



# Standard Test Method for Determination of Resistance to Stable Crack Extension under Low-Constraint Conditions<sup>1</sup>

This standard is issued under the fixed designation E 2472; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This standard covers the determination of the resistance to stable crack extension in metallic materials in terms of the critical crack-tip-opening angle (CTOA<sub>c</sub>),  $\psi_c$  and/or the crack-opening displacement (COD),  $\delta_5$  resistance curve (**1**).<sup>2</sup> This method applies specifically to fatigue pre-cracked specimens that exhibit low constraint (crack-length-to-thickness and uncracked ligament-to-thickness ratios greater than or equal to 4) and that are tested under slowly increasing remote applied displacement. The recommended specimens are the compact-tension, C(T), and middle-crack-tension, M(T), specimens. The fracture resistance determined in accordance with this standard is measured as  $\psi_c$  (critical CTOA value) and/or  $\delta_5$  (critical COD resistance curve) as a function of crack extension. Both fracture resistance parameters are characterized using either a single-specimen or multiple-specimen procedures. These fracture quantities are determined under the opening mode (Mode I) of loading. Influences of environment and rapid loading rates are not covered in this standard, but the user must be aware of the effects that the loading rate and laboratory environment may have on the fracture behavior of the material.

1.2 Materials that are evaluated by this standard are not limited by strength, thickness, or toughness, if the crack-length-to-thickness ( $a/B$ ) ratio and the ligament-to-thickness ( $b/B$ ) ratio are greater than or equal to 4, which ensures relatively low and similar global crack-front constraint for both the C(T) and M(T) specimens (**2, 3**).

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses (English) are for information purposes only.

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

## 2. Referenced Documents

### 2.1 ASTM Standards:<sup>3</sup>

- E 4 Practices for Force Verification of Testing Machines
- E 8 Test Methods for Tension Testing of Metallic Materials
- E 399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness  $K_{Ic}$  of Metallic Materials
- E 561 Test Method for **K-R** Curve Determination
- E 647 Test Method for Measurement of Fatigue Crack Growth Rates
- E 1290 Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement
- E 1820 Test Method for Measurement of Fracture Toughness
- E 1823 Terminology Relating to Fatigue and Fracture Testing
- E 2309 Practices for Verification of Displacement Measuring Systems and Devices Used in Material Testing Machines

### 2.2 ISO Standards:

- ISO/TC164/SC4-N413.4 Metallic Materials—Method of Test for the Determination of Resistance to Stable Crack Extension Using Specimens of Low Constraint<sup>4</sup>
- ISO 12135 Metallic Materials—Unified Method of Test for the Determination of Quasistatic Fracture Toughness<sup>4</sup>

## 3. Terminology

3.1 Terminology E 1823 is applicable to this test standard.

### 3.2 Definitions:

3.2.1 *crack extension*,  $\Delta a$  [ $L$ ],  $n$ —an increase in crack length.

3.2.1.1 *Discussion*—It should be noted that in thin-sheet and thick-plate materials under low constraint conditions, the crack extension observed on the surface of the specimen may be significantly less than that in the interior of the specimen due to the effects of crack tunneling. This must be considered if direct optical techniques are used to monitor and measure

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<sup>2</sup> The boldface numbers in parentheses refer to the list of references at the end of this standard.

<sup>3</sup> For referenced ASTM standards, visit the ASTM website, [www.astm.org](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

<sup>4</sup> Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

free-surface crack extension. Indirect crack extension measurement techniques such as unloading compliance and electric-potential drop method may be used in place of (or to augment) the direct optical techniques to provide a measure of average crack extension. (See Test Method E 647 for compliance methods for C(T) and M(T) specimens; and ISO 12135 for electric potential-drop methods for C(T) specimens.)

3.2.2 *crack length,  $a$  [L],  $n$* —a linear measure of a principal planar dimension of a crack. This measure is commonly used in the calculation of quantities descriptive of the stress and displacement fields of cracked specimens.

3.2.2.1 *Discussion*—A measure of the crack length after the fatigue pre-cracking stage is denoted as the original crack length,  $a_o$ . The value for  $a_o$  may be obtained using surface measurement, unloading compliance, electric-potential drop or other methods where validation procedures for the measurements are available.

3.2.3 *crack-tip-opening angle (CTOA),  $\psi$  [deg],  $n$* —relative angle of the crack surfaces measured (or calculated) at 1-mm behind current crack tip, where  $\psi = 2 \tan^{-1} (\text{CTOD}/2)$ .

3.2.4 *critical crack-tip-opening angle (CTOA<sub>c</sub>),  $\psi_c$  [deg],  $n$* —steady-state value of CTOA measured (or calculated) at 1-mm behind the current crack tip, where  $\text{CTOA}_c = 2 \tan^{-1} (\text{CTOD}_c/2)$ .

3.2.4.1 *Discussion*—The critical CTOA value tends to approach a constant, steady-state value after a small amount of crack extension (associated with crack tunneling and transition from flat-to-slant crack extension).

3.2.5 *crack-opening displacement,  $\delta_5$  [L],  $n$* —relative displacement of the crack surfaces normal to the original (undeformed) crack plane at the tip of the fatigue pre-crack length,  $a_o$ . In this standard,  $\delta_5$  is measured at the original crack length location over a gage length of 5-mm as the crack stably tears.

3.2.6 *crack-tip-opening displacement (CTOD),  $\delta$  [L],  $n$* —relative displacement resulting from the total deformation (elastic plus plastic) at variously defined locations near the original (prior to force application) crack tip.

3.2.7 *critical crack-tip-opening displacement (CTOD<sub>c</sub>),  $\delta_c$  [L],  $n$* —steady-state value of CTOD resulting from the total deformation (elastic plus plastic) measured (or calculated) at 1-mm behind current crack-tip location.

3.2.8 *crack extension resistance curve (R curve),  $n$* —variation of  $\delta_5$  with crack extension,  $\Delta a$ .

3.2.9 *effective yield strength,  $\sigma_Y$  [FL<sup>-2</sup>],  $n$* —an assumed value of uniaxial yield strength that represents the influence of plastic yielding upon fracture test parameters.

3.2.9.1 *Discussion*—Effective yield strength is calculated as the average of the 0.2 % offset yield strength  $\sigma_{YS}$ , and the ultimate tensile strength,  $\sigma_{TS}$  as follows:

$$\sigma_Y = (\sigma_{YS} + \sigma_{TS}) / 2 \quad (1)$$

NOTE 1—The yield and ultimate tensile strength are determined from Test Methods E 8.

3.2.9.2 *Discussion*—In estimating  $\sigma_Y$ , influences of testing conditions, such as loading rate and temperature, should be considered.

3.2.10 *final crack length,  $a_f$  [L],  $n$* —crack extension at end of stable tearing ( $a_f = a_o + \Delta a_f$ ).

3.2.11 *final remaining ligament,  $b_f$  [L],  $n$* —distance from the tip of the final crack length to the back edge of the specimen, that is  $b_f = W - a_f$ .

3.2.12 *force,  $P$  [F],  $n$* —force applied to specimen.

3.2.13 *minimum crack extension,  $\Delta a_{min}$  [L],  $n$* —crack extension beyond which  $\psi_c$  is nearly constant.

3.2.14 *maximum crack extension,  $\Delta a_{max}$  [L],  $n$* —crack extension limit for  $\psi_c$  and  $\delta_5$  controlled crack extension.

3.2.15 *maximum fatigue force,  $P_f$  [F],  $n$* —maximum fatigue force applied to specimen during pre-cracking stage.

3.2.16 *modulus of elasticity,  $E$  [FL<sup>-2</sup>],  $n$* —Young's modulus of elasticity.

3.2.17 *notch length,  $a_n$  [L],  $n$* —the distance from a reference plane to the tip of the machined notch, such as the load line in the compact-tension specimen to the notch tip or from the center line in the middle-crack tension specimen to the notch tip.

3.2.18 *original crack length,  $a_o$  [L],  $n$* —the physical crack length at the start of testing.

3.2.19 *original remaining ligament,  $b_o$  [L],  $n$* —distance from the original crack front to the back edge of the specimen, that is  $b_o = W - a_o$ .

3.2.20 *remaining ligament,  $b$  [L],  $n$* —distance from the crack front to the back edge of the specimen, that is  $b = W - a$ .

3.2.21 *specimen thickness,  $B$  [L],  $n$* —the side-to-side dimension of the specimen being tested (side grooving is not allowed).

3.2.22 *specimen width,  $W$  [L],  $n$* —a physical dimension on a test specimen measured from a reference position, such as the load line in the compact-tension specimen or the center line in the middle-crack tension specimen to the edge of the specimen. (Note that the total width of the M(T) specimen is defined as  $2W$ .)

## 4. Summary of Test Method

4.1 The objective of this standard is to induce stable crack extension in a fatigue pre-cracked, low-constraint test specimen while monitoring and measuring the COD at the original fatigue pre-crack tip location (4, 5) or the CTOA (or CTOD) at 1-mm behind the stably tearing crack tip (6, 7), or both. The resistance curve associated with the  $\delta_5$  measurements and the critical limiting value of the CTOA measurements are used to characterize the corresponding resistance to stable crack extension. In contrast, the CTOD values determined from Test Method E 1290 (high-constraint bend specimens) are values at one or more crack extension events, such as the CTOD at the onset of brittle crack extension with no significant stable crack extension.

4.2 Either of the fatigue pre-cracked, low-constraint test specimen configurations specified in this standard (C(T) or M(T)) may be used to measure or calculate either of the fracture resistance parameters considered. The fracture resistance parameters, CTOA (or CTOD) and  $\delta_5$ , may be characterized using either a single-specimen or multiple-specimen procedure. In all cases, tests are performed by applying slowly increasing displacements to the test specimen and measuring the forces, displacements, crack extension and angles realized during the test. The forces, displacements and angles are then

used in conjunction with certain pre-test and post-test specimen measurements to determine the material's resistance to stable crack extension.

4.3 Four procedures for measuring crack extension are: surface visual, unloading compliance, electrical potential, and multiple specimens.

4.4 Two techniques are presented for measuring CTOA: optical microscopy (OM) (8) and digital image correlation (DIC) (9).

4.5 Three techniques are presented for measuring COD:  $\delta_5$  clip gage (5), optical microscopy (OM) (8), and digital image correlation (DIC) (9).

4.6 Data generated following the procedures and guidelines contained in this standard are labeled qualified data and are insensitive to in-plane dimensions and specimen type (tension or bending forces), but are dependent upon sheet or plate thickness.

## 5. Significance and Use

5.1 This test method characterizes a metallic material's resistance to stable crack extension in terms of crack-tip-opening angle (CTOA),  $\psi$  and/or crack-opening displacement (COD),  $\delta_5$  under the laboratory or application environment of interest. This method applies specifically to fatigue pre-cracked specimens that exhibit low constraint and that are tested under slowly increasing displacement.

5.2 When conducting fracture tests, the user must consider the influence that the loading rate and laboratory environment may have on the fracture parameters. The user should perform a literature review to determine if loading rate effects have been observed previously in the material at the specific temperature and environment being tested. The user should document specific information pertaining to their material, loading rates, temperature, and environment (relative humidity) for each test.

5.3 The results of this characterization include the determination of a critical, lower-limiting value, of CTOA ( $\psi_c$ ) or a resistance curve of  $\delta_5$ , a measure of crack-opening displacement against crack extension, or both.

5.4 The recommended specimens are the compact-tension, C(T), and middle-crack-tension, M(T), specimens.

5.5 Materials that can be evaluated by this standard are not limited by strength, thickness, or toughness, if the crack-length-to-thickness ( $a/B$ ) ratio or ligament-to-thickness ( $b/B$ ) ratio are equal to or greater than 4, which ensures relatively low and similar global crack-front constraint for both the C(T) and M(T) specimens (2, 3).

5.6 The values of CTOA (and COD ( $\delta_5$ )) determined by this test method may serve the following purposes:

5.6.1 In research and development, CTOA<sub>c</sub>( $\psi_c$ ) or COD ( $\delta_5$ ), or both, testing can show the effects of certain parameters on the resistance to stable crack extension of metallic materials significant to service performance. These parameters include, but are not limited to, material thickness, material composition, thermo-mechanical processing, welding, and thermal stress relief.

5.6.2 For specifications of acceptance and manufacturing quality control of base materials.

5.6.3 For inspection and flaw assessment criteria, when used in conjunction with fracture mechanics analyses. Awareness of differences that may exist between laboratory test and field conditions is required to make proper flaw assessment.

5.6.4 The critical CTOA ( $\psi_c$ ) has been used with the elastic-plastic finite-element method to accurately predict structural response and force carrying capacity of simple and complex cracked structural components, see Appendix X1.

5.6.5 The  $\delta_5$  parameter has been related to the J-integral by means of the Engineering Treatment Model (ETM) (10) and provides an engineering approach to predict the structural response and force carrying capacity of cracked structural components.

5.6.6 The K-R curve method (Practice E 561) is similar to the  $\delta_5$ -resistance curve, in that, the concept has been applied to both C(T) and M(T) specimens (under low-constraint conditions) and the K-R curve concept has been used successfully in industry (11). However, the  $\delta_5$  parameter has been related to the J-integral and the parameter incorporates the material non-linear effects in its measurement. Comparisons have also been made among various fracture criteria on fracture of C(T), M(T) and a structurally configured crack configuration (12) that were made of several different materials (two aluminum alloys and a very ductile steel), and the K-R curve concept was found to have limited application, in comparison to the critical CTOA<sub>c</sub>( $\psi_c$ ) concept.

## 6. Apparatus

6.1 This procedure involves measurement of applied force,  $P$ , crack extension,  $\Delta a$ , and crack-opening displacement at the original fatigue crack tip location or crack-tip-opening angle at the current crack tip, or both. Testing is performed under crosshead displacement control in a tension-testing machine that conforms to the requirements of Practice E 4.

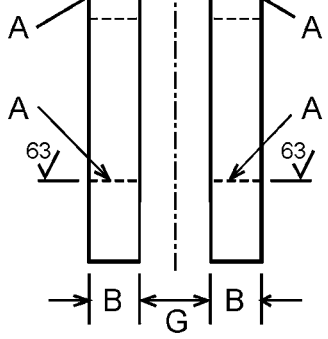
6.1.1 *Calibration*—Calibration of all measuring apparatus shall be traceable either directly or indirectly via a hierarchical chain to an accredited calibration laboratory.

6.1.2 *Force Application*—The combined force sensing and recording devices shall conform to ASTM standards, such as Practices E 4 and E 2309. The test machine shall operate at a constant displacement rate. A force measuring system of nominal capacity exceeding  $1.2P_L$  shall be used, where:

$$P_L = B(W - a_o)^2 \sigma_{TS} / (2W + a_o) \quad \text{for compact-tension specimen} \quad (2)$$

$$P_L = 2B(W - a_o) \sigma_{TS} \quad \text{for middle-crack-tension specimen} \quad (3)$$

6.2 *Fixturing for the Compact Tension [C(T)] Specimens*—Compact-tension specimens shall be loaded using a clevis and pin arrangement designed to minimize friction. The arrangement shall ensure load train alignment as the specimen is loaded in tension. A loading clevis suitable for testing C(T) specimens is shown in Fig. 1. Each leg of the specimen is held by such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. To provide rolling contact between the loading pins and the clevis holes, these holes are produced with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown.



Note 3 - Corners may be removed as necessary to accomodate clip gage.

**FIG. 1 Clevis for Compact Tension, C(T), Specimen Testing**

Round-bottomed holes shall not be allowed for single specimen (unloading compliance) tests because pin movement may be restricted. Clevises and pins should be fabricated from steels of sufficient strength and hardness (greater than 40 HRC (400 HV)) to elastically resist indentation forces. The critical tolerances and suggested proportions of the clevis and pins are given in Fig. 1. The pin diameter is  $0.24W$  ( $+0.000W/-0.005W$ ). The particular configuration and dimensions in the gripping area should be selected by the user to match the test machine fixtures and capabilities. These proportions are based on specimens having  $W/B = 8$ . If a 1900-MPa (275 000-psi) yield strength maraging or stainless steel is used for the clevis and pins, adequate strength will be obtained. If lower strength grip material is used, or if substantially larger specimens are required at a given  $\sigma_{YS}/E$  ratio, then heavier grips may be required. Attention should be given to achieving good alignment through careful machining of all auxiliary gripping fixtures. All specimens shall be tested with anti-buckling guide plates, as shown in Fig. 2. The anti-buckling guide plates must cover a large portion of the specimen. Placing thin sheets of a low friction material, such as TFE-fluorocarbon, between the anti-buckling plates and the specimen surface, and only hand-tightening the perimeter bolts has been shown to provide adequate stability while minimizing friction. As shown in Fig. 2, openings must be machined into the anti-buckling plates in the appropriate locations to allow for the monitoring and measuring of crack extension and the crack-tip-opening angles and  $\delta_5$ . Measurement of crack-mouth-opening displacements

using a clip gage may be made to determine crack length using the unloading compliance method.

**6.3 Fixturing for the Middle-Crack Tension [M(T)] Specimens**—Middle-crack tension specimens shall be loaded using hydraulically-clamped or bolted grips designed to carry the applied force in friction. Bolt bearing should be avoided to minimize non-uniform loading. The arrangement shall ensure alignment of the specimen to minimize in-plane and out-of-plane bending. All specimens shall be tested with anti-buckling guide plates, as shown in Fig. 3. The anti-buckling guide plates must cover a large portion of the specimen. Support only along the crack plane has been shown to be insufficient to prevent buckling between the grip lines and the crack plane for thin-sheet materials. Flat plates, as shown in Fig. 3(a), are sufficient for small M(T) specimens ( $2W < 600$  mm), but flat plates stiffened with I-beams, as illustrated in Fig. 3(b), have been shown to be required for M(T) specimens with widths ( $2W$ ) larger than about 600 mm. As shown in Fig. 3, gap(s) are left in the anti-buckling plates on either one or both sides of the specimen to allow for the monitoring and measuring of crack extension and the crack-tip-opening angles, and  $\delta_5$ . Measurement of crack-mouth opening displacements using a clip gage may also be made to determine crack length using the unloading compliance method.

**6.4 Crack Extension Measurement**—Several methods can be used to monitor and measure crack extension: (1) direct optical method, (2) unloading compliance method, (3) electric-potential-drop method, and (4) the multiple-specimen method.

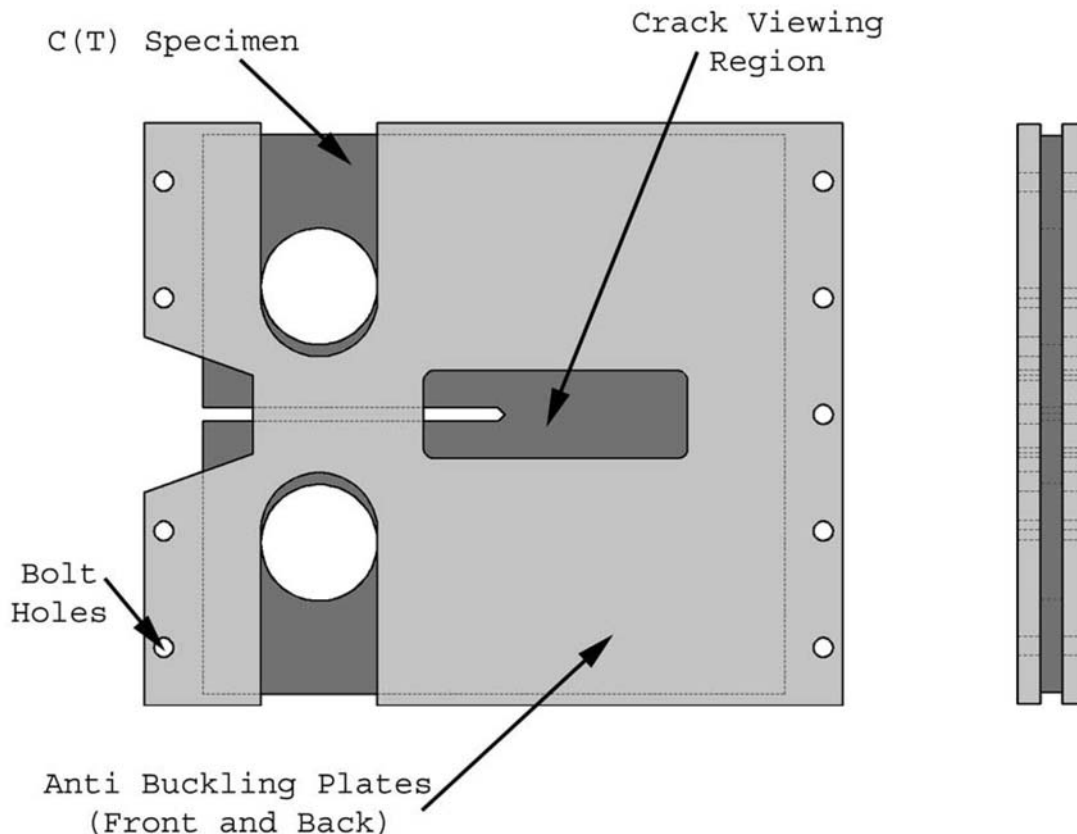


FIG. 2 Compact Tension, C(T), Specimen with Anti-Buckling Guides

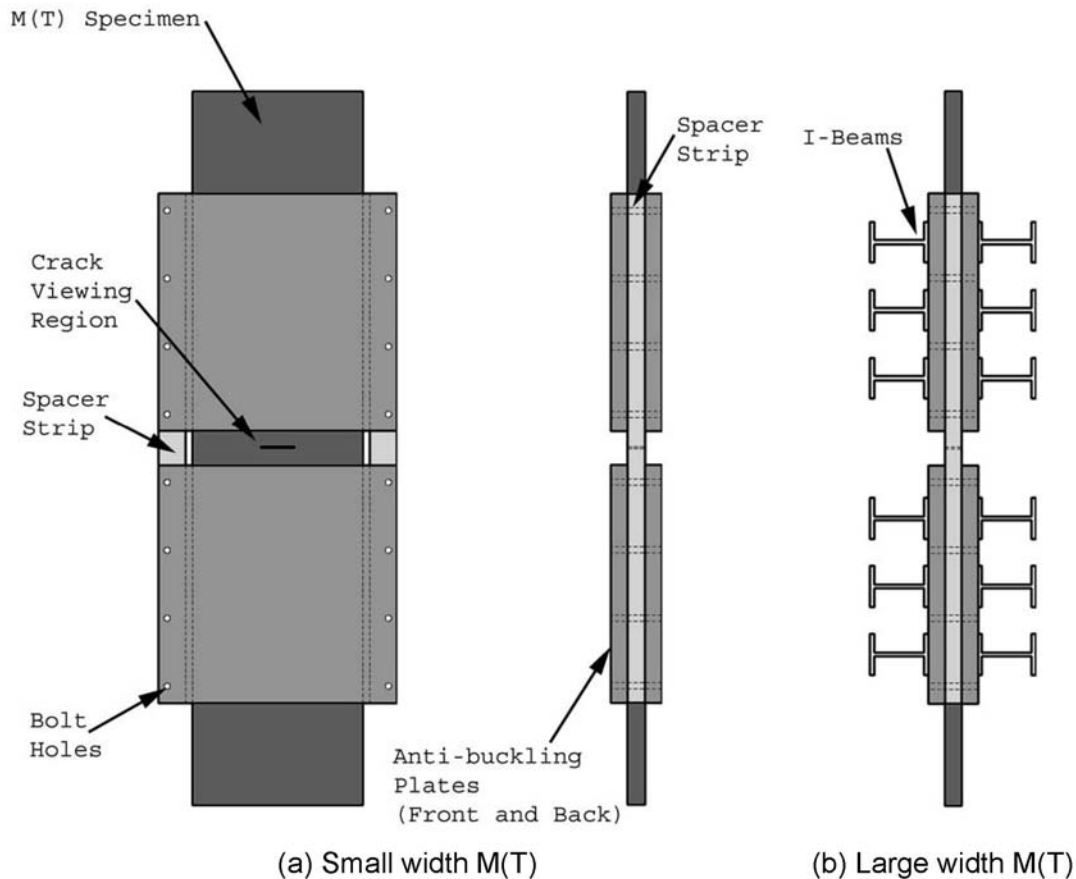


FIG. 3 Middle-Crack Tension, M(T), Specimen with Anti-Buckling Guides

Indirect crack extension measurement techniques, such as unloading compliance and electric-potential-drop methods may be used in place of (or to augment) the direct optical method to provide a measure of average through-the-thickness crack extension. The multiple-specimen method is used to provide information on the extent of tunneling and to determine a three-point ( $B < 5$  mm) or five-point ( $B > 5$  mm) weighted average crack extension.

**6.4.1 Direct Optical Method**—The direct optical method measures the crack length and crack extension on the specimen free surface using optical microscopes. It should be noted that in thin-sheet materials and low constraint specimens, the crack extension observed on the free surface of the specimen may be significantly less than that on the interior of the specimen due to the effects of crack tunneling. This must be kept in mind if direct optical techniques are used to monitor and measure free-surface crack extension.

**6.4.2 Unloading Compliance Method**—By the unloading compliance method, a specimen is partially unloaded and then reloaded at specified intervals during the test. The unloading slopes, which tend to be linear and independent of prior plastic deformation, are used to estimate the crack length at each unloading from analytical elastic compliance relationships. The specimen compliance is determined from either crack-mouth-opening or load-point compliance, and the crack length is estimated using compliance equations (see Test Methods

E 647 and E 1820). If the displacement is measured at an alternative point, then the appropriate compliance function must be developed and utilized. Errors may occur in the compliance measurement as a result of displacement-gage transducer non-linearity. Significant improvement in accuracy can be achieved by curve-fitting the lowest-order polynomial function possible through the calibration data. This method is ideally suited to computer control and subsequent analysis of the test data. However, it should be noted that the method requires careful experimentation and sophisticated test equipment in order to realize its full capability.

**6.4.3 Electric Potential Drop Method**—The electrical potential method (13-16) relies on the fact that the distribution of electrical potential in the vicinity of a crack changes with crack extension. With suitable instrumentation, the changes in potential can be detected and calibrated to provide an estimate of increase in crack length. The applied potential is either direct or alternating and the procedure referred to as either the D.C. or the A.C. potential technique, respectively. This method is ideally suited to computer control and subsequent analysis of the test data. However, it should be noted that the method requires careful experimentation and sophisticated test equipment in order to realize its full capability. (See ISO 12135 for descriptions of the electric-potential drop methods for the C(T) specimen.)

**6.4.4 Multiple-Specimen Method**—The multiple-specimen method relies on fatigue marking, heat-tinting, or other means to mark the crack front after stable tearing. The multiple-specimen method is used to provide information on the extent of tunneling and to determine a three-point ( $B < 5$  mm) or five-point ( $B > 5$  mm) weighted average crack extension.

**6.5 Force Measurement**—The sensitivity of the force-sensing device shall be sufficient to avoid distortion caused by over amplification. The combination of force sensing device and recording system shall permit the maximum force ( $P$ ) to be determined from the test record within an accuracy of  $\pm 1\%$ .

**6.6 Displacement and Angle Measuring Technique**—This test method covers the characterization of resistance to stable crack extension in fatigue pre-cracked (at low  $\Delta K$  levels), low-constraint test specimens. Two methods are introduced to provide this characterization, the first is based on the crack-tip-opening angle (CTOA),  $\psi$ , and the second is based on a measure of crack-opening displacement (COD),  $\delta_5$ . Both methods can be carried out using either a single-specimen or multiple-specimen procedure. In the following sections, these two characterizations techniques will be discussed in parallel.

**6.6.1 Crack-Tip-Opening Angle Measurement**—This procedure involves the displacement-controlled loading of a fatigue pre-cracked, low-constraint specimen C(T) or M(T) while simultaneously measuring the applied force ( $P$ ), crack extension ( $\Delta a$ ) and crack-tip-opening angle (CTOA) measured 1 mm behind the current crack tip. Several methods can be used to determine CTOA: (1) direct measurements during stable tearing using optical methods (8, 9), (2) post test measurements (microtopography) (17-19), (3) finite element analyses (6-8, 20-26), and (4) indirect determination using  $\delta_5$ . The two techniques that are used for direct measurement of  $\psi$  (CTOA) during stable tearing of cracks are the Optical Microscopy (OM) (8) and Digital Image Correlation (DIC) (8, 9) methods. Both of these methods produce nearly identical CTOA results (8, 20).

**6.6.1.1 Optical Microscopy (OM) Method**—This method includes: (a) a long focal length microscope, (b) a high-resolution video camera with resolution of 512 by 512 pixels (or better) to obtain images of the stably tearing crack, (c) a recording mechanism to store the images (PC or video recorder), and (d) a personal computer with both monitor and software to precisely control the three-dimensional positioning of the long focal length microscope and also to analyze the images to obtain CTOA. A transverse magnification of approximately 320 pixels per mm has been shown to provide satisfactory results. To obtain clear images of the crack using OM, the surface of the specimen must be polished to a mirror finish and lighting of the crack region must be carefully controlled so that the crack tip region has optimum contrast and clarity. Recommended procedures to measure CTOA using this method will be discussed in 9.1.1 of this document.

**6.6.1.2 Digital Image Correlation (DIC) Method**—This method includes: (a) a video camera, (b) a lens system to obtain the appropriate level of magnification (for example, a 200 mm lens with 2 $\times$  magnifier and several extension tubes has been used effectively in previous applications), (c) translation stage for positioning of the video camera and following

the growing crack, (d) video monitor to view the crack tip region, (e) video board to digitize images, and (f) a microcomputer with software for controlling the image acquisition process and storing images. The DIC method is similar to previously reported image correlation systems, except that in this case the video camera is translated parallel to the specimen surface during the experiment so that the current crack tip remains within the field of view. Note that, after each translation of the video camera, the current image and previous image overlap by at least 50 pixels so that a continuous record of crack length is maintained if the crack grows beyond the current field of view. Recommended procedures to measure CTOA using this method will be discussed in 9.1.2 of this document.

**6.6.2 Crack-Opening Displacement,  $\delta_5$ , Measurement**—This procedure involves the displacement-controlled loading of a fatigue pre-cracked, low-constraint specimen [C(T) or M(T)] while simultaneously measuring the applied force ( $P$ ), crack extension ( $\Delta a$ ), and crack-opening displacement ( $\delta_5$ ) measured at the original fatigue crack tip location.

**6.6.2.1 Clip-Gage Method**—This method includes a displacement gage for the determination of  $\delta_5$  at the original fatigue crack tip location and shall have an electrical output that represents the displacement between two precisely located gage positions 5-mm apart and spanning the crack at the original fatigue crack tip location. The basic arrangement for measuring  $\delta_5$  is shown in Fig. 4. The area around the expected fatigue pre-crack path is to be polished. After fatigue pre-cracking, Vickers hardness indentations are placed 2.5 mm to either side of the crack tip to give a gage length of 5 mm. A clip gage with needle tips is seated into the hardness indentations and held against the specimen using the lever mechanism shown in Fig. 5 for the compact-tension specimen. Similar arrangements and clip-gage fixtures are used for middle-crack-tension specimens. The recommended displacement gage configuration and dimensions are shown in Fig. 6. The displacement gage has a working range of not more than twice the displacement expected during the test. When the expected displacement is less than 3.75 mm (0.15 in.), the gage recommended in Fig. 6 may be used. When a greater working range is needed, an enlarged gage or the optical methods are recommended. Accuracy shall be within  $\pm 1\%$  of the full working range. In calibration, the maximum deviation of the individual data points from a linear fit to the data shall be less than  $\pm 0.3\%$  of the working range of the gage. Vickers hardness indentations at 5-mm gage length are required for seating the gage. The displacement gage should be removed from the specimen before the specimen fails. Recommended procedures to measure  $\delta_5$ -resistance curves using this method will be discussed in 9.2 of this document.

**6.6.2.2 Digital Image Correlation (DIC) Method**—This method includes: (a) a video camera, (b) a lens system to obtain the appropriate level of magnification (for example, a 200 mm lens with 2 $\times$  magnifier and several extension tubes has been used effectively in previous applications), (c) a translation stage for positioning of the video camera and following the growing crack, (d) video monitor to view the crack tip region, (e) video board to digitize images, and (f)

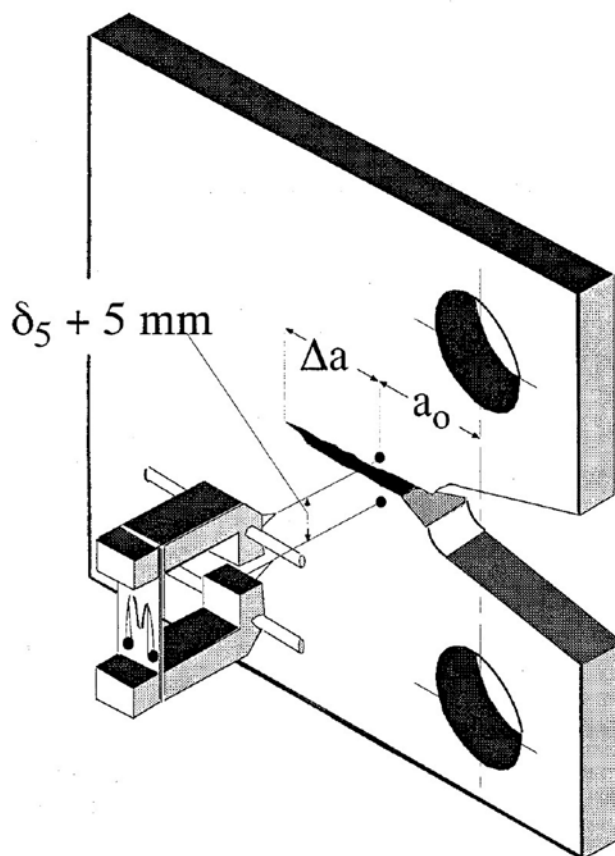


FIG. 4 Basic Clip Gage and Specimen Arrangement for Measuring  $\delta_5$

microcomputer with software for controlling the image acquisition process and storing images. The DIC method is similar to previously reported systems, except that the video camera remains stationary so that the original crack tip remains within the field of view. Recommended procedures to measure  $\delta_5$ -resistance curves using this method will be discussed in 9.2 of this document.

**6.6.2.3 Optical Microscopy (OM) Method**—This method includes: (a) a long focal length microscope positioned at the original crack-tip location, (b) a high-resolution video camera with resolution of 512 by 512 pixels (or better) to obtain images of the displacement field, (c) a recording mechanism to store the images (PC or video recorder), and (d) a personal computer with both monitor and software to measure the  $\delta_5$ -displacement. After fatigue pre-cracking, Vickers hardness indentations are placed 2.5 mm to either side of the crack tip to give a gage length of 5 mm. The displacement of the indentation marks is measured as a function of the applied force and crack extension. Recommended procedures to measure  $\delta_5$ -resistance curves using this method will be discussed in 9.2 of this document.

## 7. Specimen Configuration, Dimensions, and Preparation

**7.1 Materials** that can be evaluated by this standard are not limited by strength, thickness, or toughness, if the crack-length-to-thickness ( $a/B$ ) ratio or ligament-to-thickness ( $b/B$ )

ratio are equal to or greater than 4, which ensures relatively low and similar global crack-front constraint for both the C(T) and M(T) specimens.

NOTE 2—The total width of the M(T) specimen is defined as  $2W$ .

**7.2 Specimen Configurations**—The crack configurations of the standard specimens are shown in Annex A1 and Annex A2. To produce a reliable critical CTOA ( $\psi_c$ ) and a large amount of the  $\delta_5$ -resistance curve, the specimens have a minimum width ( $W$ ) of 150 mm.

**7.3 Crack Plane Orientation**—The crack plane orientation shall be considered in preparing the test specimen. The orientation of the crack plane in the material of interest can affect the critical crack-opening displacement parameters considered in this standard. This is discussed in Terminology E 1823.

**7.4 Specimen Pre-cracking**—All specimens shall be pre-cracked in fatigue. Experience has shown that it is impractical to obtain a reproducibly sharp, narrow machined notch that will simulate a natural crack well enough to provide a satisfactory fracture toughness test result. The most effective artifact for this purpose is a narrow notch from which extends a comparatively short fatigue crack, called the pre-crack. (A fatigue pre-crack is produced by cyclically loading the notched specimen for a number of cycles usually between about  $10^4$  and  $10^6$  depending on specimen size, notch preparation, and stress intensity level.) The dimensions of the notch and the

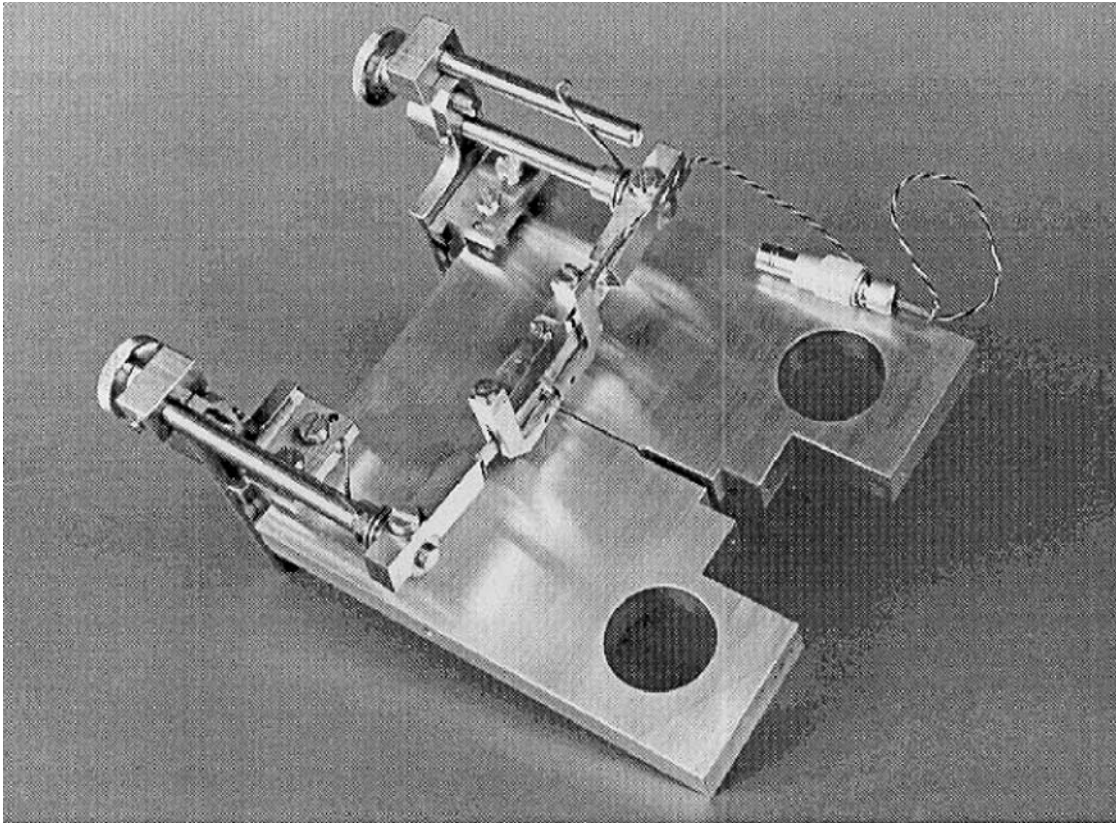


FIG. 5 Fixtures for Attachment of the  $\delta_5$  Clip Gage to Compact-Tension Specimen

pre-crack, and the sharpness of the pre-crack shall meet certain conditions that can be readily met with 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.

**7.4.1 Fatigue Crack Starter Notch**—Several forms of fatigue crack starter notches are shown in Fig. 7. The notch height,  $N$ , is equal to or less than 5 mm. The notch configurations shall not exceed the envelope, as shown by the dashed lines in Fig. 7. In the case of an electrical-discharge machined slot or a slot with a drilled hole at the tip, it will be necessary to provide a sharp stress raiser at the end of the slot or hole. To facilitate fatigue cracking at low stress-intensity factor levels, the root radius for a straight-through slot terminating in a V-notch should be 0.08 mm (0.003 in.) or less.

**7.4.2 Fatigue Crack Length**—The fatigue crack length from the notch tip shall be equal to or exceed the envelope, as shown by the dashed lines in Fig. 7. The fatigue crack extension,  $\Delta a$ , shall be equal to or greater than  $2N$ , but not less than 1.3-mm in length.

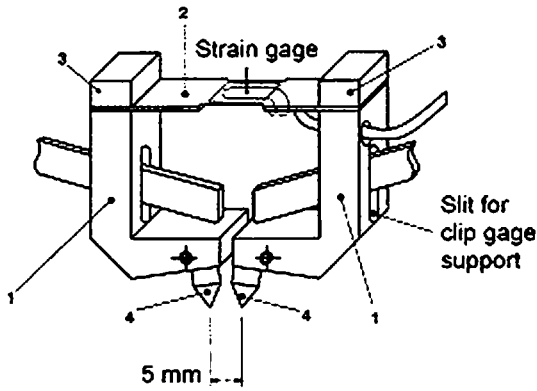
**7.4.3 Equipment and Fixtures**—The equipment and fixtures used for fatigue cracking should be such that the stress

distribution through the specimen thickness is uniform (no out-of-plane bending); otherwise the crack will not grow uniformly. The stress distribution should also be symmetrical about the plane of the prospective crack (no shear mode stress intensity factors); otherwise the crack may deviate from that plane and the test result can be significantly affected. Fixtures used for fatigue cracking should be machined with the same tolerances as those used for testing.

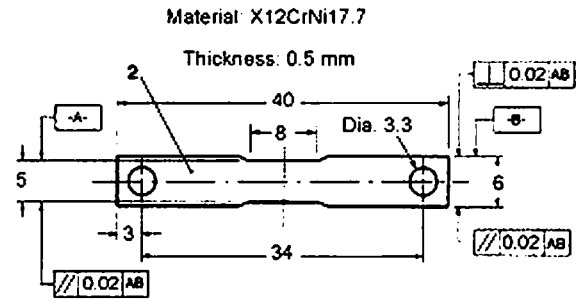
**7.4.4 Fatigue Pre-cracking Procedure**—Fatigue pre-cracking shall be performed with the material in the finally heat-treated, mechanically worked, or environmentally conditioned state. Intermediate treatments between fatigue pre-cracking and testing are acceptable only when such treatments are necessary to simulate the conditions of a specific structural application; such departure from recommended practice shall be explicitly reported.

**7.4.4.1 Maximum fatigue pre-cracking force** during any stage of the fatigue pre-cracking process shall be accurate to  $\pm 5\%$ .

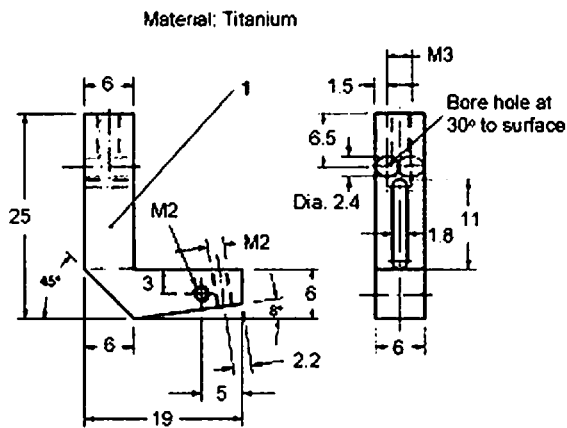
**7.4.4.2 Fatigue pre-cracking** should be carried out such that the maximum fatigue pre-cracking force ( $P_f$ ) during the pre-crack extension shall be equal to or less than:



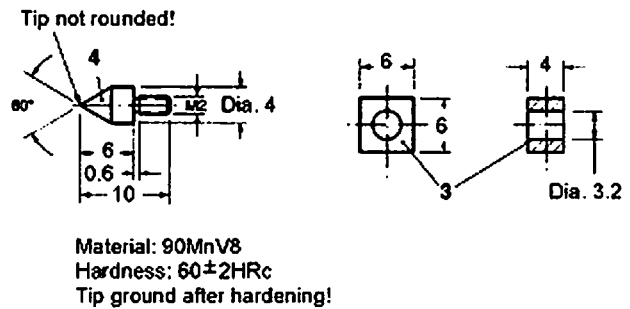
(a) Overall  $\delta_5$  clip gage design



(b) Clip gage spring



(c) Clip gage arms



(d) Clip gage tips

(All dimensions in mm.)

FIG. 6 Crack-Opening Displacement,  $\delta_5$ , Clip Gage Design

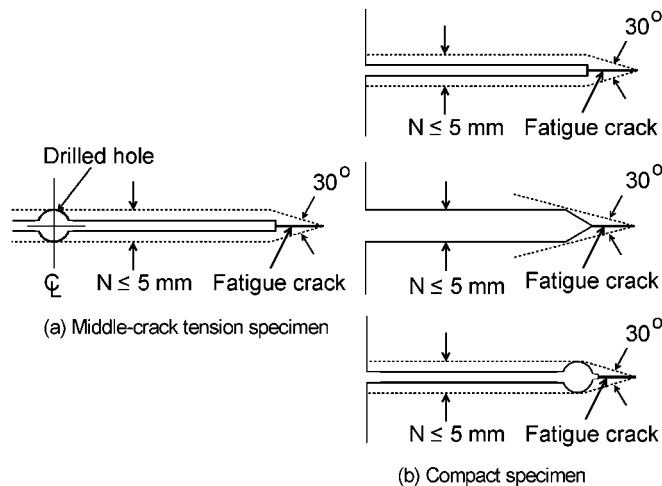


FIG. 7 Envelope of Fatigue Crack Starter Notch Configurations

For compact tension [C(T)] specimens:

$$P_f = \xi EB W^{1/2} / g_1(a_f/W) \quad (4)$$

where:

$$\xi = 1.6 \times 10^{-4} \text{ m}^{1/2} (0.001 \text{ in.}^{1/2}), \text{ and}$$

$$g_1(a_f/W) = (1 - a_f/W)^{-1.5} (2 + a_f/W) \times [0.886 + 4.64 (a_f/W) - 13.32 (a_f/W)^2 + 14.72 (a_f/W)^3 - 5.6 (a_f/W)^4] \quad (5)$$

For middle-crack tension [M(T)] specimens:

$$P_f = \xi E B W [\pi a_o \sec(\pi a_o/(2W))]^{-1/2} \quad (6)$$

where:

$$\xi = 1.6 \times 10^{-4} \text{ m}^{1/2} (0.001 \text{ in.}^{1/2})$$

7.4.4.3 Measured values of specimen thickness  $B$  and width  $W$  should be used to determine the maximum fatigue pre-cracking force  $P_f$ .

7.4.4.4 The ratio of minimum-to-maximum force ( $R$ ) in the fatigue cycle shall be in the range 0 to 0.1, except that to expedite crack initiation one cycle of  $R = -1.0$  may be first applied.

## 8. Procedure

8.1 *Testing Rate*—Tests shall be conducted under displacement control. Load-line displacement rate shall be such that within the linear elastic region the stress intensification rate is within the range  $0.2 \text{ MPa}\cdot\text{m}^{1/2} \text{ s}^{-1}$  to  $3 \text{ MPa}\cdot\text{m}^{1/2} \text{ s}^{-1}$ . For each series of tests, all specimens shall be loaded at the same nominal rate.

8.2 *Specimen Test Temperature*—Specimen test temperature shall be controlled and recorded to an accuracy of  $\pm 2^\circ\text{C}$ . Tests shall be made in situ in suitable low or high temperature media. Before testing in a liquid medium, the specimen shall be retained in the liquid for at least 30 s/mm of thickness  $B$  after the specimen surface has reached the test temperature. When using a gaseous medium, a soaking time of at least 60 s/mm of thickness shall be employed. Minimum soaking time at the test temperature shall be 15 minutes. The temperature of the test specimen shall remain within  $\pm 2^\circ\text{C}$  of the nominal test temperature throughout the test and shall be recorded.

8.3 *Crack-Tip-Opening Angle*—The objective of this procedure is to identify CTOA values that can be used as measures of resistance to stable crack extension in fatigue pre-cracked, low-constraint specimens [C(T) or M(T)]. This procedure involves the displacement-controlled loading of a fatigue pre-cracked, low-constraint specimen, C(T) or M(T) while simultaneously measuring the applied force ( $P$ ), crack extension ( $\Delta a$ ) and crack-tip-opening angle (CTOA) measured 1-mm behind the current crack tip. Using either of the recommended specimens specified in this test method, the resistance to stable crack extension may be characterized using the crack-tip-opening angle in either a single-specimen or multiple-specimen technique.

8.3.1 *Testing*—The stable tearing fracture tests performed on the pre-cracked, low-constraint specimens consist of a displacement controlled ramp waveform that would slowly pull the specimen apart until stable tearing was initiated. Using the

appropriate video equipment, the region around the stably growing crack is to be continuously monitored to allow for the determination of post-test CTOA and crack extension measurements. During the fracture tests, the force and load line displacement signals are to be continuously recorded.

8.3.2 *Single-Specimen CTOA Characterization Technique*—In this approach, a single specimen is used to generate CTOA against crack extension data from which the critical CTOA value can be determined. Using the displacement rate specified earlier, the fatigue pre-cracked specimen is loaded until a stable crack extension event is detected. As the fracture test is initiated, the video recording equipment is started (for example, typically a video recorder when using OM method and a digital camera for the DIC method). For both methods, images of the crack tip are displayed on a monitor. When a stable tearing event is observed, the testing machine is paused and a record of the force, time, crack length, and displacement is obtained. At the same time, images are acquired by the image acquisition system(s) just prior to and also just after crack extension.

8.3.2.1 While the testing system is paused, adjustments are made to the image acquisition equipment. In the OM method, lighting is adjusted and the imaging system is refocused. In the DIC method, the digital camera is translated parallel to the crack extension direction to ensure that the crack tip region will remain in the field of view during future crack extension. The displacement loading is then resumed until another stable tearing event is observed. This process is repeated until complete specimen fracture occurs.

8.3.2.2 As an alternate single specimen CTOA characterization approach, the displacement controlled fracture test may be run in a continuous (rather than incremental) manner. During this process, images of the crack tip region must be continuously recorded in a synchronized manner with the crack extensions, force, and displacement measurements. For both the OM and DIC methods, this may require automated translation stages to keep the crack tip region in the field of view. Once a test is completed, the entire video history is reviewed to obtain CTOA and crack length measurements.

8.3.3 *Multiple-Specimen CTOA Characterization Technique*—In this approach, multiple specimens are used to generate a series of CTOA against crack extension data points. Each specimen is used to analyze a single stable tearing event, at various stages of crack extension. These data are then combined to create a CTOA against crack extension history from which the critical CTOA value can be determined. This approach has an advantage (over the single specimen technique) in that it provides for the measurement of the entire crack front profile (surface and interior) associated with a single stable tearing event. As mentioned earlier, in thin-sheet materials and low constraint specimens, the crack extension observed on the surface of the specimen during the early stages of flat crack extension may be significantly less than that in the interior of the specimen due to the effects of crack tunneling. In this approach, the test is performed as described above in the single specimen approach, except that, once the stable tearing event of interest has occurred, the specimen is subjected to a fatigue loading (at high ratio  $R \sim 0.8$  and 70 % of the force at

the last tearing event) to mark the current crack front profile. The specimen is then pulled apart and analyzed. Using the video history of the crack tip region, the crack extension measurements obtained from the fracture surface examination, and the force record, the CTOA against crack extension point can be determined.

**8.3.4 Data Requirements**—Six or more CTOA data points as a function of crack extension are required to calculate a critical CTOA value. Loading the first specimen to a point just past maximum force and measuring the resulting stable crack extension helps to determine the applied displacement levels needed to equally-position data points in additional tests.

**8.4 Crack-Opening Displacement ( $\delta_5$ )**—The objective of this procedure is to measure  $\delta_5$  against crack extension in fatigue pre-cracked, low-constraint specimens [C(T) or M(T)]. This procedure involves the displacement-controlled loading of a fatigue pre-cracked, low-constraint specimen [C(T) or M(T)] while simultaneously measuring the applied force ( $P$ ), crack extension ( $\Delta a$ ), and crack-tip-opening displacement,  $\delta_5$ , measured at the original pre-crack length over a gage length of 5-mm as the crack stably tears. Using either of the recommended specimens specified in this test method, the resistance to stable crack extension can be characterized using the crack-tip-opening displacement in either a single-specimen or multiple-specimen technique.

**8.4.1 Testing**—The stable tearing fracture tests performed on the pre-cracked, low-constraint specimens consist of a displacement controlled ramp waveform that would slowly pull the specimen apart until stable tearing was initiated. Using the appropriate clip gage fixtures or DIC equipment, or both, the displacements at the  $\delta_5$  location are to be continuously monitored as a function of crack extension measurements. Using the OM method, the displacement at the  $\delta_5$  location is measured as a point value against the corresponding crack-extension measurement. During the fracture tests, the force and load line displacement signals are to be continuously recorded.

**8.4.2 Single-Specimen  $\delta_5$  Characterization Technique**—A continuous record of  $\delta_5$  against crack extension,  $\Delta a$ , is determined in a test in the crack extension range zero to  $\Delta a_{max}$ . Due to the non-local nature of  $\delta_5$  for an extending crack,  $\delta_5$  loses its ability to uniquely correlating crack extension for large amounts of crack extension under bending force, such as those for the compact-tension specimen. However, the middle-crack tension specimen exhibits a different behavior, in that, the  $\delta_5$  resistance curve is unique for large amounts of crack extension.

**8.4.3 Multiple-Specimen  $\delta_5$  Characterization Technique**—A series of nominally identical specimens are loaded to selected displacement levels and the corresponding amounts of crack extension are determined. Each specimen tested provides one point on the  $\delta_5$ - $\Delta a$  crack resistance curve (hereafter referred to generically as the R-curve).

**NOTE 3**—Four or more equally-positioned data points in terms of crack extension are required to generate an R-curve. Loading the first specimen to a point just past maximum force and measuring the resulting stable crack extension helps to determine the applied displacement levels needed to equally-position data points in additional tests.

## 9. Measurements and Interpretation

**9.1 Critical CTOA Determination**—Once the CTOA characterization testing is complete (using either the single- or multiple-specimen approach), the crack tip opening angle must be determined from the video history of the stable crack extension. Two methods, the Optical Microscopy (OM) and the Digital Image Correlation (DIC) method can be used to make the measurement of the CTOA. Either method may be used to record tearing events on the surface of the specimens. The critical CTOA value is calculated as the average of the values measured within a specified crack extension range ( $\Delta a_{min}$  and  $\Delta a_{max}$ ; see below). It has been shown that using data within this range will provide an accurate characterization of critical CTOA, unbiased from the early effects of crack blunting and severe tunneling and the later effects of specimen dependent constraint variations. The value of  $\Delta a_{min}$  that shall be used corresponds to the location on the CTOA against crack extension plot where the initial transient effects are completed and the CTOA has leveled off to a nearly constant value. In thin-sheet materials, the value of  $\Delta a_{min}$  has been shown to exhibit a wide variability, ranging from one to seven times the specimen thickness (7, 20), whereas in a thicker material the value of  $\Delta a_{min}$  has been shown to be significantly less than the specimen thickness (20). In order to cover a wide range in materials and thicknesses, the value of  $\Delta a_{min}$  is calculated from:

$$\Delta a_{min} = 50/(5 + B) \text{ for } B \geq 1 \text{ mm} \quad (7)$$

and the value of  $\Delta a_{max}$  is calculated from:

$$\Delta a_{max} = W - a_0 - 4B \quad (8)$$

The  $\Delta a_{max}$  equation is based on the observation that if the crack-length-to-thickness ( $a/B$ ) ratio or uncracked-ligament-to-thickness ( $b/B$ ) ratio are equal to or greater than 4, then similar global crack-front constraints are obtained for both the C(T) and M(T) specimens (3). CTOA values measured outside the crack-extension requirements are for informational purposes only. For a given stable crack extension event, the CTOA shall be measured by determining the angle between the pair of lines extended from the current crack tip to the two points located on opposite crack faces at a nominal distance of 1-mm behind the current crack tip. The recommended technique to obtain this measurement is to take 3 to 5 measurements of the CTOA within the range of 0.5 to 1.5 mm behind the current crack tip and averaging these values to obtain the representative value of that particular stable tearing event. For  $\Delta a$  less than  $\Delta a_{min}$ , the measurement distance from the crack tip may be less than the 1-mm requirement. For  $\Delta a$  greater than  $\Delta a_{min}$ , the measurement distance from the crack tip may be between 0.5 and 1.5 mm, as illustrated in Fig. 8.

**NOTE 4**—The definition of  $\Delta a_{min}$  needs further study. Future testing of other materials and thicknesses should help to verify or establish a better relationship than Eq 7.

**9.1.1 Determining CTOA using Optical Microscopy (OM) Method**—The CTOA is measured by recalling an individual image recorded on video tape and (a) locating the crack tip, (b) locating points on both crack surfaces in the range of 0.5 to 1.5 mm behind the crack tip, (c) fitting straight lines between the crack tip and each point and (d) computing the angle,  $\psi$ ,

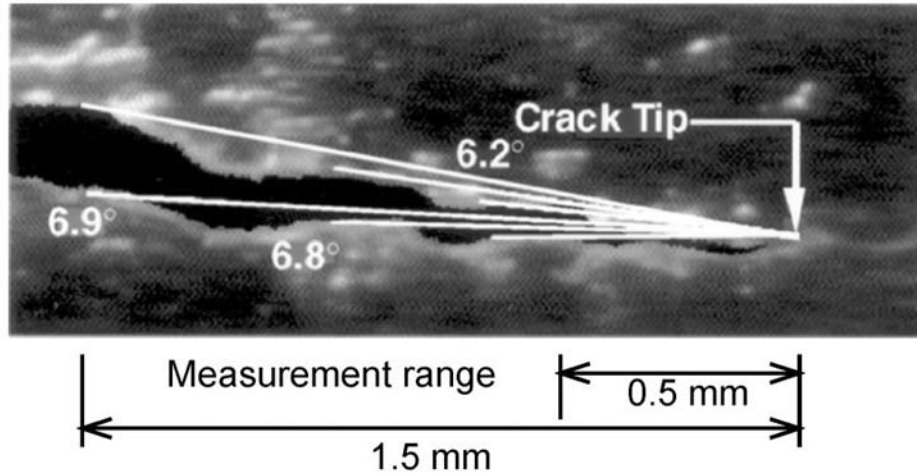


FIG. 8 Measurement Range for Critical CTOA Values

between the straight lines. The value of the angle  $\psi$  for a given crack length is defined to be the average of 3 to 5 measurements. It is important to note that OM measures CTOA in the deformed configuration, without regard for the deformations in the surrounding material. To obtain clear images of the crack using OM, the surface of the specimen must be polished to a mirror finish and lighting of the crack region must be carefully controlled so that the crack tip region has optimum contrast and clarity. Three typical images obtained using OM are shown in Fig. 9. In the first image, Fig. 9(a), a fatigue crack was grown about 0.75 mm under stable tearing. The second and third images, Fig. 9(b) and Fig. 9(c), contain the same crack after stable tearing of about 1.3 mm and 6 mm, respectively.

**9.1.2 Determining CTOA using Digital Image Correlation (DIC) Method**—For the DIC method and a transverse magnification of approximately 125 pixels per 1 mm, a high contrast random pattern is obtained by lightly spraying the specimen's surface with white acrylic paint and diffusely spreading black toner powder (from a laser printer) on the surface. If the powder is dispersed onto the wet paint, and a pattern of appropriate size and density is obtained, no further preparation is required. If the powder is dispersed onto a dry, painted surface, the prepared specimen is then baked at approximately 200°F for 25 minutes to adhere the powder to the surface. A typical set of images, before and during stable crack extension, obtained by the DIC method is shown in Fig. 10(a) and Fig. 10(b).

**9.1.2.1** Because the DIC obtains the displacement vector for a small subset, the general procedure is as follows: (a) choose a particular crack tip location and deformed image, *DI*, for analysis, (b) choose a “reference” image, *RI*, (c) estimate the crack tip location in the deformed image, *DI*, (d) in the region of 0.5 to 1.5 mm behind the crack tip in image *DI*, select pairs of subsets (each pair has one subset above the crack line and one subset below the crack line) that are a distance  $r_i$  behind the crack tip, (e) compute the crack opening displacement vector ( $u_i$  for upper and  $l_i$  for the lower subset) for each small subset using DIC, (f) subtract the displacement vectors for each pair of subsets, (g) estimate the normal vector for the crack line,  $n_i$  and (h) compute angle for each pair of subsets using:

$$\psi = 2 \tan^{-1} [(u_i - l_i) n_i / (2r_i)] \quad (9)$$

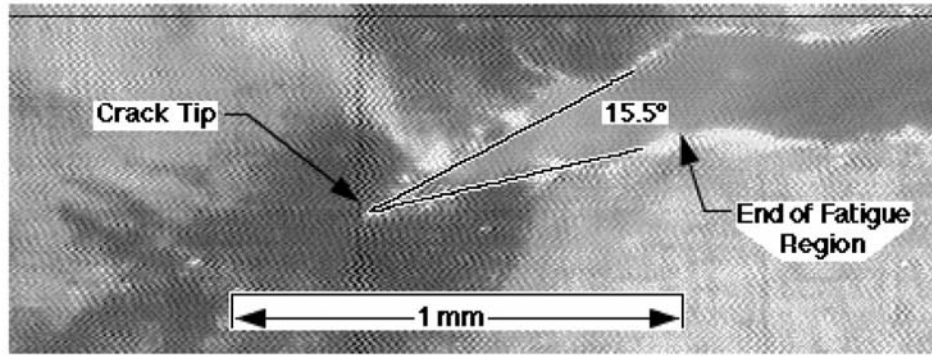
where the components of the normal vector and displacement vectors typically are measured relative to the digital camera's sensor plane coordinate system.

**9.1.2.2** The average of the values, between  $\Delta a_{min}$  and  $\Delta a_{max}$ , is the critical  $\psi_c$  value. Fig. 10 shows two images and two pairs of subsets that were used to define  $\psi$  using DIC. Though the procedure described is straightforward, there are three points that must be discussed: (a) choice of “reference” image, (b) choice of subsets and (c) errors in the measurement.

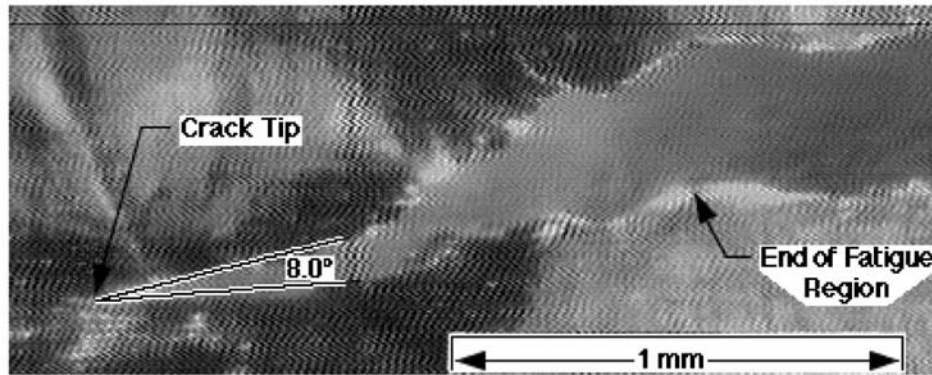
**9.1.2.3** Relative to (a), note that the DIC method uses finite-sized subsets to estimate the displacement of the subset center point. If the “reference” image is an undeformed image, then the undeformed subsets will experience total strains exceeding 10 % during the fracture process (most of which is plastic strain that is not recovered when the crack grows past a subset). Thus, the relative displacement used to estimate  $\psi$  would be overestimated due to a combination of plasticity and the offset of the subset center from the crack line. To minimize this difficulty, the “reference” image is always chosen to be a deformed crack configuration that is close to the current crack length. Thus, the subsets in the “reference” image already have incurred most of the intense plastic deformation that occurs during an increment of crack extension and the center point displacements for the subsets that are used to obtain CTOA should be relatively unbiased by plasticity.

**9.1.2.4** Relative to (b), it is noted that subsets have to (b-1) be small, (b-2) be close to the crack line and (b-3) have sufficient contrast for accurate DIC analysis. Due to the random nature of the speckle pattern, it is generally true that there were very few pairs of useful subsets in the region 0.5 to 1.5 mm behind the crack tip. Thus, it is likely that the  $\psi_c$  value obtained by DIC will be obtained by averaging between two and four values.

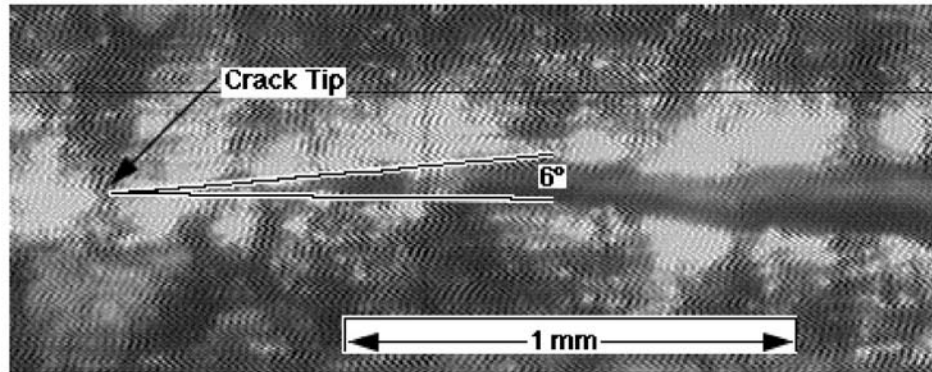
**9.1.2.5** Relative to (c), the primary source of error in estimating  $\psi_c$  is in locating the current crack tip. The errors in locating the crack are due to lack of contrast between painted surface and crack surfaces, small crack opening near tip and a small amount of cracking of the thin paint layer near the tip.



(a) OM image after about 0.75-mm of stable tearing



(b) OM image after about 1.3-mm of stable tearing



(c) OM image after about 6-mm of stable tearing

FIG. 9 Typical OM Images and CTOA Measurements for Stable Tearing Cracks in 2.3-mm Thick 2024-T3 Aluminum Alloy

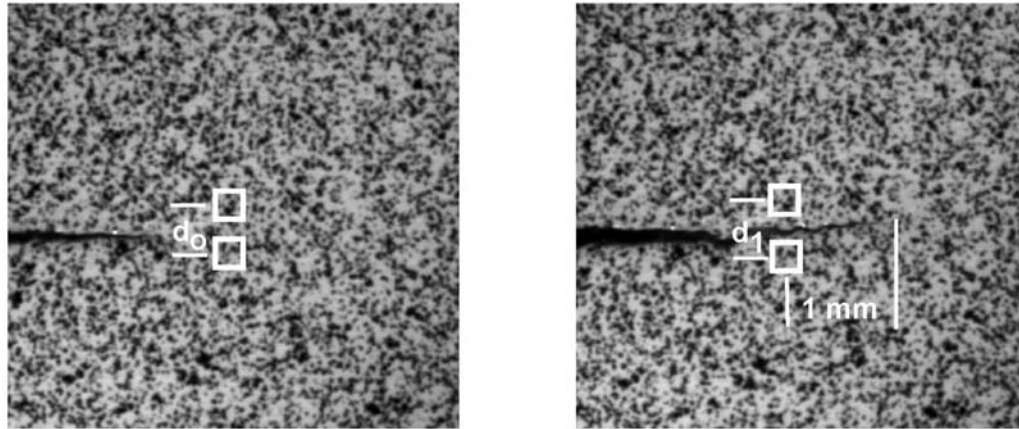
Care must be taken to identify the current crack tip location with as much accuracy as is possible.

9.1.3 *Determination of Critical Crack-Tip-Opening Angle*—Plot  $\psi$  against  $\Delta a$  as shown in Fig. 11. The critical CTOA ( $\psi_c$ ) is determined from the  $\psi$ - $\Delta a$  plot between limiting crack extension,  $\Delta a_{min}$  and  $\Delta a_{max}$ . The  $\psi_c$  value is evaluated as:

$$\psi_c = (\sum \psi_n) / N \quad (10)$$

where  $\psi_n$  is the point value and  $N$  is the total number of measured values ( $n = 1$  to  $N$ ) satisfying the  $\Delta a_{min}$  and  $\Delta a_{max}$  requirements. Suggested data reporting is given in Annex A3.

NOTE 5—Crack-tip-opening angles,  $\psi$ , measured on the surface of a specimen during the initiation of stable tearing exhibit large values of  $\psi$  due to crack blunting and crack tunneling. But in the interior region, which is under high local constraint, the  $\psi$  values are generally lower than the surface values (18). After a small amount of crack extension, about the material thickness for thin sheets and less than the thickness for thicker materials (7, 20), the  $\psi$  values approach a nearly constant value, if the requirements in Section 9 are satisfied. The critical CTOA is determined by averaging the  $\psi$  values between  $\Delta a_{min}$  and  $\Delta a_{max}$ , as shown by the solid line in Fig. 11. For crack extension values less than  $\Delta a_{min}$ , the critical CTOA value is influenced by the three-dimensional nature of crack extension in this region.



(a) Image of current crack tip region

(b) Image after crack extension

FIG. 10 DIC Images of Crack Before and After Crack Extension

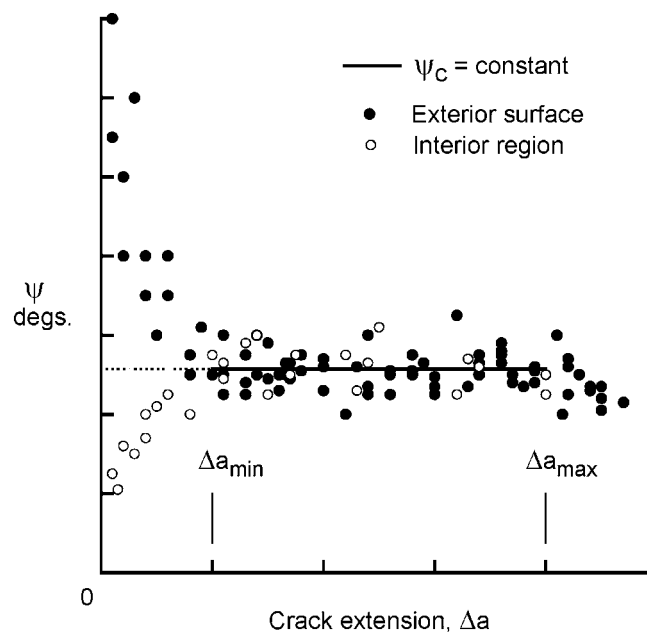


FIG. 11 Determination of Critical CTOA Value

**9.1.4 Final Crack Front Straightness**—To determine final crack front straightness, fatigue marking, heat-tinting, or other means of marking the crack front are required. The final crack length shall be determined as the sum of the original crack length and final stable crack extension measured using the five-point weighted average method for specimen thickness ( $B$ ) greater than 5 mm and three-point weighted average for  $B < 5$  mm. None of the interior final crack length measurements shall differ from the three- or five-point average value by more than  $0.1 a_o$ ; otherwise, the result is not acceptable.

**9.2 Determination of  $\delta_5$ - $\Delta a$  Resistance Curve**—A single-specimen procedure makes use of elastic compliance or electrical potential to obtain multiple or continuous points on the resistance curve.

**9.2.1 Elastic Compliance**—Using the elastic compliance method, the estimated final crack extension  $\Delta a_f$  shall be within

15 % of the measured (post test) crack extension or 0.15 mm, whichever is greater, for  $\Delta a_f < 0.2 (W - a_o)$  and within 0.03  $(W - a_o)$  for  $\Delta a_f > 0.2 (W - a_o)$ . For techniques that require an a priori estimate of the original crack length  $a_o$  for subsequent determination of crack extension, such as the unloading compliance technique, the estimated  $a_o$  shall be within 2 % of the (post-test) measured  $a_o$  value. (See Test Method E 647 for compliance method for C(T) and M(T) specimens.)

**9.2.2 Electrical Potential**—Using the electrical potential method, the first specimen shall be used to establish a correlation between experimental output and visually measured crack extension to beyond the  $\Delta a_{max}$  limit. At least one additional specimen shall be conducted to estimate crack extension using the results from the first test. Agreement between estimated and actual crack extension  $\Delta a$  shall be within 15 % of  $a_o$  or 0.15 mm, whichever is greater; otherwise

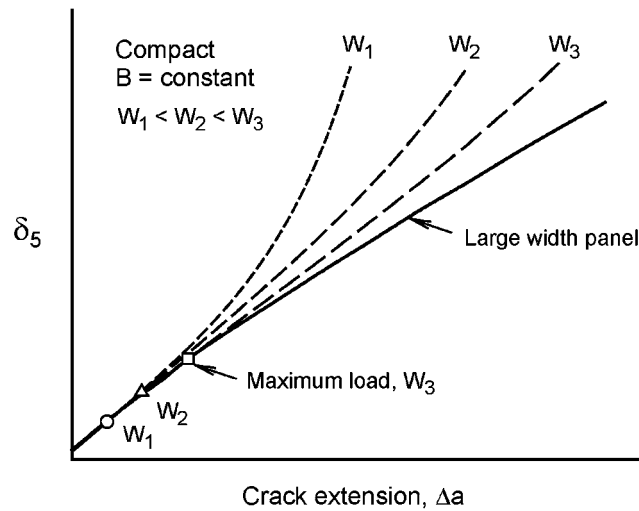
the procedure shall not be acceptable. (See ISO 12135 for electric-potential drop method for C(T) specimens. Additional information may be found in Refs 13-16.)

**9.2.3 Final Crack Front Straightness**—To determine final crack front straightness, fatigue marking, heat-tinting, or other means of marking the crack front are required. The final crack length shall be determined as the sum of the original crack length and final stable crack extension measured using the five-point weighted average method for specimen thickness ( $B$ ) greater than 5 mm and three-point weighted average for  $B < 5$  mm. None of the interior final crack length measurements shall differ from the three- or five-point average value by more than  $0.1a_o$ ; otherwise, the result is not acceptable.

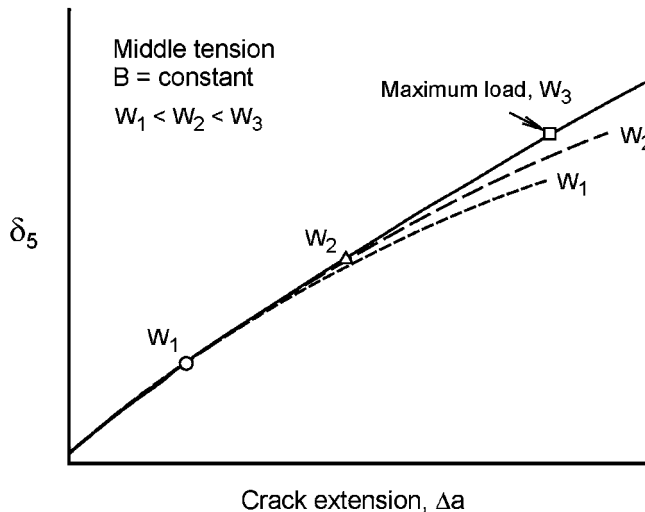
**9.2.4 Resistance-Curve ( $\delta_5$ - $\Delta a$ ) Plot**—The points of  $\delta_5$  against crack extension,  $\Delta a$ , form the resistance curve. Some

typical behaviors that have been measured on C(T) and M(T) specimens are shown in Fig. 12. An equation may be fitted to the graph for analysis, or the plot itself may be used for analysis. For compact-tension specimens, the maximum crack extension shall not exceed  $\Delta a_{max} = 0.25 (W - a_o)$ ; and for the middle-crack tension specimen, the maximum crack extension shall not exceed  $\Delta a_{max} = W - a_o - 4B$ .(2,3) The R-curve data from the C(T) specimens tend to deviate from the solid curve more rapidly than M(T) specimens for smaller specimen widths. For both C(T) and M(T) specimens, these criteria use some of the R-curve data beyond the maximum force points.

**9.2.4.1 Data Spacing and Curve Fitting**—A minimum of six data points shall be used to define the resistance curve. When an equation is to be fitted to the resistance curve, at least one data point shall reside in each of the four equal crack-extension



(a) Compact specimens



(b) Middle-crack tension specimens

FIG. 12 Schematic of  $\delta_5$  Resistance Curves for C(T) and M(T) configurations

regions from zero to  $\Delta a_{max}$ , as shown in Fig. 13. The curve shall be best-fitted through the data points lying between zero and  $\Delta a_{max}$  exclusion lines using the power-law equation:

$$\delta_5 = A + C(\Delta a)^D \quad (11)$$

where  $A$  and  $C$  are greater than or equal to 0, and  $0 < D < 1$ . (Note—A method to evaluate the constants  $A$ ,  $C$ , and  $D$  is given in Annex A4.) The resistance curve obtained characterizes the material for the thickness and specimen configuration tested, and is independent of in-plane dimensions of either compact-tension or middle-crack tension specimens.

**9.3 Post-Test Crack Measurements**—The specimen is broken open after testing and its fracture surface is examined to determine the original crack length,  $a_o$ , and the final stable crack extension,  $\Delta a_f$ , and the final crack length,  $a_f$ .

NOTE 6—For some tests, it may be necessary to mark the extent of stable crack extension before breaking open. Marking of stable crack extension may be done by either heat tinting or post-test fatiguing. Care should be taken to minimize post-test deformation of the specimen. Cooling ferritic steels to ensure brittle behavior may be helpful.

**9.3.1 Original Crack Length**—Measurement of the original crack length,  $a_o$ , depends upon the absolute thickness of the specimen and the amount of tunneling due to fatigue pre-cracking.

**9.3.1.1 Compact-tension Specimen**—Original crack length  $a_o$  is measured from the centerline of the pinhole to the tip of the fatigue crack with an instrument accurate to  $\pm 0.1\%$  or

0.025 mm, whichever is the greater. Measurements are made using a five-point weighted average. The value of  $a_o$  is obtained by first averaging the two surface measurements ( $a_1$  and  $a_5$ ) made at positions  $0.01B$  inward from the surface and then averaging these values with those at the three equally-spaced ( $a_2$ ,  $a_3$ , and  $a_4$ ) inner measurement points:

$$a_o = [(a_1 + a_5)/2 + a_2 + a_3 + a_4] / 4 \quad \text{for } B > 5 \text{ mm} \quad (12)$$

**9.3.1.2 Middle-Crack Tension Specimen**—Original crack length  $a_o$  is measured as one-half of the total crack length to the tips of both fatigue cracks with an instrument accurate to  $\pm 0.1\%$  or 0.025 mm, whichever is the greater. Measurements are made using a five-point weighted average. The value of  $a_o$  is obtained by first averaging the two surface measurements ( $a_1$  and  $a_5$ ) made at positions  $0.01B$  inward from the surface and then averaging these values with those at the three equally-spaced ( $a_2$ ,  $a_3$ , and  $a_4$ ) inner measurement points, as given by Eq 12.

**9.3.1.3 Thickness Less Than or Equal to 5 mm**—For both compact-tension and middle-crack tension specimens of thickness  $B$  less than or equal to 5 mm a three-point weighted average is used. The value of  $a_o$  is obtained by first averaging the two surface measurements  $a_1$  and  $a_3$ , and then averaging with the measurement made at the mid-plane of the specimen,  $a_2$ :

$$a_o = [(a_1 + a_3)/2 + a_2] / 2 \quad (13)$$

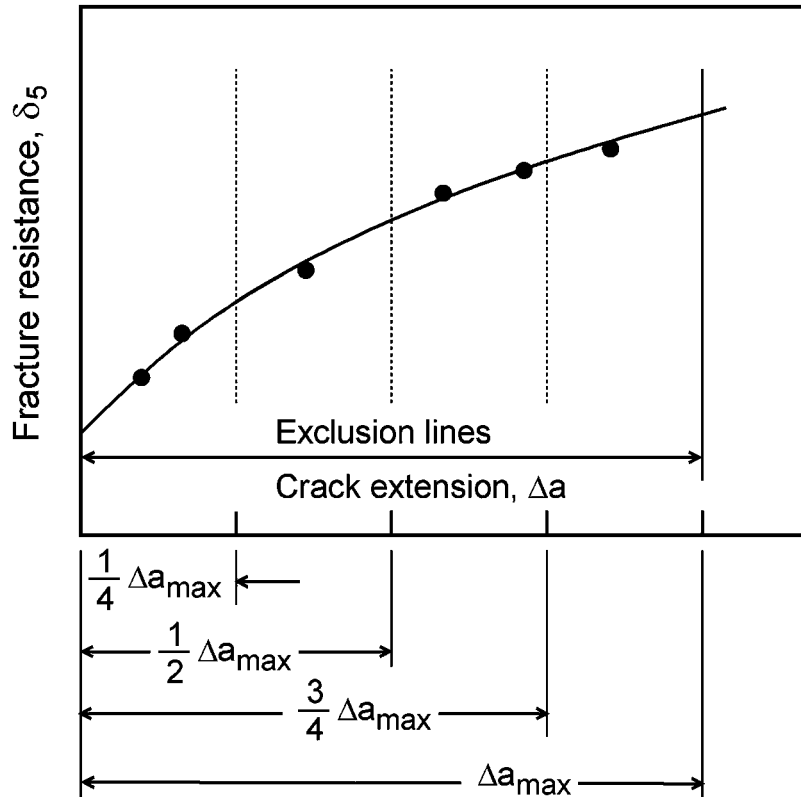


FIG. 13 Data Spacing for  $\delta_5$  Resistance Curve Determination

9.3.1.4 *Requirements*—The original crack length  $a_o$  shall satisfy the following:

(1) The ratio  $a_o/W$  shall be within the range 0.4 to 0.7 for compact-tension specimens, and within the range 0.25 to 0.4 for middle-crack-tension specimens.

(2) The difference between any one of the central points and the average shall not exceed  $0.1 a_o$ .

(3) No part of the fatigue pre-crack front shall be closer to the crack starter notch than 1.3 mm or  $2N$  (twice the crack-starter notch height, whichever is the larger).

9.3.2 *Stable Crack Extension and Final Crack Length*—Total crack extension (including any crack tip blunting)  $\Delta a_f$  between the original and final crack fronts shall be measured with an instrument accurate to  $\pm 0.025$  mm using the three- or five-point averaging procedure of 9.3.1. For the middle-crack-tension specimens, the crack extension  $\Delta a_f$  is given by the average of the crack extension values measured at both crack fronts. Any irregularities in crack extension, such as isolated “islands” of crack extension, shall be reported. The final crack length is  $a_f$ .

## 10. Report

10.1 A recommended table for reporting results is given in Annex A1.

10.2 Report the following information for CTOA and  $\delta_5$  R-curve determination:

10.2.1 Type of test specimen and orientation of test specimen according to Terminology E 1823 identification codes,

10.2.2 Material designation (ASTM, AISI, SAE, and so forth) and material product form (plate, forging, casting, and so forth),

10.2.3 Specimen dimensions, thickness  $B$ , width  $W$ , nominal values of  $a_o/W$ ,  $a_o/B$  and  $(W - a_o)/B$ ,

10.2.4 Test temperature and stress-intensity factor rate under displacement control,

10.2.5 Tensile properties (Young’s modulus, yield strength and tensile strength) at test temperature,

10.2.6 Fatigue pre-cracking conditions, final fatigue force, stress ratio,  $K_{max}$ ,  $\Delta K/E$ , and fatigue test temperature,

10.2.7 Original measured crack length ( $a_o$ ), final measured crack length ( $a_f$ ), crack-front appearance—straightness and planarity, and fracture appearance,

10.2.8 Qualification of fracture parameter measurement based on size requirements, and based on crack extension, and

10.2.9 Qualified value of the fracture parameter,  $(CTOA)_c$  or the  $\delta_5$  resistance curve, or both, as appropriate.

## 11. Precision and Bias

11.1 *Precision*—The precision of the two fracture parameters (CTOA and  $\delta_5$ ) cited in this test method is a function of the precision and bias of the various measurements of linear dimensions of the specimens and test fixtures, the precision of the displacement measurement devices, the bias of the force measurement, as well as, the bias of the recording devices used to produce the photographic images, and the precision of the constructions made on these images. It is not possible to make meaningful statements concerning precision and bias for all of these measurements. However, it is possible to derive useful information concerning the precision of the fracture parameters (CTOA and  $\delta_5$ ) measured in a global sense from inter-laboratory test programs. Inter-laboratory test programs have not been conducted to evaluate the fracture parameters that can be determined by this procedure.

11.2 *Bias*—There is no accepted “standard” value for any of the fracture parameters employed in this test method. In the absence of such a true value no meaningful statement can be made concerning bias of data.

## 12. Keywords

12.1 crack-opening displacement (COD); crack-tip-opening angle, CTOA; crack-tip-opening displacement, CTOD; critical CTOA ( $\psi_c$ );  $\delta_5$  resistance curve; ductile fracture; elastic-plastic fracture; fracture instability; low-constraint specimens; stable crack extension

## ANNEXES

### (Mandatory Information)

#### A1. SPECIAL REQUIREMENTS FOR TESTING COMPACT-TENSION SPECIMENS

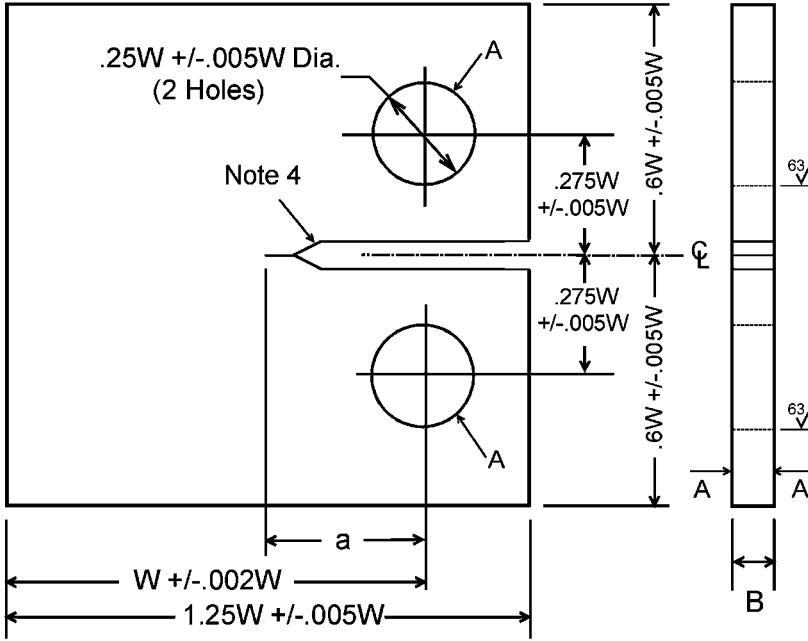
##### A1.1 Specimen

A1.1.1 The compact-tension specimen, C(T), is a single-edge-notched and fatigue pre-cracked sheet or plate specimen loaded in tension, as shown in Fig. A1.1. The plan-form is the same as the standard compact-tension specimen (see Test Method E 399 or Test Method E 1820), except the thickness of the specimen is the actual thickness of the material being tested.

A1.1.2 The C(T) specimen half-height-to-width ( $H/W$ ) ratio is 0.6, width-to-thickness ( $W/B$ ) ratio must be greater than or equal to 8. The minimum width ( $W_{min}$ ) recommended shall be greater than or equal to 150 mm. The  $a_o/B$  and  $b_o/B$  ratios must be greater than or equal to 4.

A1.1.3 The original crack length,  $a_o$ , (after fatigue pre-cracking) of the compact-tension specimen shall be within the range  $0.4W \leq a_o \leq 0.7W$ . The minimum fatigue pre-crack extension shall be larger of 1.3 mm or  $2N$  (twice the crack-starter notch height). The notch plus fatigue pre-crack shall be within the limiting envelopes (dashed lines) shown in Fig. 7.

A1.1.4 Dimensions of specimen shall conform to Fig. A1.1. Measurement of thickness  $B$  and width  $W$  shall be within 0.02 mm or to  $\pm 0.2\%$  whichever is larger. Specimen thickness  $B$  shall be measured, before testing, at a minimum of three equally spaced positions along the intended crack extension path. The average of these measurements shall be taken as the thickness  $B$ . The width  $W$  shall be measured with reference to



Note 1 - A Surfaces shall be perpendicular and parallel as applicable to within 0.05 mm (0.002 in.) T.I.R.

Note 2 - Intersection of crack starter notch tip shall be equal distance between top and bottom of specimen edges within 0.5 mm (0.02 in.).

Note 3 - Integral or attached knife edges for clip gage at crack mouth may be used.

Note 4 - For starter-notch and fatigue-crack configuration see Fig. 7.

Note 5 - Loading pins are of 0.24W (+0.000W/-0.005W) diameter.

**FIG. A1.1 Compact-Tension Specimen for CTOA and  $\delta_5$  Testing**

the loading-hole centerline. Customarily, the loading-hole centerline is first established, and then the dimension  $W$  measured to the specimen edge ahead of the tip in the plane of the crack. The width measurement shall be made at a minimum of three equally spaced positions across the specimen thickness. The dimension  $1.25W$  (between the specimen edges ahead and behind crack tip) shall be measured in addition, at the same equally spaced positions across the thickness in a plane close as possible to the plane of the crack.

### A1.2 Apparatus

A1.2.1 For generally applicable specifications concerning the loading clevis, see 6.2. The loading clevises shall be aligned to within 0.25 mm, and the specimen shall be centered on the loading pins within 0.75 mm with respect to the clevis opening.

A1.2.2 For specifications concerning the crack-tip-opening angle or displacement measuring devices (optical or digital-image), see 6.6.1.

A1.2.3 For specifications concerning the crack-opening displacement,  $\delta_5$ , measuring devices (clip gage or digital-image), see 6.6.2.

### A1.3 Specimen Preparation

A1.3.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A1.3.2 All specimens shall be fatigue pre-cracked at a force based on a  $K_{max}/E$  value less than or equal to 0.00016 m<sup>1/2</sup> (0.001 in.<sup>1/2</sup>) using the original crack length, thickness and width, see 7.4.4.2.

### A1.4 Compact-Tension Specimen Testing

A1.4.1 The crack-tip-opening angle,  $\psi$ , is measured as described in 6.6.1; and measurement of corresponding crack-extension values, data requirements and determination of the critical CTOA,  $\psi_c$ , are described in 9.1.

A1.4.2 The crack-opening displacement,  $\delta_5$ , is measured as described in 6.6.2; and measurement of corresponding crack-extension values, data requirements and curve fitting are described in 9.2.

## A2. SPECIAL REQUIREMENTS FOR TESTING MIDDLE-CRACK-TENSION SPECIMENS

### A2.1 Specimen

A2.1.1 The middle-crack-tension specimen, M(T), is a centrally-notched and fatigue pre-cracked sheet or plate specimen loaded in tension, as shown in Fig. A2.1. The plan-form is the same as the standard middle-crack-tension specimen (see Practice E 561). The thickness of the specimen is the actual thickness of the material being tested.

A2.1.2 The M(T) specimen length-to-width ( $L/W$ ) ratio must be greater than or equal to 1.5, width-to-thickness ( $W/B$ ) ratio must be greater than or equal to 8. The minimum width ( $W_{min}$ ) recommended shall be greater than or equal to 150 mm. The  $a_o/B$  and  $b_o/B$  ratios must be greater than or equal to 4.

A2.1.3 The original crack length,  $a_o$ , (after fatigue pre-cracking) of the compact-tension specimen shall be within the range  $0.25W < a_o < 0.7W$ . The minimum fatigue pre-crack extension shall be larger of 1.3 mm or  $2N$  (twice the crack-starter notch height). The notch plus fatigue pre-crack shall be within the limiting envelopes (dashed lines) shown in Fig. 7.

A2.1.4 Dimensions of specimen shall conform to Fig. A2.1. Measurement of thickness  $B$  and width  $W$  shall be within 0.02 mm or to  $\pm 0.2\%$  whichever is larger. Specimen thickness  $B$  shall be measured, before testing, at a minimum of three equally spaced positions along the intended crack extension path. The average of these measurements shall be taken as the thickness  $B$ . The M(T) specimen width  $W$  shall be measured at a minimum of three equally spaced positions across the specimen thickness on a line not further than 10 % of the nominal width away from the plane. The average of these measurements shall be taken as the width  $W$ .

### A2.2 Apparatus

A2.2.1 For generally applicable specifications concerning the loading fixtures, see 6.3. The fixture shall be designed to

distribute the force uniformly over the cross-section of the specimen. The fixture may be rigidly connected to the machine if uniform loading of the specimen in the machine can be assured at all forces. Otherwise, pin loading via detachable grips is recommended.

A2.2.2 For specifications concerning the crack-tip-opening angle or displacement measuring devices (optical or digital-image), see 6.6.1.

A2.2.3 For specifications concerning the crack-opening displacement,  $\delta_s$ , measuring devices (clip gage or digital-image), see 6.6.2.

### A2.3 Specimen Preparation

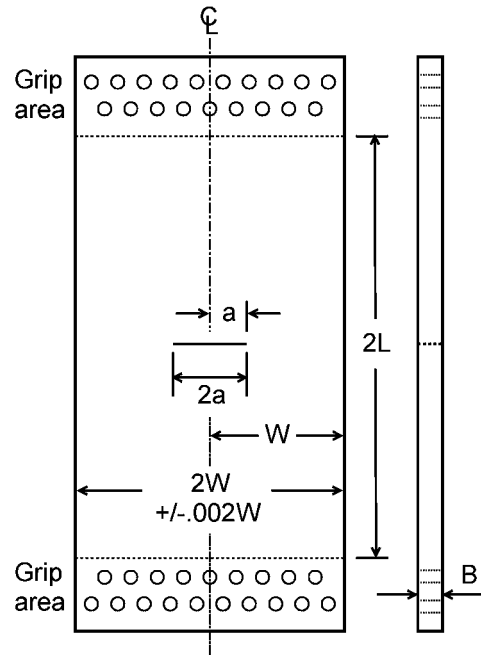
A2.3.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A2.3.2 All specimens shall be fatigue pre-cracked at a force based on a  $K_{max}/E$  value less than or equal to  $0.00016 \text{ m}^{1/2}$  ( $0.001 \text{ in.}^{1/2}$ ) using the original crack length, thickness and width, see 7.4.4.2.

### A2.4 Middle-Crack-Tension Specimen Testing

A2.4.1 The crack-tip-opening angle,  $\psi$ , is measured as described in 6.6.1; and measurement of corresponding crack-extension values, data requirements and determination of the critical CTOA,  $\psi_c$ , are described in 9.1.

A2.4.2 The crack-opening displacement,  $\delta_s$ , is measured as described in 6.6.2; and measurement of corresponding crack-extension values, data requirements and curve fitting are described in 9.2.



- Note 1 - Length-to-width ( $L/W$ ) ratio shall be greater than 1.5.  
 Note 2 - Grip area may be friction clamped in hydraulic grips or bolted-joint connection (avoid bolt-bearing contact loading).  
 Note 3 - For starter-notch and fatigue-crack configuration see Fig. 7.

**FIG. A2.1 Middle-Crack-Tension Specimen for CTOA and  $\delta_s$  Testing**

### A3. TEST REPORTS

NOTE A3.1—It is the content and not the format of the test reports that is important.

**TABLE A3.1 Suggested Data Reporting Format**

|                                     |                                               |             |
|-------------------------------------|-----------------------------------------------|-------------|
| Operator: _____                     | Test Machine: _____                           | Date: _____ |
| Specimen:                           |                                               |             |
| Type [C(T) or M(T)]                 | _____                                         |             |
| Identification                      | _____                                         |             |
| Orientation                         | _____                                         |             |
| Location within product             | _____                                         |             |
| Material:                           |                                               |             |
| Material designation                | _____                                         |             |
| Material form/condition             | _____                                         |             |
| Basic Dimensions:                   |                                               |             |
| $B$ =                               | _____ [mm]                                    |             |
| $W$ =                               | _____ [mm]                                    |             |
| $a_o/W$ (nominal) =                 | _____                                         |             |
| $a_o/B$ (nominal) =                 | _____                                         |             |
| $(W-a_o)/B$ (nominal) =             | _____                                         |             |
| Basic Test Information:             |                                               |             |
| Test Temperature =                  | _____ [°C]                                    |             |
| Stress-Intensity Factor Rate =      | _____ [MPa-m <sup>1/2</sup> s <sup>-1</sup> ] |             |
| Tensile Properties:                 |                                               |             |
| $E$ [Young's Modulus] =             | _____ [MPa]                                   |             |
| $\sigma_{YS}$ [Yield Stress] =      | _____ [MPa]                                   |             |
| $\sigma_{TS}$ [Ultimate Strength] = | _____ [MPa]                                   |             |
| Pre-cracking:                       |                                               |             |
| Fatigue Temperature =               | _____ [°C]                                    |             |
| Final $P_f$ =                       | _____ [N]                                     |             |
| Final $K_{max}$ =                   | _____ [MPa-m <sup>1/2</sup> ]                 |             |
| Final $\Delta K/E$ =                | _____ [m <sup>1/2</sup> ]                     |             |

**E 2472 – 06**

[illegible]

<sup>B</sup> OM = Optical method or  
DIC = Digital-imaging method

### Data Reporting for $\delta_5$ Resistance Curve

[illegible]

<sup>A</sup> UC = Unloading compliance,  
ACPD = Alternating current potential drop, or  
DCPD = Direct current potential drop

#### A4. POWER-LAW FIT TO $\delta_c$ AGAINST CRACK-EXTENSION DATA

A4.1 An equation in the form:

$$\delta_5 = A + C (\Delta a)^D \quad (\text{A4.1})$$

where:

$$r = (S_{xx} S_{yy})^{1/2} \quad (\text{A4.2})$$

where:

$A$ ,  $C$ , and  $D$  = constants used to fit the  $\delta_5$ -crack extension data.

$$S_{xx} = \sum x^2 - (\sum x)^2 / N \quad (\text{A4.3})$$

$$S_{yy} = \sum y^2 - (\sum y)^2 / N \quad (\text{A4.4})$$

and  $N$  is the number of data points. A value of  $D$  that maximizes  $r$  is selected.  $A$  and  $C$  are evaluated from:

$$C = S_{xy} / S_{xx} \text{ and } A = y^* - m x^* \quad (\text{A4.5})$$

where:

$$S_{xx} = \sum x y^2 - (\sum x \sum y) / N \quad (\text{A4.6})$$

$$x^* = \sum x / N \text{ and } y^* = \sum y / N \quad (\text{A4.7})$$

A4.3 A detailed approach for making these calculations is given in the following:

A4.3.1 Values of  $D$  are taken from 0 to 1 in steps of 0.01. For each value of  $D$ ,  $x = (\Delta a)^D$  is calculated as well as the correlation coefficient  $r$  from:

## APPENDIXES

### (Nonmandatory Information)

#### X1. GUIDELINES FOR ANALYZING STABLE TEARING USING FINITE-ELEMENT METHODS

X1.1 A number of elastic-plastic finite-element (FE) analysis codes have been used to determine the critical CTOA from force versus crack extension data. The approach was to assume a constant CTOA from initiation to instability and find, by trial and error, the  $\psi_c$  value that fit the maximum force. These FE codes have included two-dimensional constant-strain and linear-strain codes, a shell code, and three-dimensional linear-strain codes. In studying the stable tearing behavior of a variety of materials (6) it was found for elements that 0.5-mm size constant-strain elements were required in the crack-tip region, and along the line of crack extension, to fit the force-crack-extension behavior. Further studies using a three-dimensional FE code (21, 22) and a shell code (23, 24) with linear-strain

elements found that 1-mm size elements were sufficient to model stable tearing for a wide range of cracked specimens. If the crack length and ligament criteria ( $a/B > 4$  and  $b/B > 4$ ) are met, then the critical CTOA has been shown to be independent of specimen type (compact-tension or middle crack tension). These CTOA values have been used to predict the stable tearing behavior of complex structure quite accurately for a thin-sheet aluminum alloy (25). In these analyses, the critical CTOA was held constant throughout the analysis from initiation through maximum force. As long as sufficient crack extension exists to establish a stable CTOA value, the maximum force is not sensitive to the initial transient in CTOA measurements, thus a CTOA R-curve may not be necessary.

#### X2. CORRELATION BETWEEN $\delta_5$ RESISTANCE CURVES AND CRITICAL CTOA

X2.1 The measurement of  $\delta_5$ -resistance curves are simpler and less costly than the determination of the critical CTOA values. Thus, it would be desirable to be able to determine the critical CTOA values from  $\delta_5$  measurements.

X2.2 Finite-element analyses of crack-extension simulations have also shown a close relationship between a unique CTOA and the  $\delta_5$  R-curve. Fig. X2.1 shows the results of an elastic-plastic, finite-element analyses of a wide range of specimen widths for compact-tension and middle-cracked tension specimens made of a 2024-T351 ( $B = 6.35$  mm) aluminum alloy. The analyses were performed with a constant critical CTOA value of 6.35 degrees. The  $\delta_5$ -resistance curves were obtained from the analysis of each specimen. The results

are only shown up to the maximum force on each specimen. These results demonstrate that a unique  $\delta_5$ -resistance curve is related to a constant critical CTOA value (26).

X2.3 Recently, a relationship has been proposed (27) that allows the critical CTOA to be determined from the  $\delta_5$  R-curve. An increment of crack extension,  $\Delta a$ , causes an increment in the CTOD, as well as an increment in  $\delta_5$ . If the increment of  $\delta_5$  is equal to the increment in CTOD, then the crack tip opening angle is given by:

$$(CTOA)_c = d\delta_5/d\Delta a \quad (X2.1)$$

X2.4 Further study is required to experimentally verify this relationship for a variety of materials and thicknesses.

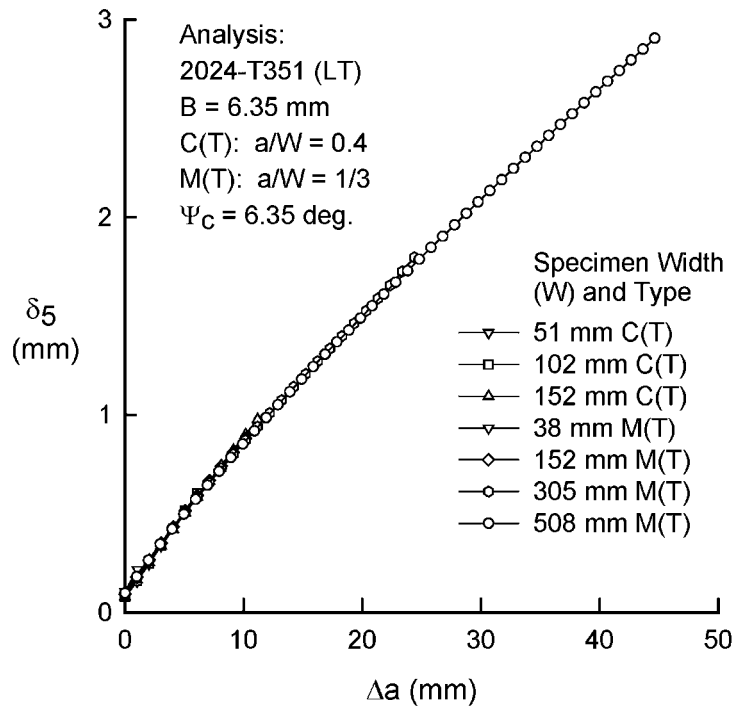


FIG. X2.1 Predicted  $\delta_5$ -Resistance Curve from a Constant Critical CTOA Analysis

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