Designation: E2472 – 12$^{\varepsilon 1}$

Standard Test Method for Determination of Resistance to Stable Crack Extension under Low-Constraint Conditions[1]

This standard is issued under the fixed designation E2472; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε^1 NOTE—3.2.5 and 3.2.6 were editorially revised in March 2013.

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), ψ_c and/or the crack-opening displacement (COD), δ_5 resistance curve (**1**).[2] This method applies specifically to fatigue pre-cracked specimens that exhibit low constraint (crack-size-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 test specimens are the compact, C(T), and middle-crack-tension, M(T), specimens. The fracture resistance determined in accordance with this standard is measured as ψ_c (critical CTOA value) and/or δ_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-size-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 standard. No other units of measurement are included in this standard.

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:*[3]

E4 Practices for Force Verification of Testing Machines

E8/E8M Test Methods for Tension Testing of Metallic Materials

E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials

E561 Test Method for ***K-R*** Curve Determination

E647 Test Method for Measurement of Fatigue Crack Growth Rates

E1290 Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement (Withdrawn 2013)[4]

E1820 Test Method for Measurement of Fracture Toughness

E1823 Terminology Relating to Fatigue and Fracture Testing

E2309 Practices for Verification of Displacement Measuring Systems and Devices Used in Material Testing Machines

2.2 *ISO Standards:*[5]

ISO 22889:2007 Metallic Materials—Method of Test for the Determination of Resistance to Stable Crack Extension Using Specimens of Low Constraint

ISO 12135 Metallic Materials—Unified Method of Test for the Determination of Quasistatic Fracture Toughness

3. Terminology

3.1 Terminology E1823 is applicable to this test standard.

3.2 *Definitions:*

3.2.1 *crack extension, Δa [L], n*—an increase in crack size.

[1] This test method is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.07 on Fracture Mechanics.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

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

[4] The last approved version of this historical standard is referenced on www.astm.org.

[5] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.ch.

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 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 complement) the direct optical techniques to provide a measure of average crack extension. (See Test Method E647 for compliance methods for C(T) and M(T) specimens; and ISO 12135 and Test Method E647 for electric potential-drop methods for C(T) specimens.)

3.2.2 *crack size, a [L], n*—principal linear dimension used in the calculation of fracture mechanics parameters for through thickness cracks.

3.2.2.1 *Discussion*—A measure of the crack size after the fatigue pre-cracking stage is denoted as the original crack size, 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), ψ [deg], n*—relative angle of crack surfaces resulting from the total deformation (elastic plus plastic) measured (or calculated) at 1-mm behind the current crack tip as the crack stably tears, where $\psi = 2\tan^{-1}(\delta_1/2)$.

3.2.4 *critical crack-tip-opening angle (CTOA$_c$), ψ_c [deg], n*—steady-state relative angle of crack surfaces resulting from the total deformation (elastic plus plastic) measured (or calculated) at 1-mm behind the current crack tip as the crack stably tears, where $\psi_c = 2\tan^{-1}(\delta_{1c}/2)$.

3.2.4.1 *Discussion*—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, (COD) δ_5 [L]*—force-induced separation vector between two points. The direction of the vector is normal to the crack plane (normal to the facing surfaces of a crack) at a specified gage length. In this standard, δ_5 is measured at the fatigue precrack tip location over a gage length of 5-mm as the crack stably tears.

3.2.6 *crack-tip-opening displacement (CTOD), δ_1 [L], n*—relative displacement of crack surfaces resulting from the total deformation (elastic plus plastic) measured (or calculated) at 1- mm behind the current crack tip as the crack stably tears.

3.2.7 *critical crack-tip-opening displacement (CTOD$_c$), δ_{1c} [L], n*—steady-state relative displacement of crack surfaces resulting from the total deformation (elastic plus plastic) measured (or calculated) at 1-mm behind the current crack tip as the crack stably tears.

3.2.8 *crack extension resistance curve (R curve), n*—variation of δ_5 with crack extension, Δa.

3.2.9 *effective yield strength, σ_Y [FL^{-2}], 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 σ_{YS}, and the ultimate tensile strength, σ_{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 E8/E8M.

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

3.2.10 *final crack size, 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 size to the back edge of the specimen, that is $b_f = W - a_f$.

3.2.12 *force, P [F], n*—force applied to a test specimen or to a component.

3.2.13 *minimum crack extension, Δa_{min} [L], n*—crack extension beyond which ψ_c is nearly constant.

3.2.14 *maximum crack extension, Δa_{max} [L], n*—crack extension limit for ψ_c and δ_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^{-2}], n*—the ratio of stress to corresponding strain below the proportional limit.

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

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

3.2.19 *original 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 physical crack front to the back edge of the specimen, that is $b = W - a$.

3.2.21 *specimen thickness, B [L], n*—distance between the parallel sides of a test specimen or component. Side grooving is not allowed.

3.2.22 *specimen width, W [L], n*—distance from a reference position (for example, the force line of a compact specimen or center line in the middle-crack-tension specimen) to the rear surface of the specimen. (Note that the total width of the M(T) specimen is defined as 2*W*.)

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 δ_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 E1290 (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 δ_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: δ_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), ψ and/or crack-opening displacement (COD), δ_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 (ψ_c) or a resistance curve of δ_5, a measure of crack-opening displacement against crack extension, or both.

5.4 The test specimens are the compact, 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-size-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 (δ_5) determined by this test method may serve the following purposes:

5.6.1 In research and development, CTOA (ψ_c) or COD (δ_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 (ψ_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 δ_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 E561) is similar to the δ_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 δ_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 $CTOA_c$ (ψ_c) concept.

6. Apparatus

6.1 This procedure involves measurement of applied force, P, crack extension, Δa, 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 E4.

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 E4 and E2309. 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:

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

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

6.2 *Fixturing for the Compact [C(T)] Specimens*—Compact 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 half 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. 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 $0.24W$ ($+0.000W$/$-0.005\,W$). 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 yield strength maraging or stainless steel is used for the clevis and pins, adequate strength will be obtained. If a lower strength grip material is used, or if substantially larger specimens are required at a given σ_{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 δ_5. Measurement of crack-mouth-opening displacements using a clip gage may be made to determine crack size using the unloading compliance method.

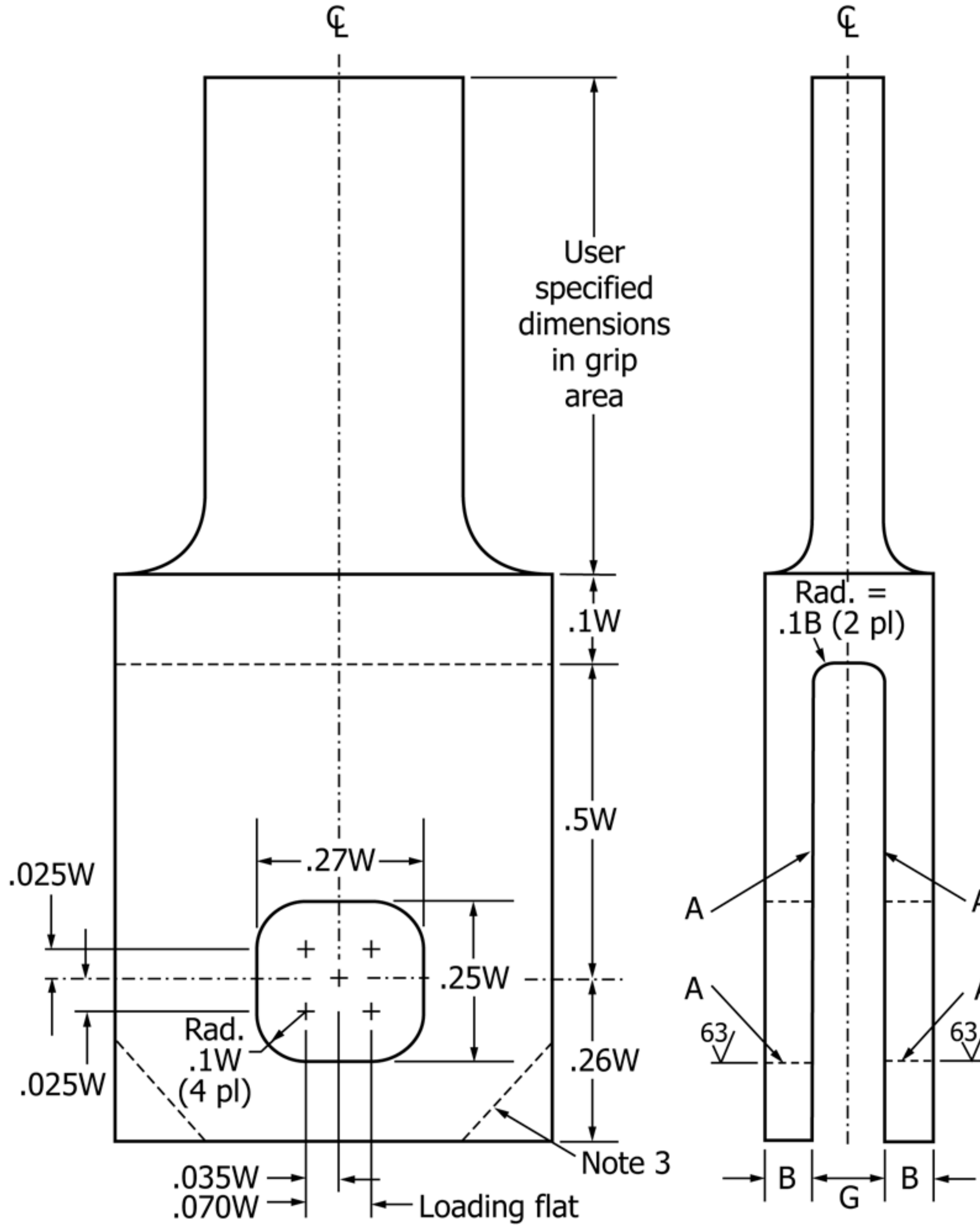
6.3 *Fixturing for the Middle-Crack–Tension [M(T)] Specimens*—Middle-crack-tension specimens shall be loaded using hydraulically-clamped or bolted grips designed to carry the applied force in friction. Bolt bearing should be avoided to minimize non-uniform loading. The arrangement shall ensure alignment 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 δ_5. Measurement of crack-mouth-opening displacements using a clip gage may also be made to determine crack size 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)* multiple-specimen method. Indirect crack extension measurement techniques, such as unloading compliance and electric-potential-drop methods may be used in place of (or to complement) 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 ($B \leq 5$ mm) or five-point ($B > 5$ mm) weighted average crack extension.

6.4.1 *Direct Optical Method*—The direct optical method measures the crack size 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 size at each unloading from analytical elastic compliance relationships. The specimen compliance is determined from either crack-mouth-opening or force-line compliance, and the crack size is estimated using compliance equations (see Test Methods E647 and E1820). 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 size. The applied potential is either direct or



Note 1 - A Surfaces must be flat, in-line and perpendicular, as applicable, to within 0.05 mm (0.002 in.) T.I.R. (Total Indicator Reading)
Note 2 - Value of G must include maximum expected specimen thickness, B, plus twice the guide plate thickness, and extra space for free fixture rotation.
Note 3 - Corners may be removed as necessary to accomodate clip gage.

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

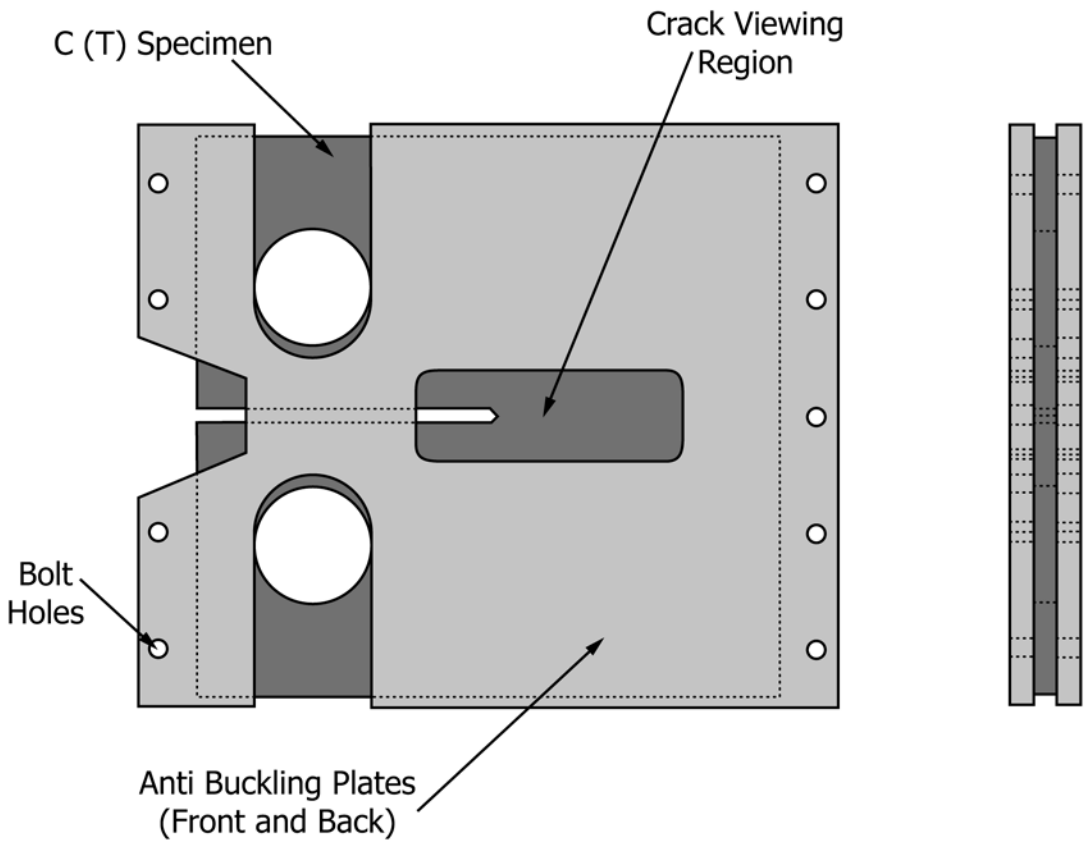


FIG. 2 Compact, C(T), Specimen with Anti-Buckling Guides

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 and Test Method E647 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 ($B \leq 5$ 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 ±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 ΔK levels), low-constraint test specimens. Two methods are introduced to provide this characterization, the first is based on the crack-tip-opening angle (CTOA), ψ, and the second is based on a measure of crack-opening displacement (COD), δ_5. Both methods may employ 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 (Δa) 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 δ_5. The two techniques that are used for direct measurement of ψ (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

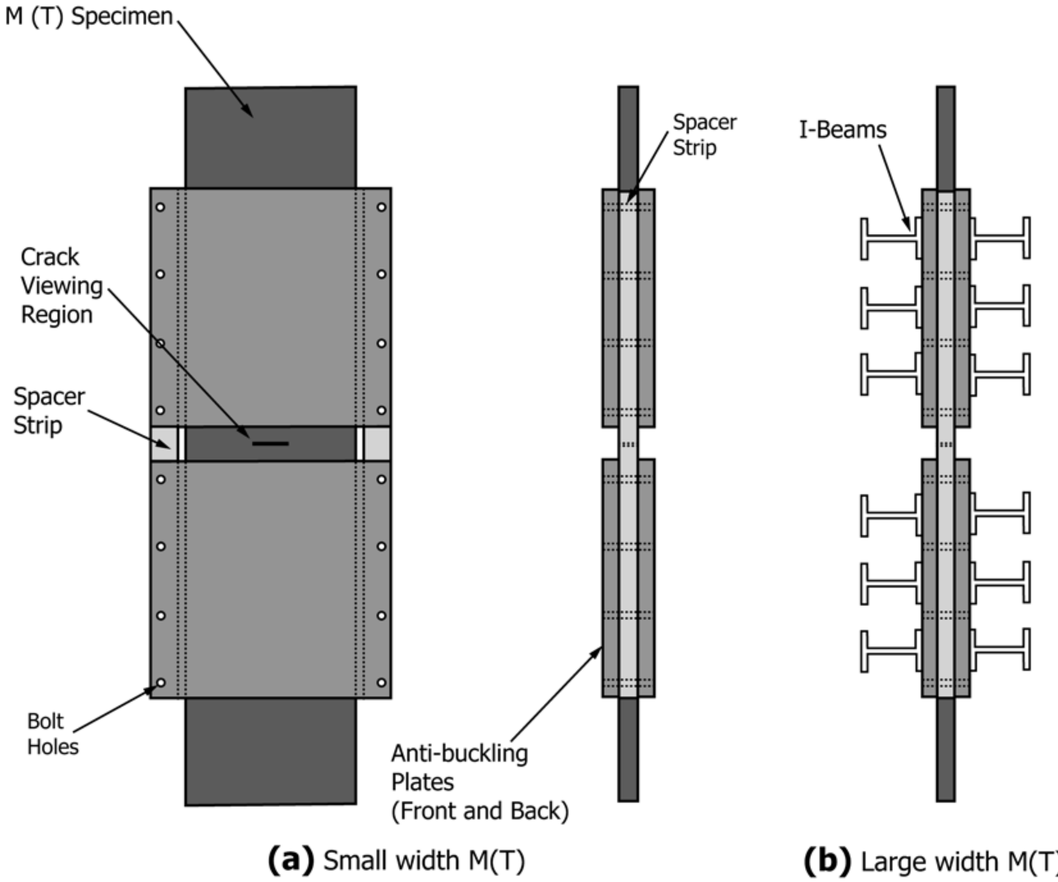


FIG. 3 Middle-Crack-Tension, M(T), Specimen with Anti-Buckling Guides

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× 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 size 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, δ_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 (Δa), and crack-opening displacement (δ_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 δ_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 δ_5 is shown in Fig. 4. The area around the expected fatigue pre-crack path is to be polished. After fatigue precracking, 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 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 , 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 ±1 % of the full working range. In calibration, the maximum deviation of the individual data

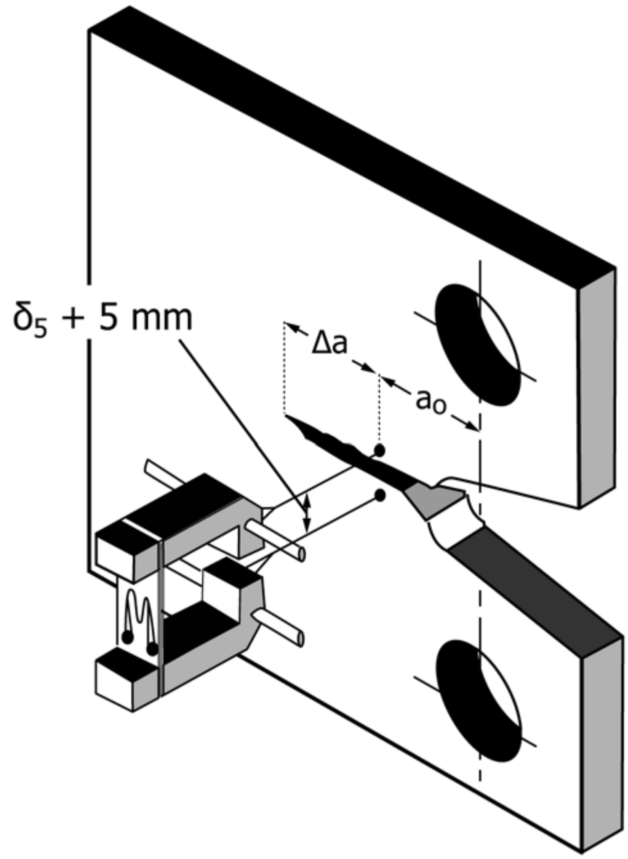


FIG. 4 Basic Clip Gage and Specimen Arrangement for Measuring δ_5

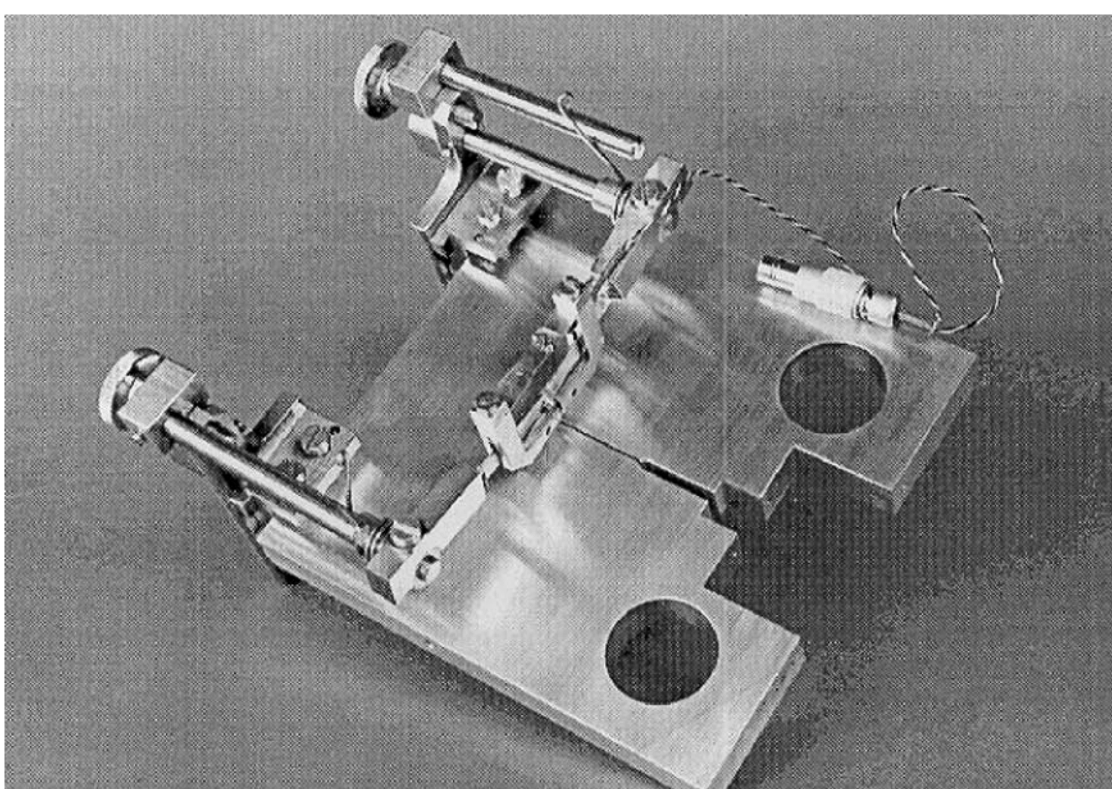


FIG. 5 Fixtures for Attachment of the δ_5 Clip Gage to Compact Specimen

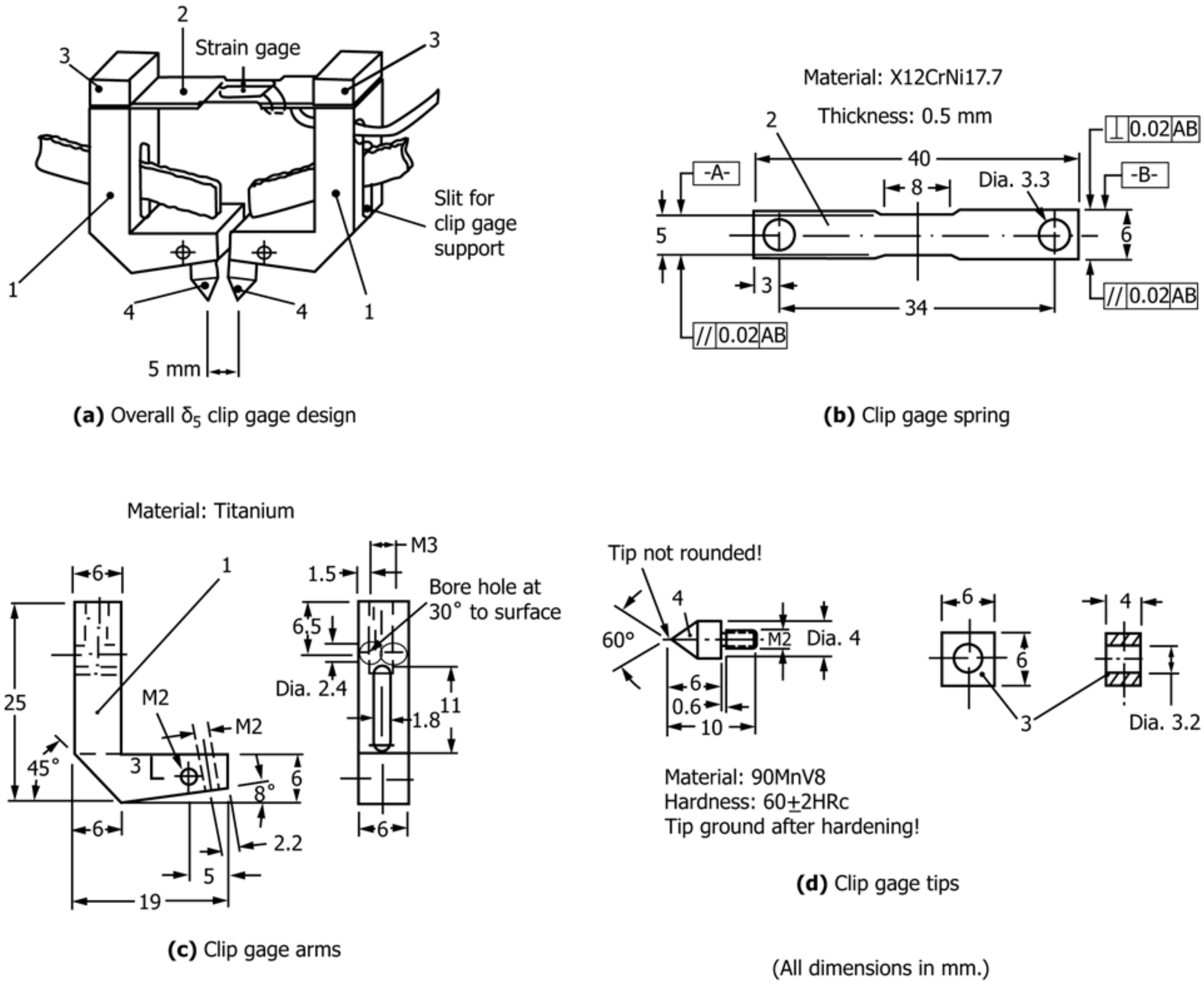


FIG. 6 Crack-Opening Displacement, δ_5, Clip Gage Design

points from a linear fit to the data shall be less than ±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 δ_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× 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)* 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 δ_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 δ_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 δ_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-size-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 (ψ_c) and a large amount of the δ_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 (see Terminology E1823).

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 artifice 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 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 fit within the envelope 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 0.2 mm or less.

7.4.2 *Fatigue Crack Size*—The fatigue crack size from the notch front shall be equal to or exceed the envelope, as shown by the dashed lines in Fig. 7. The fatigue crack extension, Δa, shall be equal to or greater than $0.5N$, but not less than 2-mm in size.

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

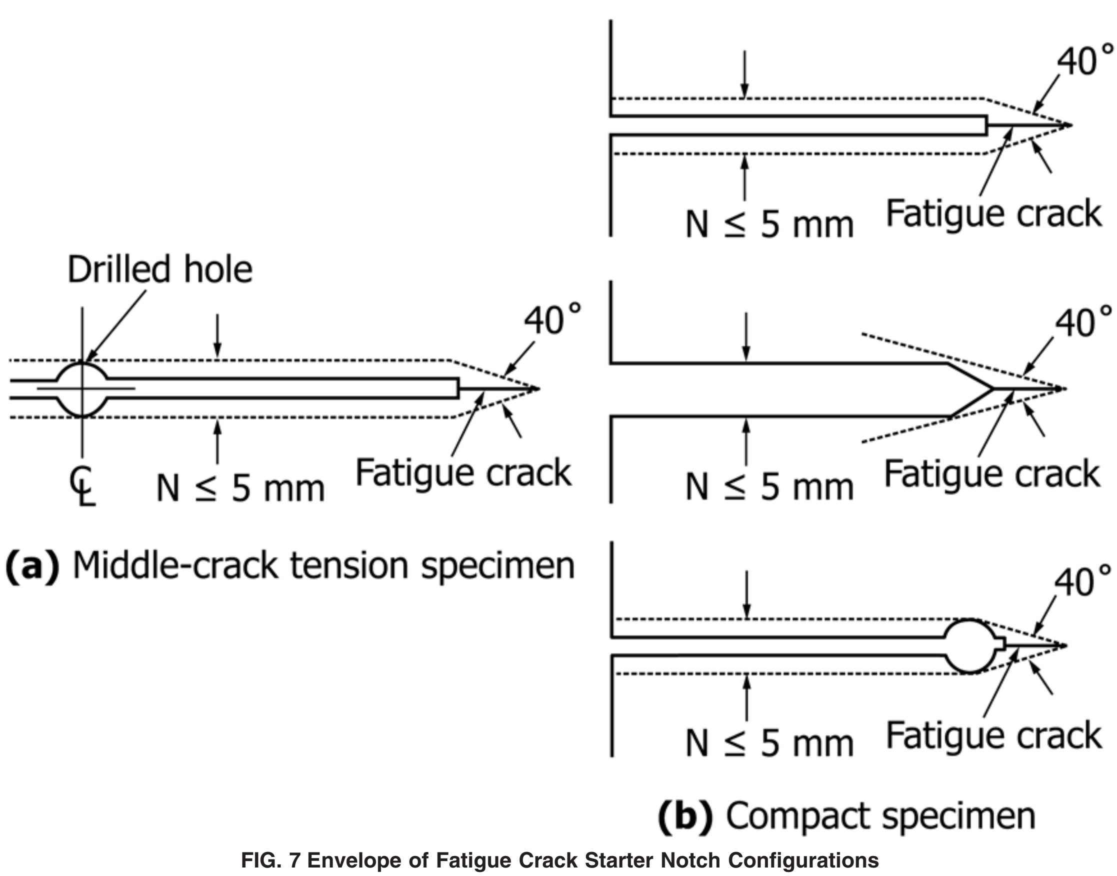


FIG. 7 Envelope of Fatigue Crack Starter Notch Configurations

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 The maximum fatigue pre-cracking force during any stage of the fatigue pre-cracking process shall be accurate to ±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:

For compact [C(T)] specimens:

$$P_f = \xi EB\, W^{1/2}/g_1(a_o/W) \tag{4}$$

where:
$\xi = 1.6 \times 10^{-4}$ m$^{1/2}$, and

$$g_1(a_o/W) = (1 - a_o/W)^{-1.5}\,(2 + a_o/W) \times \tag{5}$$

$$[0.886 + 4.64\,(a_o/W) - 13.32\,(a_o/W)^2 + 14.72\,(a_o/W)^3 - 5.6\,(a_o/W)^4]$$

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

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

where:
$\xi = 1.6 \times 10^{-4}$ m$^{1/2}$

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 formation one cycle of $R = -1.0$ may be first applied.

8. Procedure

8.1 *Testing Rate*—Tests shall be conducted under displacement control. Force-line displacement rate shall be such that within the linear elastic region the stress intensification rate is within the range 0.2 MPa-m$^{1/2}$ s^{-1} to 3 MPa-m$^{1/2}$ 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 ±2°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 ±2°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 (Δa) 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 size, 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 size 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 ~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 position data points uniformly in additional tests.

8.4 *Crack-Opening Displacement (δ_5)*—The objective of this procedure is to measure δ_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 (Δa), and crack-tip-opening displacement, δ_5, measured at the original pre-crack size 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 δ_5 location are to be continuously monitored as a function of crack extension measurements. Using the OM method, the displacement at the δ_5 location is measured as a point value against the corresponding crack-extension measurement. During the fracture tests, the force and force-line displacement signals are to be continuously recorded.

8.4.2 *Single-Specimen δ_5 Characterization Technique*—A continuous record of δ_5 against crack extension, Δa, is determined in a test in the crack extension range zero to Δa_{max}. Due to the non-local nature of δ_5 for an extending crack, δ_5 loses its ability to uniquely correlating crack extension for large amounts of crack extension under bending force, such as those for the compact specimen. However, the middle-crack-tension specimen exhibits a different behavior, in that the δ_5 resistance curve is unique for large amounts of crack extension.

8.4.3 *Multiple-Specimen δ_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 δ_5-Δa crack resistance curve (hereafter referred to generically as the R-curve).

NOTE 3—Four or more uniformly-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 uniformly-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 may be used meaure 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 (Δa_{min} and Δa_{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 Δa_{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 Δa_{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 Δa_{min} is calculated from:

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

and the value of Δa_{max} is calculated from:

$$\Delta a_{max} = W - a_o - 4B \tag{8}$$

The Δa_{max} equation is based on the observation that if the crack-size-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 Δa less than Δa_{min}, the measurement distance from the crack tip may be less than the 1-mm requirement. For Δa greater than Δa_{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 Δa_{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, ψ, between the straight lines. The value of the angle ψ for a given crack size 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:

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

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 Δa_{min} and Δa_{max}, is the critical ψ_c value. Fig. 10 shows two images and two pairs of subsets that were used to define ψ 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 ψ 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

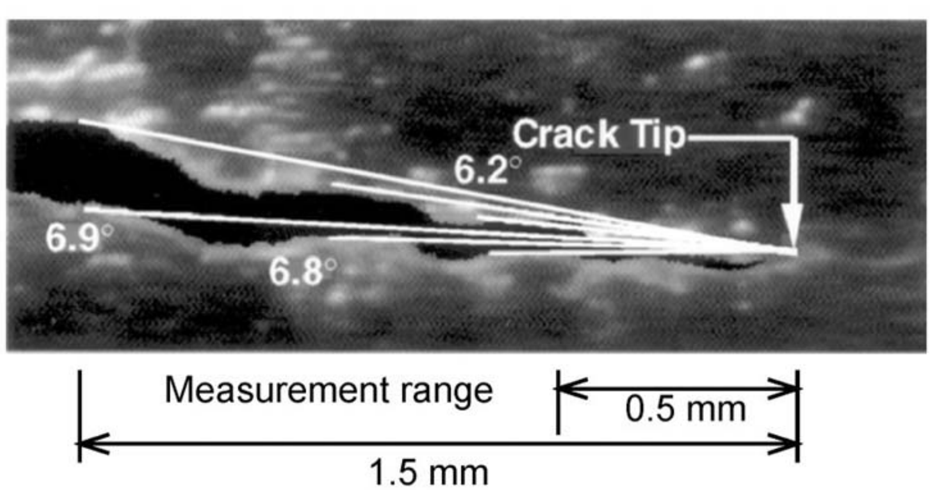
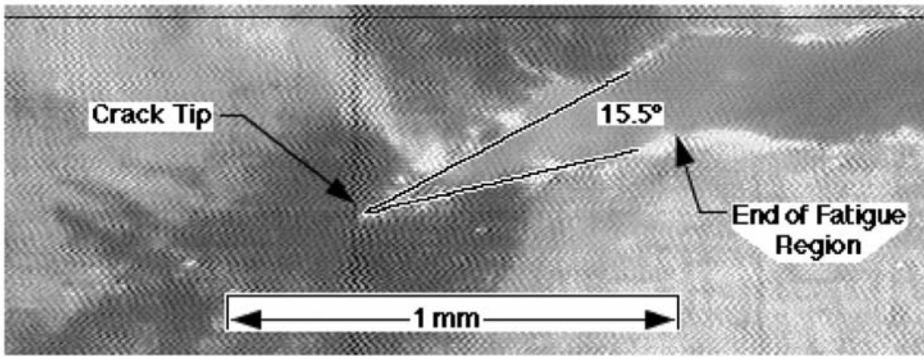
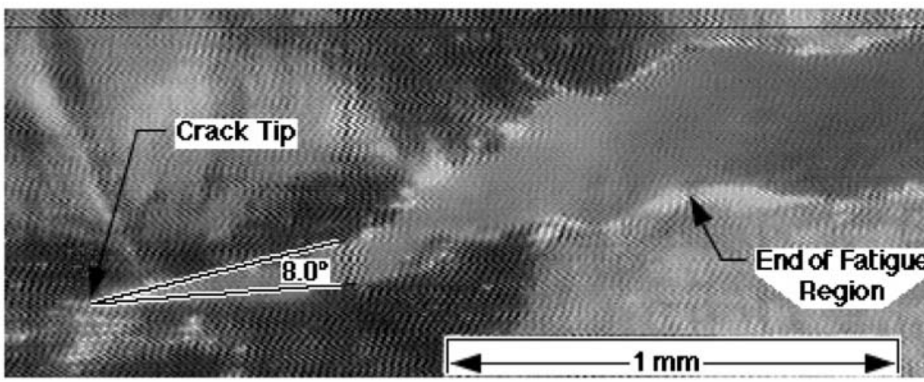


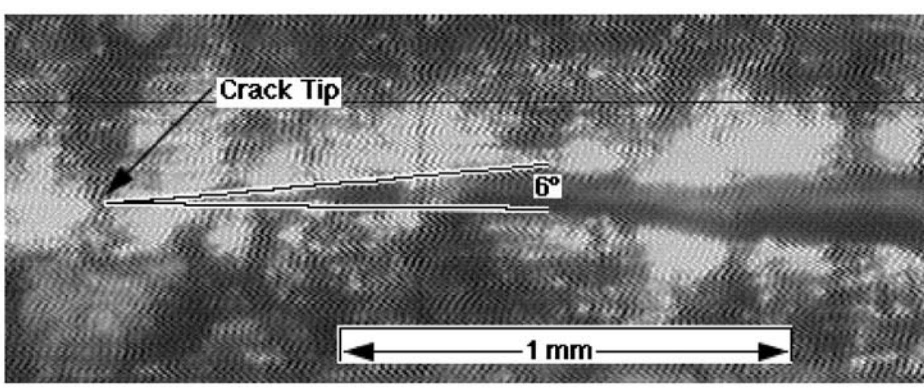
FIG. 8 Measurement Range for Critical CTOA Values



(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

size. 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 be small, be close to the crack line and have sufficient contrast for accurate DIC analysis. Due to the random nature of the speckle pattern, it is generally true that there are 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 ψ_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 ψ_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 the tip and a small amount of cracking of the thin paint layer near the tip. Care must be taken to identify the current crack tip location as accurately as possible.

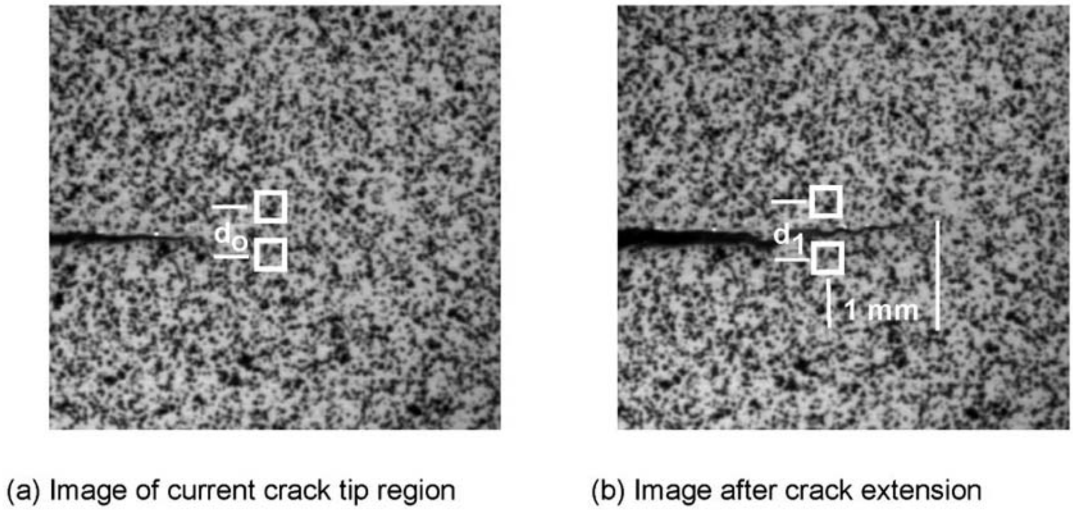


FIG. 10 DIC Images of Crack Before and After Crack Extension

9.1.3 *Determination of Critical Crack-Tip-Opening Angle*—Plot ψ against Δa as shown in Fig. 11. The critical CTOA (ψ_c) is determined from the ψ-Δa plot between limiting crack extension, Δa_{min} and Δa_{max}. The ψ_c value is evaluated as:

$$\psi_c = \left(\sum \psi_n\right)/N \tag{10}$$

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

NOTE 5—Crack-tip-opening angles, ψ, measured on the surface of a specimen during the initiation of stable tearing exhibit large values of ψ due to crack blunting and crack tunneling. But in the interior region, which is under high local constraint, the ψ 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 ψ values approach a nearly constant value, if the requirements in Section 9 are satisfied. The critical CTOA is determined by averaging the ψ values between Δa_{min} and Δa_{max}, as shown by the solid line in Fig. 11. For crack extension values less than Δa_{min}, the critical CTOA value is influenced by the three-dimensional nature of crack extension in this region.

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 size shall be determined as the sum of the original crack size 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 $B \leq 5$ mm. None of the interior final crack size measurements shall differ

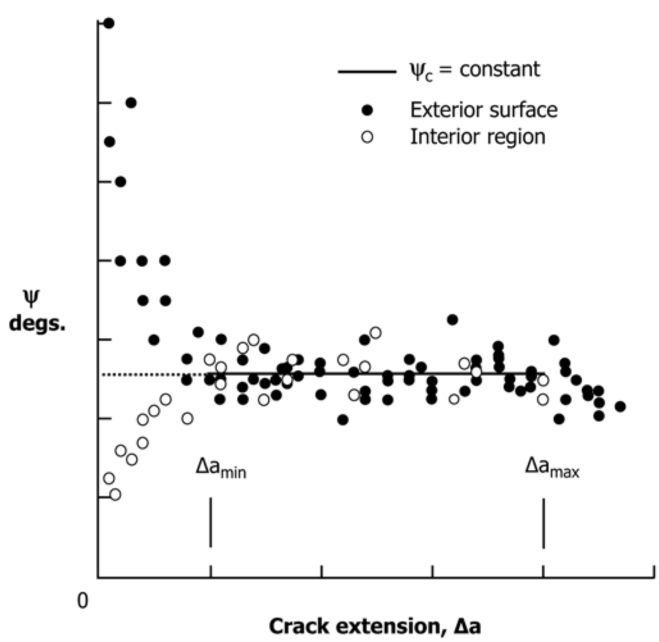


FIG. 11 Determination of Critical CTOA Value

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* δ_5-Δa *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 Δa_f shall be within 15 % of the measured (post test) crack extension or 0.15 mm, whichever is greater, for $\Delta a_f \leq 0.2\ (W - a_o)$ 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 size 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 E647 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 Δa_{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 Δa shall be within 15 % of a_o or 0.15 mm, whichever is greater; otherwise the test results 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 size shall be determined as the sum of the original crack size 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 $B \leq 5$ mm. None of the interior final crack size 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* (δ_5-Δa) *Plot*—The points of δ_5 against crack extension, Δa, form the resistance curve. Some typical behaviors that have been observed for 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 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 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 regions from zero to Δa_{max}, as shown in Fig. 13. The curve shall be best-fitted through the data points lying between zero and the Δa_{max} exclusion lines using the power-law equation:

$$\delta_5 = A + C(\Delta a)^D \tag{11}$$

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 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 size, a_o, and the final stable crack extension, Δa_f, and the final crack size, 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 Size*—Measurement of the original crack size, a_o, depends upon the absolute thickness of the specimen and the amount of tunneling due to fatigue precracking.

9.3.1.1 *Compact Specimen*—Original crack size a_o is measured from the centerline of the pinhole to the tip of the fatigue crack with an instrument accurate to ±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 be first averaging the two surface measurements (a_1 and a_5) made at positions 0.01*B* 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:

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

9.3.1.2 *Middle-Crack-Tension Specimen*—Original crack size a_o is measured as one-half of the total crack size to the tips of both fatigue cracks with an instrument accurate to ±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 be first averaging the two surface measurements (a_1 and a_5) made at positions 0.01*B* 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 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:

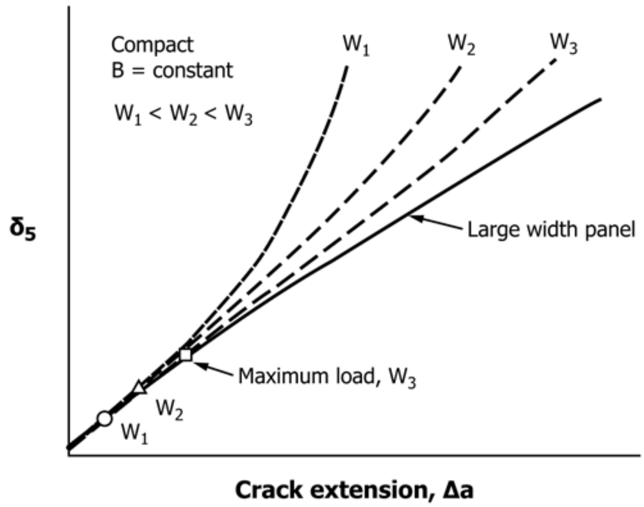
$$a_o = [(a_1 + a_3)/2 + a_2]/2 \tag{13}$$

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

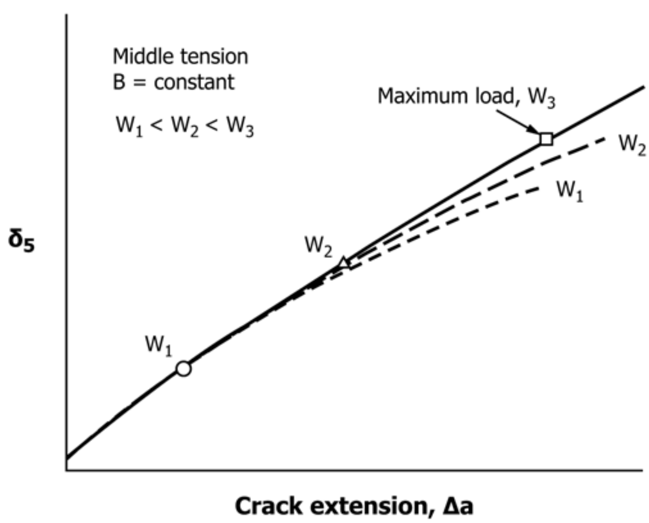
(1) The ratio a_o/W shall be within the range 0.4 to 0.7 for compact specimens, and within the range 0.25 to 0.5 for middle-crack-tension specimens.

(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 2-mm or 0.5*N* (one–half of the crack-starter notch height, *N*, for 60–degree or less included notch angle), whichever is the larger.



(a) Compact specimens



(b) Middle-crack tension specimens

FIG. 12 Schematic of δ_5 Resistance Curves for C(T) and M(T) configurations

9.3.2 *Stable Crack Extension and Final Crack Size*—Total crack extension (including any crack tip blunting) Δa_f between the original and final crack fronts shall be measured with an instrument accurate to ±0.025 mm using the three- or five-point averaging procedure of 9.3.1. For the middle-crack-tension specimens, the crack extension Δa_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 size is a_f.

10. Report

10.1 A recommended table for reporting results is given in Annex A3.

10.2 Report the following information for CTOA and δ_5 R-curve determination:

10.2.1 Type of test specimen and orientation of test specimen according to Terminology E1823 identification codes,

10.2.2 Material designation (ASTM, AISI, SAE, etc.) and material product form (plate, forging, casting, ect.),

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

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 size (a_o), final measured crack size (a_f), crack-front appearance—straightness and planarity, and fracture appearance,

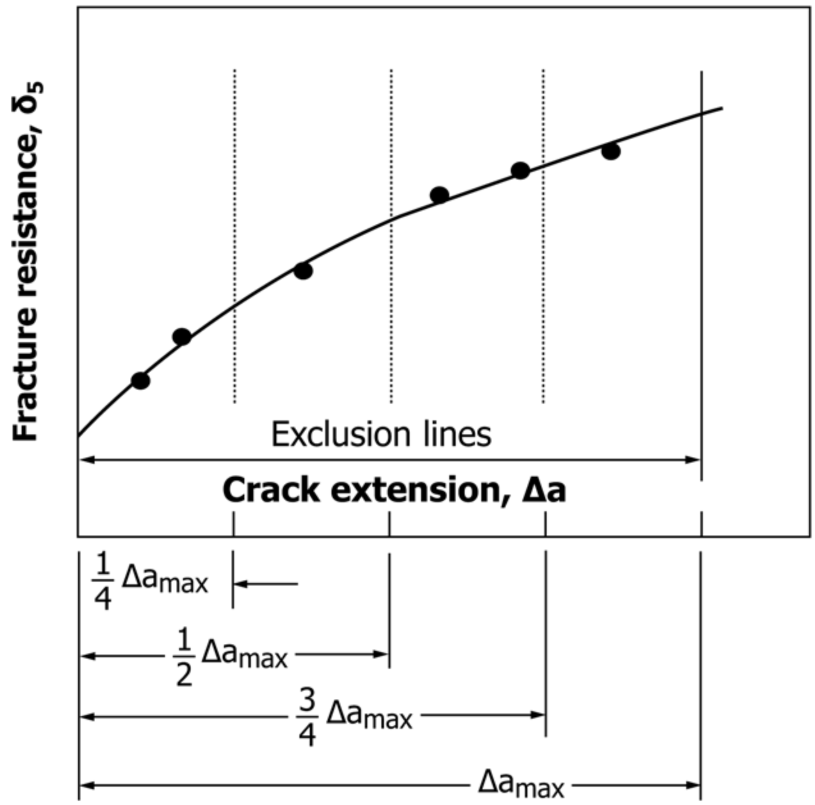


FIG. 13 Data Spacing for δ_5 Resistance Curve Determination

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 δ_5 resistance curve, or both, as appropriate.

11. Precision and Bias

11.1 *Precision*—The precision of the two fracture parameters (CTOA and δ_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 devises, 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 δ_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 (ψ_c); δ_5 resistance curve; ductile fracture; elastic-plastic fracture; fracture instability; low-constraint specimens; stable crack extension

ANNEXES

(Mandatory Information)

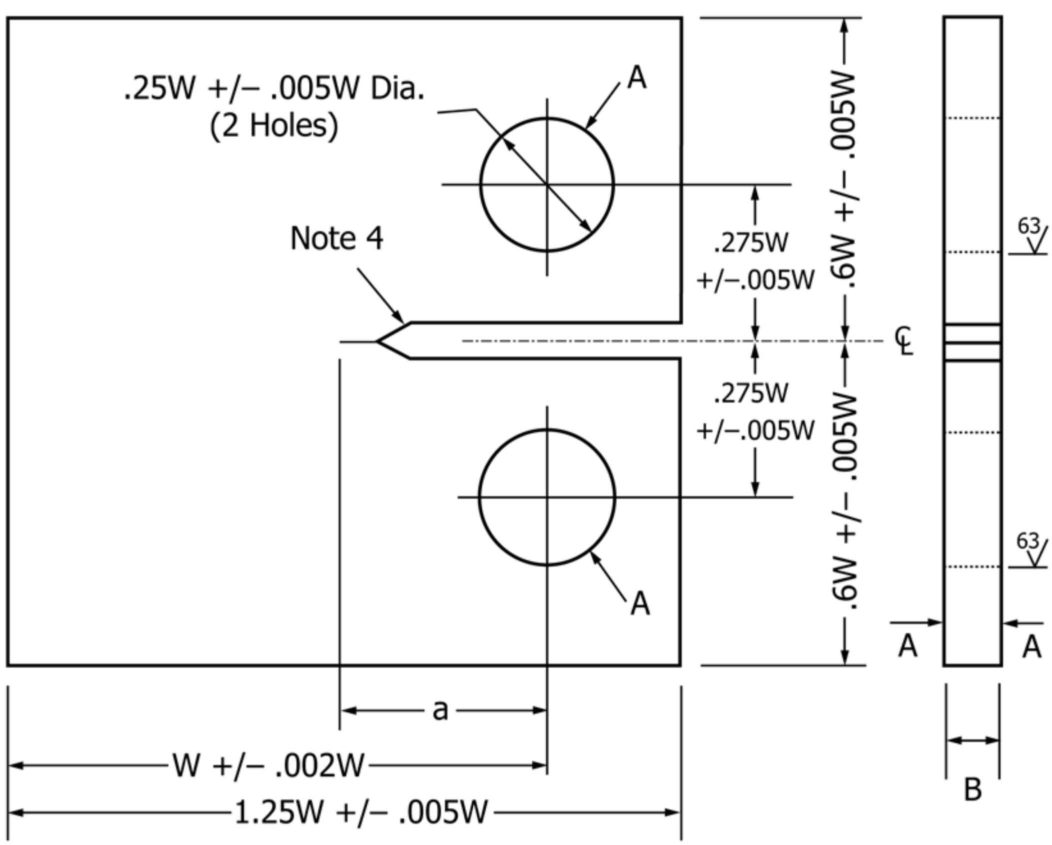
A1. SPECIAL REQUIREMENTS FOR TESTING COMPACT SPECIMENS

A1.1 Specimen

A1.1.1 The compact 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 in–plane relative dimensions are same as the standard compact specimen (see Test Method E399 or Test Method E1820), 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}) 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 size, a_o, (after fatigue pre-cracking) of the compact specimen shall be within the range $0.4W \leq a_o \leq 0.7W$. The minimum fatigue pre-crack extension shall be larger of 2-mm or 0.5*N* (one-half the crack-starter notch height, *N*, for 60–degree or less included notch angle). The notch plus fatigue pre-crack shall be within the limiting envelopes (dashed lines) shown in Fig. 7.



Note 1 - A Surfaces shall be perpendicular and parallel as applicable to within 0.05 mm (0.002 in.) T.I.R. (Total Indicator Reading)
Note 2 - 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 Specimen for CTOA and δ_5 Testing

A1.1.4 Dimensions of specimen shall conform to Fig. A1.1. The thickness *B* and width *W* shall be measured within 0.02 mm or to ±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 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 1.25*W* (between the specimen edges ahead and behind crack tip) shall be measured in addition, at the same uniformly 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 correlation), see 6.6.1.

A1.2.3 For specifications concerning the crack-opening displacement, δ_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 K_{max}/E level less than or equal to 0.00016 $m^{1/2}$ using the original crack size, thickness and width, see 7.4.4.2.

A1.4 Compact Specimen Testing

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

A1.4.2 The crack-opening displacement, δ_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 in-plane relative dimensions are the same as the standard middle-crack-tension specimen (see Test Method E561). 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}) 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 size, a_o, (after fatigue pre-cracking) of the middle-crack-tension specimen shall be within the range $0.25W \leq a_o \leq 0.7W$. The minimum fatigue pre-crack extension shall be larger of 2-mm or 0.5*N* (one-half the crack-starter notch height, *N*, for 60–degree or less included notch angle). 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. The thickness *B* and width *W* shall be measured within 0.02 mm or to ±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 fixtures shall be designed to distribute the force uniformly over the cross-section of the specimen. The fixtures 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, δ_5, measuring devices (clip gage or digital-image), see 6.6.2.

A2.3 Specimen Preparation

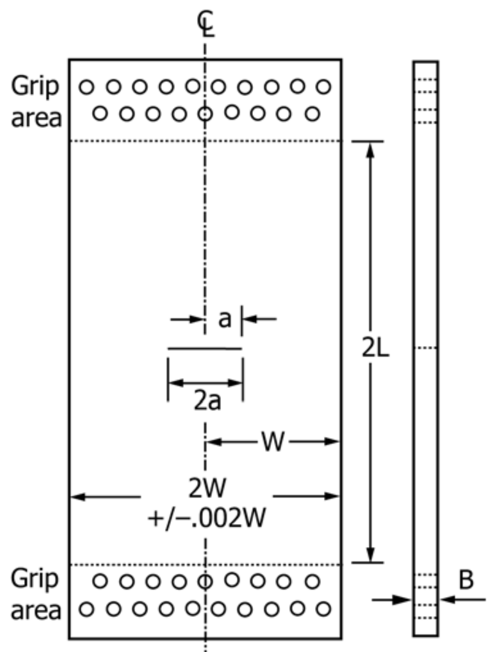
A2.3.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A2.3.2 All specimens shall be fatigue pre-cracked at a K_{max}/E level less than or equal to 0.00016 $m^{1/2}$ using the original crack size, thickness and width, see 7.4.4.2.

A2.4 Middle-Crack-Tension Specimen Testing

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

A2.4.2 The crack-opening displacement, δ_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.



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 δ_5 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) =	__________	
$(W-a_f)/B$ (nominal) =	__________	
Basic Test Information:		
Test Temperature =	__________ [°C]	
Stress-Intensity Factor Rate =	__________ [MPa-m$^{1/2}$ s^{-1}]	
Tensile Properties:		
E [Young's Modulus] =	__________ [MPa]	
σ_{YS} [Yield Strength] =	__________ [MPa]	
σ_{TS} [Ultimate Strength] =	__________ [MPa]	
Pre-cracking:		
Fatigue Temperature =	__________ [°C]	
Final P_f =	__________ [N]	
Final K_{max} =	__________ [MPa-m$^{1/2}$]	
Final $\Delta K/E$ =	__________ [m$^{1/2}$]	

TABLE A3.2 Data Reporting for Critical Crack-Tip-Opening Angle (ψ_c)

Event	P [kN]	a [mm]	Δa [mm]^A	ψ_1 [deg]^B	ψ_2 [deg]^B	ψ_3 [deg]^B

^{A} Measurement at specimen surface.
^{B} OM = Optical method or
DIC = Digital-imaging method

TABLE A3.3 Data Reporting for δ_5 Resistance Curve

Event	P [kN]	a [mm]	Δa [mm]^A	δ_5 [mm]

^{A} UC = Unloading compliance,
ACPD = Alternating current potential drop, or
DCPD = Direct current potential drop

A4. POWER-LAW FIT TO δ_5 AGAINST CRACK-EXTENSION DATA

A4.1 An equation in the form:

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

where:

A, C, and D = are constants used to fit the δ_5-crack extension data.

A4.2 To evaluate the constants, let $y = \delta_5$ and $x = (\Delta a)^D$ and substitute a given value of D into the equation to enable A and C to be evaluated using linear regression in statistical analysis packages or hand calculators. A value of D is chosen that will maximize the correlation coefficient.

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:

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

where:

$$S_{xx} = \sum x^2 - \left(\sum x^2\right)/N \tag{A4.3}$$

$$S_{yy} = \sum y^2 - \left(\sum y^2\right)/N \tag{A4.4}$$

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

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

where:

$$S_{xy} = \sum x\,y^2 - \left(\sum x \sum y\right)/N \tag{A4.6}$$

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

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 ψ_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 on 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 size 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 or middle-crack-tension). These CTOA values have been used to predict the stable tearing behavior of complex structures 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 δ_5 RESISTANCE CURVES AND CRITICAL CTOA

X2.1 The measurement of δ_5-resistance curves is 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 δ_5 measurements.

X2.2 Finite-element analyses of crack-extension simulations have also shown a close relationship between a unique CTOA and the δ_5 R-curve. Fig. X2.1 shows the results of an elastic-plastic, finite-element analysis of a wide range of specimen widths for compact and middle-crack-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 δ_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 δ_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 δ_5 R-curve. An increment of crack extension, Δa, causes an increment in the CTOD, as well as an increment in δ_5. If the increment of δ_5 is equal to the increment in CTOD, then the crack tip opening angle is given by:

$$\psi_c = d\delta_5/d\Delta a \quad \text{(X2.1)}$$

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

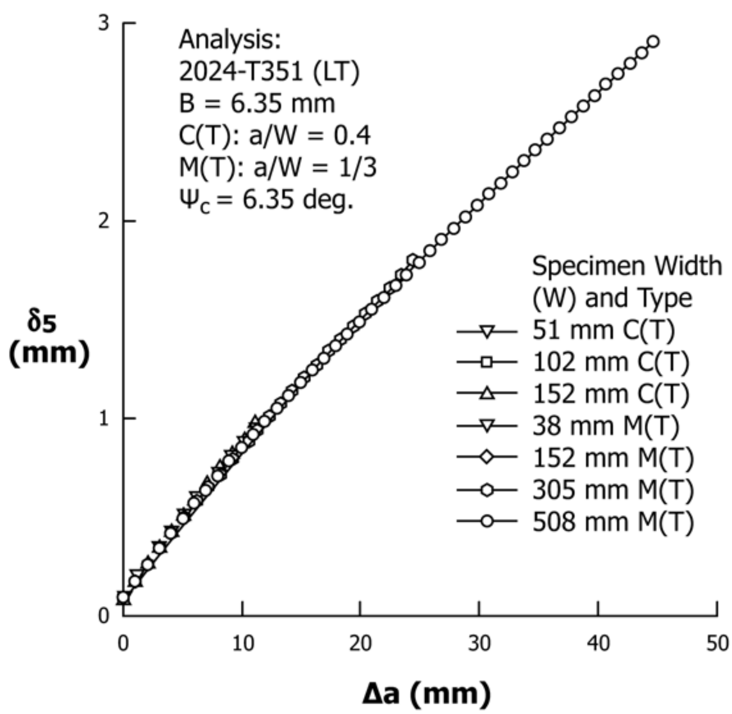


FIG. X2.1 Predicted δ_5-Resistance Curve from a Constant Critical CTOA Analysis

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