5.2 Tension Testing Clamps Design

FIG. A5.3 Measurement of Outer Radius (r) and Crack Length for the Arc-shaped Specimen (see A5.4.1)
A5.5.1 For general requirements and procedures in investigations of the test record see 9.1.

A5.5.2 For a description of the validity requirements in terms of limitations on $F_{eq}/F_{0}$ and the specimen size requirements see 9.1.9 through 9.1.13.

A5.5.3 Calculation of $K_{eq}$—For the arc-shaped specimen the calculation of $K_{eq}$ in terms of $u_{eq}^{a}$ from the following expression (Note A5.2):

$$K_{eq} = \frac{F_{max} W}{B W G X W} + \frac{1}{1 + 1.11 W} x 1 + 0.251 + -b W^{2} - r_{1} - r_{2} - b W^{2}$$

where:

$F_{max}$ = maximum load that the specimen was able to sustain
$B$ = thickness of the specimen as determined in 8.2.1
$X$ = load height as determined in 8.2.2 and A5.4.1.1
$W$ = specimen width as determined in 8.2.1.1
$G$ = $\frac{1}{1 + 1.11 W}$
$u_{eq}^{a}$ = yield strength in tension as offset (0.2 %) (see Method B 8.1.2.5)

A5.5.4 Calculation of crack mouth opening compliance using crack length measurements—For arc-shaped specimen, calculate the crack mouth opening compliance $\Delta a/\Delta F$ in units of $mN$ (in. lb) as follows (see Note A5.3) for the specimen with $X/W = 0$:

$$\Delta a/\Delta F = \frac{P_{eq} \Delta E}{W}$$

where:

$P_{eq} = \frac{1}{1 + 1.11 W}$
$\Delta E = 0.34 \times 1.33$ $a_{eq}^{a}$ $W = 12.33(a_{eq}^{a})^{2}$ $W = 6.576(a_{eq}^{a})^{2}$

or, for the specimen with $X/W = 0.5$:

$$\Delta a/\Delta F = \frac{P_{eq} \Delta E}{W}$$

where:

$P_{eq} = \frac{1}{1 + 1.11 W}$
$\Delta E = 0.399 \times 12.63a_{eq}^{a}W = 9.838(a_{eq}^{a})^{2}$

and $a_{eq}^{a}$ = crack length as determined in 8.2.2 and A5.4.1.1.
A.5.5.6 Calculation of Crack Lengths Using Crack Mouth Opening Compliance Measurements—For arc-shaped specimens, calculate the normalized crack length as follows (see Eq. (5A.4.41) for the specimen with \( X/W = 0 \)):

\[
\frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)}
\]

where:

\[
U = U_w(1 + \left[ \frac{E}{W_w^2} \left( 1 + \frac{\nu}{1-2} \right) \right] \left( 1 - \frac{r_1/r_2}{} \right) )
\]

or, for the specimen with \( X/W = 0.5 \):

\[
\frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)} = \frac{a/W}{w/(W_w)}
\]

where:

\[
U = U_w(1 + \left[ \frac{E}{W_w^2} \left( 1 + \frac{\nu}{1-2} \right) \right] \left( 1 - \frac{r_1/r_2}{} \right) )
\]

Note A5—This expression fits the equations in A5.5.5 within ±0.003 for \( 0.2 < a/W < 0.8 \), \( r_1/r_2 > 0.4 \), and \( X/W = 0 \) or \( X/W = 0.5 \).

A6. SPECIFIC REQUIREMENTS FOR THE TESTING OF THE DISK-SHAPED COMPACT SPECIMEN

A6.1 Specimen

A6.1.1 The standard disk-shaped compact specimen is either edge-notched or fatigue-cracked disk segment loaded

A6.1.2 Alternative specimens may have \( 2 < W/B < 4 \) but no change in other proportions.

A6.2 Specimen Preparation

A6.2.1 For generally applicable specifications concerning specimen size and preparation see Section 7.

A6.3 Apparatus

A6.3.1 Tension Testing Clamps—A loading clamps suitable to test disk-shaped compact specimens is shown in Fig. 6A.2. Both ends of the specimen are held in a set of clamps through which the specimen is passed in order to reduce rotation of the specimen during testing. In order to provide rolling contact between the loading pins and clamps, there are holes which are loaded with small flats on the loading surfaces (4). Other type of designs may be used if it can be demonstrated that they accomplish the same result as the design shown.

A6.3.2 Displacement Gage—For generally applicable details concerning the displacement gage see 6.3. For the disk-shaped compact specimen the displacement will be essentially independent of the gage length up to 0.5 W.

A6.4 Procedure

A6.4.1 Measurement—The analysis assumes the specimen was machined from a circular blank and therefore measurements of circularity as well as width, \( W \), and crack length, \( a \), must be made for this specimen.

A6.4.1.1 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 \( r \) more than 5%, the specimen blank is not suitable for test. Otherwise, \( D = 2r \).

A6.4.1.2 Measure the width, \( W \), and the crack length, \( a \), from the plane of the centerline of the loading holes (the notch edge is a convenient reference line but the distance from the centerline of the holes to the notch edge must be subtracted to determine \( W \) and \( a \)). Measure the depth, \( T \), to the nearest 0.001 in. (0.025 mm) or 0.1%, whichever is larger, at not less than three positions near the notch

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where:

\[ \frac{f_{u}}{W} = \frac{2 + \frac{1.3}{W} + 6.5%}{W} + \frac{5.5%}{W} + \frac{12.5%}{W} + \frac{2.5%}{W} \]

A detailed explanation of the formula and its derivation can be found in the referenced sections of the document. The formula is used to calculate the stress in a specimen under load, considering various factors such as specimen size, thickness, and crack length. The calculations are crucial for determining the material's strength and reliability under specific conditions.
In tensionless and has the same value in any consistent set of units as follows:

\[ R_{se} = \frac{2P_{max}(W + a)}{B W} - a f_{V_S} \]

where:
- \( P_{max} \) = maximum load that the specimen was able to sustain.
- \( W \) = thickness of the specimen as determined in 8.2.1,
- \( W \) = specimen width as determined in A6.4.1.2.
- \( a \) = crack length as determined in 8.2.2 and A6.4.1.2.
- \( f_{V_S} \) = yield strength in tension (offset = 0.2%) (see Test Methods E 8).

A6.5.5 Calculation of Crack Mouth Opening Compliance

Using Crack Length Measurement—For disk-shaped compact specimens, calculate the crack mouth opening compliance, \( V_{m}/P \), in units of \( \text{mN}/(\text{in.}/\text{lb}) \) as follows (see Note A6.5.2):

\[ V_{m}/P = (1/E) B d_{a}/W \]

where:
- \( d_{a} \) = crack mouth opening displacement, \( \text{m} \) (in.),
- \( W \) = applied load, \( \text{N} \) (lb).
- \( E \) = Effective Young’s Modulus (= \( E \) for plane stress, \( Pa \) (psi); \( E/(1 - \nu^2) \) for plane strain, \( Pa \) (psi)),
- \( \nu \) = Poisson’s Ratio, and
- \( B \), \( W \), and \( a \) are as defined in A6.5.3.

Note A6.5.2—This expression is considered to be accurate to within ±10% for \( a/W \) ≥ 0.2 (25). This expression is valid only for crack mouth displacements measured at the location of the integral knife edges shown in Fig. 5. If attachable knife edges are used, they must be removed or set off to provide the same measurement point location.

A6.5.5.1 To facilitate the calculation of crack mouth opening compliances, values of \( d_{a}/W \) are given in the following table for specific values of \( a/W \):

<table>
<thead>
<tr>
<th>( a/W )</th>
<th>( d_{a}/W )</th>
<th>( d_{a}/W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.450</td>
<td>43.4</td>
<td>50.0</td>
</tr>
<tr>
<td>0.470</td>
<td>44.4</td>
<td>50.5</td>
</tr>
<tr>
<td>0.460</td>
<td>45.3</td>
<td>51.0</td>
</tr>
<tr>
<td>0.465</td>
<td>46.5</td>
<td>51.5</td>
</tr>
<tr>
<td>0.470</td>
<td>47.7</td>
<td>52.0</td>
</tr>
<tr>
<td>0.475</td>
<td>48.8</td>
<td>52.5</td>
</tr>
<tr>
<td>0.480</td>
<td>50.0</td>
<td>53.0</td>
</tr>
<tr>
<td>0.485</td>
<td>51.2</td>
<td>53.5</td>
</tr>
<tr>
<td>0.490</td>
<td>52.5</td>
<td>54.0</td>
</tr>
<tr>
<td>0.495</td>
<td>53.8</td>
<td>54.5</td>
</tr>
<tr>
<td>0.500</td>
<td>55.0</td>
<td>55.0</td>
</tr>
</tbody>
</table>

A6.5.6 For disk-shaped compact specimens, calculate the normalized crack length as follows (see Note A6.3):

\[ a/W = 1000 - 4.49/\nu + 2.06/\nu^2 + 13.04/\nu^3 \]

where:
- \( U = 1/1 + (E/E_n)/(\text{psi}) \)

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A6.5 Precision and Bias (see also Section 11)

A6.6.1 There has been no round-robin test program for the disk-shaped specimen. However, the results of two testing programs (16) designed to compare the results of the disk-shaped specimens with those of the compact specimen and the arc-shaped specimen are summarized in Table A6.1. Based on the results in Table A6.1 and the geometric similarity of the specimens, there is no reason to suspect that the precision for the disk-shaped specimen would differ from that for the compact specimen. The arc-tension specimen has been shown (18) to have essentially the same grand mean and standard deviation as the compact specimen.

Notes: A6.2. Units of mean and standard deviation are MPA m(1/2)in.

A7. SPECIAL REQUIREMENTS FOR RAPID-LOAD PLANE-STRAIN FRACTURE TOUGHNESS \( K_I(d) \) TESTING

A7.1 Scope

A7.1.1 This annex covers the determination of plane-strain fracture toughness \( K_I(d) \) properties of metallic materials under conditions where the loading rates exceed those for conventional (static) plane-strain fracture toughness testing. This description of these requirements does not include impact or quasi-impact testing (free-falling or drop-weight masses). Conventional fracture toughness test specimens are prepared as described in this method, tested under rapid-loading conditions, and a fracture toughness value is calculated. Load-deflection, load-time, and deflection-time curves are recorded for each test. The load-deflection curves resulting from these tests are analyzed to ensure that the initial linear portion of the load-displacement record is sufficiently well defined that \( P_d \) can be determined unambiguously. In addition to a time \( t \) (unitless or more than one ms) is determined. This test time and an optionally calculated average stress intensity factor rate \( K_i \) characterize the rapid load test. The yield strength of the material must be determined or estimated for the loading time of the fracture test and is used in the analysis of the fracture test data. All of the criteria for static \( K_I \) determination apply to the rapid-load plane-strain fracture toughness test. The rapid-load plane-strain fracture toughness property is denoted by \( K_{ID} \) where the time to reach the load corresponding to \( K_{ID} \) is indicated in the brackets ( ).

A7.2 Summary of Requirements

A7.2.1 Special requirements are necessary for plane-strain fracture toughness testing at loading rates exceeding those of conventional (static) plane-strain fracture toughness testing. This description of these requirements does not include impact or quasi-impact testing (free-falling or drop-weight masses). Conventional fracture toughness test specimens are prepared as described in this method, tested under rapid-loading conditions, and a fracture toughness value is calculated. Load-deflection, load-time, and deflection-time curves are recorded for each test. The load-deflection curves resulting from these tests are analyzed to ensure that the initial linear portion of the load-displacement record is sufficiently well defined that \( P_d \) can be determined unambiguously. In addition to a time \( t \) (unitless or more than one ms) is determined. This test time and an optionally calculated average stress intensity factor rate \( K_i \) characterize the rapid load test. The yield strength of the material must be determined or estimated for the loading time of the fracture test and is used in the analysis of the fracture test data. All of the criteria for static \( K_I \) determination apply to the rapid-load plane-strain fracture toughness test. The rapid-load plane-strain fracture toughness property is denoted by \( K_{ID} \) where the time to reach the load corresponding to \( K_{ID} \) is indicated in the brackets ( ).

A7.3 Significance and Use

A7.3.1 The significance of the conventional (static) \( K_I \) properties applies also to the case of rapid loading. The plane-strain fracture toughness of certain materials is sensitive to the loading rate and substantial decreases in toughness may be noted as the loading rate increases. Generally, such materials also show a pronounced dependence of \( K_I \) on test temperature. For example, the loading rate sensitivity of structural grade steels has required the development of a lower bound \( K_{ID} \) curve, given in Appendix G of Division III of the ASME Boiler and Pressure Vessel Code, for the fracture-safety design of heavy-wall nuclear pressure vessels. Additionally, \( K_{ID} \) values for steels tested at various temperatures and loading rates are required for correlation with small-scale production control tests (such as the Charpy V-notch test) for setting material specifications and fracture-safe design procedures.

A7.4 Terminology

A7.4.1 Definitions:

A7.4.1.1 The definitions given in Terminology E 69 are applicable to this test method.

A7.4.2 Stress-Intensity Factor—See Section 5 of this test method.

A7.4.3 Plane-Strain Fracture Toughness—See Section 1 of this test method.

A7.4.4 Rapid Load—In fracture testing, any load that results in an average stress-intensity factor rate in excess of 150,000 psi-in. (2.75 MPa m(1/2)).

A7.4.5 Stress-Intensity Factor Rate, K \( (FL-20) \):—The crack extension resistance under conditions of crack-tip plane strain at average loading rates exceeding 150,000 psi-in. (2.75 MPa m(1/2)).

A7.4.6 Crack-Plane Orientation—See Section 1.3 of this test method.

A7.4.7 Description of Terms Specific to this Method:

A7.4.8 Load-Plane-Strain Fracture Toughness \( K_{ID} \) (FL-20):—The crack extension resistance under conditions of crack-tip plane strain at average loading rates exceeding 150,000 psi-in. (2.75 MPa m(1/2)).

A7.5 Apparatus

A7.5.1 Loading—Generally, hydraulic machines with rapid-acting servo-controlled valves are used. Depending on the compliance of the loading system and the pump capacity, an accumulator may be required.

A7.5.2 Fixtures—The fixtures used for static plane-strain fracture toughness tests are generally suitable for rapid-load tests. However, consideration should be given to the pump...
ify that the toughness of the fixture material may be
affected by rapid loading.
A7.5.2 Load and Displacement Transducers.—The trans-
cducers used for static plane-strain fracture toughness tests are
particularly suitable for rapid-load tests. However, these trans-
cducers must have response characteristics that will ensure
that inertial effects will not contaminate the load and
displacement signals.

Note A7.5.2—While not required, the resonant frequencies of these
transducers may be determined by exciting them and observing
the wave characteristics on an oscilloscope. If ringing (high frequency
oscillations) is observed within the time period required to reach the PG
level, the stiffness of the transducers should be increased or their mass
reduced. Load cells are quite stiff and should provide no problem at the
greater loading time of 1 ms. The displacement transducer might be
more critical depending on its design. The cantilever beam
configuration used in Annex A6 has been successfully used at
strain rates slightly lower than 1 mm (20). The resonant frequency of
the beam when mounted in a specimen in a conventional manner and
loaded by tapping was about 3000 Hz. The free-arm resonant frequency
is about 200 Hz. Other stages of the same type but having different
guiaerts should operate satisfactorily if their free arm resonant
is at 70 Hz. The following equation may be used to estimate the
effective resonant frequency of such a gage:

\[ f = \frac{1}{2\pi} \cdot \frac{1}{T} \]

Table

A7.5.3 Signal Conditioners.—Amplification or filtering of the
transducer signals may be necessary. Such signal condi-
tioning units should have a frequency response from dc to at
least 30 kHz (kHz) where \( t \) is the test time in milliseconds
as defined in A7.5.3. As described in A7.6.2, conventional
mechanical recording devices may not have sufficient fre-
quency response to permit direct plotting of the load versus
time and the displacement versus time signals.

A7.6 Procedure
A7.6.1 Loading Rate.—The rate of loading is optional with
the investigator but the time to reach the load corre-
sponding to \( P_{50} \) shall not be less than 1 ms. Use a period to
eliminate ringing in the load or displacement transducers
that will be dependent on the load train being
sufficiently taken up by the start of rapid loading.
A7.6.2 For each test conducted, a load versus time, a
displacement versus time, and a load versus displacement
record shall be obtained. The time scale of these records shall
be accurately determined since the time is used to charac-
terize the test. Examine the time-dependent records for the
presence of ringing before reaching the PG load. Such ringing
will result from inertial effects as described in Note A7.5.1. The
special record analysis procedure described in A7.7.3 may be
helpful in assessing the magnitude of such effects.

Note A7.2.—It should be recognized that some materials may
exhibit a burst of crack extension at loads less than \( P_{50} \) that is sufficiently
abrupt to produce ringing in the displacement transducer signal. Such an
abrupt advance of the crack may be associated with material
inhomogeneities both to the fatigue crack tip. If the ringing is where
it may not be possible to achieve maximum load extension should be recorded for those
tests having analyzable load versus displacement records.

Note A7.3.—The test data may be directly recorded if the recording
devices have sufficient frequency response. Generally, it is advantageous
to use a storage device that will capture the data and permit playing it
out at 2 x 102 sufficient slow speed that a pen recorder can be used in pro-
ducing the required records. Such storage devices are commonly avail-
able in the form of digital storage oscilloscopes having pen recorder out-
puts. Separate storage instruments are also available. In general these
digital storage devices have performance characteristics that are more
than adequate to capture, store, and replay the transducer signals from a
1 ms test. For example, calculations show that for a typical fracture test
such as described in (20) the track mode displacement resolution
would be about 0,030 mils (0,76 \( \mu \)m) per sample and the load resolu-
tion would be about 1600 ft (40 mm) (712 N). It should be possible
to obtain at least 1000 simultaneous samples of load and displace-
during such a test. A digital storage scope capable of at least
such performance would have the following characteristics: maximum digit-
ating rate 1 MHz, maximum sensitivity a 100 mV, resolution 0.05 %,
and memory of 4096 words by 12 bits. It may be necessary to amplify
the output of the clip gauge moderately and possibly that the load cell
depending on its capacity in terms of the range required. The above
values of resolution are based on a typical noise figure of about 50 \( \mu \)V.

A7.7 Calculation and Interpretation of Results
A7.7.1 Special requirements are placed on the analysis of the
load versus displacement record. These take into account the fact that experience (20) has shown load versus displace-
ment records from rapid-load fracture toughness tests are not always as smooth in the linear range as those obtained
from static tests. The special analysis technique described in
shall be used to ensure that an unambiguous value of \( P_{50} \) can be
determined.

A7.7.1.1 The test time must be determined from the load
versus time record.

A7.7.1.2 An additional analysis of the load versus displace-
ment record is illustrated in Fig. A7.1. The procedure is as follows:
Construct the straight line \( O4 \) best representing the
initial portion of the test record which is expected to be linear but may not be smooth (also see Note 6). Then
construct the line \( OP \), as described in 9.1.1 (Fig. 8) and
determine \( P_{50} \). Draw a vertical line at \( P_{50} \), passing through \( P_{50} \) and
define \( P_{50} \) at the point of intersection of this line with the
line \( O4 \). Determine 5 % of \( P_{50} \). Construct two lines \( BC \)
and \( DE \) parallel to \( O4 \) with \( BC \) passing through \( P_{50} - 0.05 \) \( P_{50} \)
and \( DE \) passing through \( P_{50} - 0.05 \) \( P_{50} \). Draw a horizontal
line at \( P_{50} = 0.5 \) \( P_{50} \). For the test to be valid the
recorded load versus displacement curve up to \( P_{50} \) must lie
within the envelope described by these parallel lines for the
portion of the record with \( P_{50} 0.5 \) \( P_{50} \).

A7.7.3 The time \( t \) in milliseconds is determined from the
record of load versus time as indicated in Fig. A7.2.
Construct the best straight line \( O4 \) through the most linear
portion of the record. \( t \) is then determined from the point
of intersection of this line with the time axis to the
point corresponding to \( P_{50} \). This time \( t \) is shown in the brackets
( ) following \( K_{C} \). An average stress intensity rate \( R \) may be
calculated by dividing \( K_{C} \) or \( K_{C} \) by \( t \) with the result being
expressed in ksi-in. \( 1/2 \) or MPa-m \( 1/2 \). It should be recog-
nized that some errors in determining the loading time are
not significant because significant changes in the toughness
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strength considerations are necessary.

A7.7.5 If the test is invalid using such a yield strength, tension test should be conducted on the test material at the temperature and loading time of the rapid-load toughened test with the time to reach the yield load in the tension test, approximately equal to the time \( t \) defined in A7.7.3.

A7.7.6 In the absence of \( \sigma_{YS} \) values as defined in A7.7.5, the dynamic yield strength \( \sigma_{YS} \) of certain steels may be estimated using the following equations (21) (22):

\[
\sigma_{YS} = \sigma_{YS}^{0} + \frac{A}{T \log_{10} (t \times 10^{3})} - B
\]

where:
- \( \sigma_{YS} \) is the 0.2% offset room temperature static strength,
- \( t \) is the loading time in milliseconds (see A7.7.3.3), and
- \( T_{S} \) is the temperature of the rapid-load toughness test.

Units:
- If \( \sigma_{YS} \) is in pound per square inch, then \( A = 174 \times 10^{3} \), \( B = 50.7 \times 10^{3} \).
- If \( \sigma_{YS} \) is in megapascals, then \( A = 1193 \times 10^{3} \), \( B = 187 \times 10^{3} \).
- If the test temperature \( T \) is measured in °F, then \( T_{S} = \left( T - 460 \right) \).

If the test temperature \( T \) is measured in K, then

\[
T_{S} = \left( T - 460 \right)
\]

Note: A7.4.—The equation in A7.7.6 has been found useful only in estimating the low temperature dynamic yield strength of construction steels having room temperature yield strengths below 50 ksi.

A7.8 Report

A7.8.1 The report must include the following additional information:

A7.8.1.1 The test time written in ( ) after \( K_{0} \) or \( K_{f} \).

A7.8.1.2 The method by which the value of \( \sigma_{YS} \) used is.

A7.8.1.3 Indications of ratch, that occur before \( P_{R}^{0} \) is reached, in the load versus time or displacement versus time graphs.

A7.9 Precision and Bias

A7.9.1 Bias—There is no accepted "standard" value for the plane-strain fracture toughness of any material. In the absence of such a true value, any statement concerning bias is not meaningful.

A7.9.2 Precision—Eighteen valid values of \( K_{0} \) at \(-40°F \) (\(-51°C \)) were reported (20), with \( \sigma_{YS} \) being determined by extrapolation of dynamic yield stress values obtained at strain rates of 0.01 to 1.0 s\(^{-1}\) and temperatures from room to \(-40°F \). No statistical analysis of the dynamic yield stress strength data was made. The rapid-load fracture toughness tests represented bend \( S_EB \) and compact \( C_T \) specimens tested in three thicknesses by several laboratories. Not all laboratories tested all the thicknesses. Statistical tests for outliers and for the differences between means indicated that the data should be pooled. Considering all the valid data the grand mean is \( 56.64 \) ksi (\( 392 \) MPa at \( 8 \) ksi MPa at \( 65°C \)) with the standard deviation \( S = 7.50 \text{ ksi} \) (\( 51.6 \) MPa at \( 65°C \)) and the coefficient of variation is 14% of the average.
A8. SPECIAL REQUIREMENTS FOR THE TESTING OF BERYLLIUM

1. Scope

1.1 This annex describes the special requirements for the determination of the plane strain fracture toughness of hot worked beryllium. With a few exceptions, the provisions of Method E 399 are applicable to the fracture toughness testing of beryllium. However, certain modifications to the procedure and record analysis, as described in the annex, are because of beryllium's potential toxicity, emphasized by OSHA. The test specimen, performed in a vacuum or sub-atmospheric environment, can result in strain rate effects. Machining and testing of beryllium require special precautions. Method E 399 is intended for laboratory testing of beryllium. Adherence to OSHA Standards should be observed prior to a beryllium testing program started.

1.2.1 Specimen Size—For hot-pressed material, the specimen thickness shall be 13 mm (0.5 in.) or larger to avoid excessive nonlinearity in the elastic portion of the a-W diagram.

1.2.2 Specimen Configuration—The bend (SE(B)) or compact (CT) specimen may be used. A straight through-notch (Fig. 7) shall be employed to provide sufficient fatigue crack extension in the required reversed loading.

1.2.3.3 Machining—Beryllium is not difficult to machine; however, machining is often encountered in beryllium and tends to have a tendency to break. Experience has shown that such a procedure is not necessary in the preparation of the specimen for fracture toughness testing.

1.2.3.2 Fatigue Cracking—Fatigue cracking should be accomplished with a compression load 2 to 3 times that in 1.2.3.1(2). The rate of fatigue crack growth will vary with crack extension under this type of loading, and a series of tests shall be necessary to determine the crack growth rate. Generally, this will require that the last 2.5 % of crack growth be accomplished at greater than 60 % of the anticipated Kc value. To avoid breaking the specimen, values of KMAX greater than 60 % of the anticipated Kc should not be used. As a rule, Kc at room temperature and in normal laboratory environments shall be assumed to be between 10 and 11 MPa m1/2 (10 ksi in. 1/2). Fatigue crack progress should be followed on both sides of the specimen. It has proven helpful to use a dye solution (such as those used for penetrant testing) to define the crack tips because the crack opening is relatively small for this high-modulus metal.

Fatigue cracking of SE(B) specimens has been successfully accomplished in cantilever bending (26, 29). There the expression for three-point bending given in A3.5.2 is used as a conservative approximation of Kc for the case of cantilever bending. A more recent approximation of Kc for the case of cantilever bending, Kc = P(L/8)(B/W/2)(a/W)1/2, is valid for cantilever bend specimens with (a/W)2 = 2, and where:

\[
\frac{a}{W} = 0.326 + 0.318(a/W) - 59.90(a/W)^2 + 68.89(a/W)^3
\]

and:

\[
P = \text{maximum cyclic load,} \ \text{kN} (\text{lbf}),
\]

\[
L = \frac{R}{2}, \ \text{one-half span,} \ \text{cm} (\text{in}),
\]

\[
S, B, W, a, \text{and} \ W \text{are as defined in A3.5.3 or 4.5.3.}
\]

NOTE A8.2—This expression is considered to be accurate to within ±5 % for a/W ≤ 0.6 (7).

1.3.4.4 To facilitate calculation of Kc for loading of SE(B) specimens in cantilever bending, values of (a/W)2 are tabulated in the following table for specific values of a/W:

<table>
<thead>
<tr>
<th>a/W</th>
<th>f(a/W)</th>
<th>a/W</th>
<th>f(a/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.450</td>
<td>0.12</td>
<td>0.50</td>
<td>0.12</td>
</tr>
<tr>
<td>0.455</td>
<td>0.23</td>
<td>0.55</td>
<td>0.12</td>
</tr>
<tr>
<td>0.500</td>
<td>0.30</td>
<td>0.60</td>
<td>0.15</td>
</tr>
<tr>
<td>0.555</td>
<td>0.45</td>
<td>0.65</td>
<td>0.18</td>
</tr>
<tr>
<td>0.600</td>
<td>0.60</td>
<td>0.70</td>
<td>0.25</td>
</tr>
<tr>
<td>0.655</td>
<td>0.75</td>
<td>0.75</td>
<td>0.30</td>
</tr>
<tr>
<td>0.700</td>
<td>0.90</td>
<td>0.80</td>
<td>0.33</td>
</tr>
<tr>
<td>0.750</td>
<td>1.05</td>
<td>0.85</td>
<td>0.36</td>
</tr>
<tr>
<td>0.800</td>
<td>1.20</td>
<td>0.90</td>
<td>0.39</td>
</tr>
<tr>
<td>0.850</td>
<td>1.35</td>
<td>0.95</td>
<td>0.42</td>
</tr>
<tr>
<td>0.900</td>
<td>1.50</td>
<td>1.00</td>
<td>0.45</td>
</tr>
<tr>
<td>0.950</td>
<td>1.65</td>
<td>1.05</td>
<td>0.48</td>
</tr>
</tbody>
</table>

When using cantilever bending, excessive clamping forces will produce cracks at the specimen edges which will invalidate the test.

1.3.5 Testing and Record Analyzes

1.3.5.1 Loads and displacements will be relatively low, and the production of a satisfactory test record will require high gain in the clip gage circuit. It is an advantage to use a relatively slow loading rate corresponding to about 0.18 MPa m1/2 (10 ksi in.1/2) in order to provide an opportunity to unload the specimen and to ensure that recording gain controls are not adjusted to give the slope range specified by this method. When a nonlinear elastic portion of the load-displacement record is encountered, an initial slope should be established by drawing a straight line between two points on the load-deformation record, one point at 20 % of the maximum load and another at 80 % of maximum load.

1.3.5.4 Precision and Bias (see also Section 11)

A3.4.1 Hot pressed beryllium from two suppliers was tested in six laboratories in accordance with the procedures of this Annex with the following results:

<table>
<thead>
<tr>
<th>Batch 1</th>
<th>Batch 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>r = 216 MPa</td>
<td>r = 197 MPa</td>
</tr>
<tr>
<td>(32.5 ksi)</td>
<td>(28.6 ksi)</td>
</tr>
</tbody>
</table>

| Total mean | T | 10.68 (1.12) | 10.68 (1.50) |
| Standard deviation, S | 0.13 (0.18) | 0.13 (0.17) |

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A9. SPECIAL REQUIREMENTS FOR TESTING ARC-SHAPED BEND SPECIMENS

A9.1 Specimen

A9.1.1 The arc-shaped bend specimen (33) is a single-edge notched and fatigue cracked ring segment loaded in bending. The general proportions of the standard specimen are shown in Fig. A9.1. The value of the radius ratio \( r_2/r_1 \) is limited to the range of 0.6 to 1.0, when the specimen is loaded with a span-to-width ratio \( S/W \) of 4, and from 0.4 to 1.0 when the specimen is loaded with a span-to-width ratio \( S/W \) of 3. For cylinders with radius ratios of less than these limits, the arc-shaped tension-loaded specimen or the disk-shaped specimen should be used.

A9.1.2 The arc-shaped bend specimen is intended to measure the fracture toughness so that the normal to the crack plane is in the circumferential direction and the direction of crack propagation is in the radial direction. This is the C-R orientation as defined in 5.1.3. For other orientations, a bend (Annex A3) or a compact (Annex A4) specimen should be used.

A9.1.3 Alternative specimens may have \( 2 < W/B < 4 \) but with no change in other proportions. The use of the alternative specimen proportions for the arc-shaped bend specimen can be advantageous because in many cases it is possible to test ring segments with no machining of the inner or outer radii, that is, with no change in \( W \).

A9.2 Specimen Preparation

A9.2.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A9.3 Apparatus

A9.3.1 Bend Test Fixture—The bend test fixture in

Annex A3 is suitable for the arc-shaped bend specimen as well.

A9.3.2 Displacement Gauge—For generally applicable details concerning the displacement gauge, see 6.3.

A9.4 Procedure

A9.4.1 Measurement—Before testing an arc-shaped bend sample, measure \( r_2 - r_1 \) to the nearest 0.025 mm (0.001 in) or to 0.1 %, whichever is greater, at mid-thickness positions on both sides of and immediately adjacent to the crack starter notch mouth. Record the average of these two readings at \( W \). Also measure \( r_2 - r_1 \) at four positions two as close as possible to the intersection of the inside radius and the machined flat surfaces, and two at approximately half the circumferential distance between the machined flat surfaces and the crack plane. If any of these four measurements differ from \( W \) by more than 10 % or for any of the specimen, next, measure to the nearest 0.025 mm (0.001 in.) or to the nearest 0.1 %, whichever is greater, the distance in the crack plane between the chord that connects the top machined flat surfaces and the outer radius of the specimen. This measurement should be on both sides of the specimen referring each flat machined surface. Subtract \( W \) from the average of these two measurements and record the result as \( X \). Measure within 5 % the distance \( (g) \) across the crack mouth at the reference point for the measurement of the crack mouth opening displacement (For example, \( g = 0.25 \) in. in Fig. 5). It should be noted that \( g \) may be equal to the notch width \( (N) \) or larger than \( N \) if machined knife edge is used. Measure within 5 % the outer radius, \( r_2 \), if this is not possible, determine the average value of \( r_2 \) as follows (see Note A9.1): Measure within 5 % the length, \( L \), of the chord of the outer surface, that is, the chord established by the fl

Note 1—4 surfaces shall be perpendicular and parallel \( \pm 0.001 \) to the flat surface of the bars.
Note 1—2 Crack starter notch shall be perpendicular to 4-44 in. flat surface at right angles.
Note 3—Integral or detachable knife edges for flat gage attachment shall be used (see Figs. 5 and 6).
Note 4—For starter notch and fatigue crack configuration see Fig. 7.

FIG. A9.1 Arc-Shaped Bend Specimens A(8)—Standard Proportions and Tolerances
amphibian surfaces (see Fig. A9.2). Using this measurement, calculate

\[ t_2 = \frac{L^2}{4(BW + Z^2) \left( \frac{W}{Z} + 2 \right)} \]

Two \( t_1 = \frac{1}{W - t_2} \)

Note: A 10% variation of the ratio \( r_1/r_2 \) will affect the value of the stress intensity factor by 1.2% or less providing that the relative crack length \( a/W \) is not less than 0.3. However, the stress analysis is made on the assumption that the specimens are to be cut from stock of uniform cross-section. If inspection shows that the thickness varies from uniformity by more than 10% it should be reworked to within this tolerance.

A9.4.1 After fracture, measure the crack length in accordance for the arc-shaped specimen due to its curvature. Use a length measurement, \( m \), made from a reference point a distance \( r \) greater than the corresponding distance from the virtual point of intersection of the crack plane and the inside circumference of the specimen (see Fig. A9.2). The error, \( e \), can be computed from the following expression:

\[ e = r_1 - (r_1^2 - g^2/4)^{1/2} \]

where: \( g = m \) (if the relative error \( m/n < 0.01 \), then record \( m \) as the crack length; otherwise \( e \) should be subtracted from \( m \) and the result recorded as the crack length).

A9.4.2 Arc-Shaped Bend Specimen Testing—Set up the test fixture such that the span, \( S \), is nominally equal to four times (or three times) the width, \( W \). Further adjust the fixture such that the line of action of the applied load shall pass midway between the support roll centers within 1% of the distance between these centers. Measure the span to within 0.5%. Locate the specimen with the crack tip midway between the rolls to within 1% of the span and perpendicular to the roll axes within 2°. Seat the displacement gage on the knife edges to maintain registry between knife edges and gage grooves. In the case of attachable knife edges, seat the gage before the knife edge positioning screws are tightened.

A9.4.2.1 Load the specimen at a rate such that the rate of increase of the stress intensity factor is within the range 0.55 to 2.75 MPa m\(^{-1/2}\) (30 to 150 ksi in.\(^{-1/2}\)). The corresponding loading rates for a standard \((W/B = 2)\) 25 mm (1 in.) thick specimen are between 0.3 and 2.4 kN/s (4500 and 32000 lbf/min) for the \( S = 3W \) specimen, and between 0.2 and 1.7 kN/s (3200 and 23000 lbf/min) for the \( S = 4W \) specimen.

A9.4.3 For details concerning the recording of the test record, see 8.4.

A9.5 Calculations

A9.5.1 Interpretation of Test Record—For general requirements and procedures for interpretations of the test record, see 9.1.3.

A9.5.2 Validity Requirements—For a description of the validity requirements in terms of limitations on \( P_{\max}/P_0 \) and the specimen size requirements, see 9.1.2 through 9.1.3.

A9.5.3 Calculation of \( K \)—For the arc-shaped bend specimen, calculate \( K \) in units of MPa m\(^{1/2}\) (ksi in.\(^{-1/2}\)) as follows (Note A9.2):

For specimens with \( S = 4W \):

\[ K_0 = \frac{P_0(BW)^{1/2}}{2} \left[ 1 + \left( r_1 + r_2 \right)/2 \right] \frac{g}{a} \frac{h(a/W)}{f(a/W)} \]

where:

\[ h(a/W) = 0.29 - 0.66(a/W) + 0.37(a/W)^2 \]

and

\[ f(a/W) = 0.677 + 0.079(a/W) - 0.143(a/W)^2 + 0.066(a/W)^3 \]

(1 - \( 1/W^2 \))\(^{1/2} \)

For specimens with \( S = 3W \):

\[ K_0 = \frac{P_0(BW)^{1/2}}{2} \left[ 1 + \left( r_1 + r_2 \right)/2 \right] \frac{g}{a} \frac{h(a/W)}{f(a/W)} \]

where:

\[ h(a/W) = 0.20 - 0.32(a/W) + 0.12(a/W)^2 \]

and

\[ f(a/W) = 0.644 + 1.11(a/W) - 1.49(a/W)^2 + 0.73(a/W)^3 \]

(1 - \( 1/W^2 \))\(^{1/2} \)

where:

\( P = \) load as determined in 9.1.1, kN (Ibf)

\( B = \) specimen thickness as determined in 8.2.1, cm (in.)

\( S = \) span as determined in A9.4.2, cm (in.)

\( W = \) specimen depth (width) as determined in A9.4.1, cm (in.)

\( a = \) crack length as determined in 8.2.2, cm (in.)

\( r_1 = \) inner radius as determined in A9.4.1, cm (in.)

\( r_2 = \) outer radius as determined in A9.4.1, cm (in.)

Note A9.2—The above expressions are considered to be accurate to within 1% for \( 0.2 \leq a/W \leq 1.0 \) and 6% for \( 2 \geq a/W \geq 1.0 \) for \( S = 4W \) and within 5% for \( 0.2 \leq a/W \leq 1.0 \) and 4% for \( 2 \geq a/W \geq 1.0 \) for \( S = 3W \) (32).

A9.5.3.1 To facilitate calculation of \( K_0 \), values of \( f(a/W) \) are given in the following table for specific values of \( a/W \):

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