Designation: E 1820 – 08a

Standard Test Method for Measurement of Fracture Toughness[1]

This standard is issued under the fixed designation E 1820; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers procedures and guidelines for the determination of fracture toughness of metallic materials using the following parameters: *K, J*, and CTOD (δ). Toughness can be measured in the *R*-curve format or as a point value. The fracture toughness determined in accordance with this test method is for the opening mode (Mode I) of loading.

1.2 The recommended specimens are single-edge bend, [SE(B)], compact, [C(T)], and disk-shaped compact, [DC(T)]. All specimens contain notches that are sharpened with fatigue cracks.

1.2.1 Specimen dimensional (size) requirements vary according to the fracture toughness analysis applied. The guidelines are established through consideration of material toughness, material flow strength, and the individual qualification requirements of the toughness value per values sought.

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

NOTE 1—Other standard methods for the determination of fracture toughness using the parameters *K, J*, and CTOD are contained in Test Methods E 399, E 813, E 1152, E 1290, and E 1737. This test method was developed to provide a common method for determining all applicable toughness parameters from a single test.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E 4 Practices for Force Verification of Testing Machines

E 8 Test Methods for Tension Testing of Metallic Materials

E 21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials

E 399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials

E 1290 Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement

E 1823 Terminology Relating to Fatigue and Fracture Testing

E 1921 Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range

E 1942 Guide for Evaluating Data Acquisition Systems Used in Cyclic Fatigue and Fracture Mechanics Testing

3. Terminology

3.1 Terminology E 1823 is applicable to this test method.

3.2 *Definitions:*

3.2.1 *compliance* $[LF^{-1}]$, *n*—the ratio of displacement increment to force increment.

3.2.2 *crack displacement [L], n*—the separation vector between two points (on the surfaces of a deformed crack) that were coincident on the surfaces of an ideal crack in the undeformed condition.

3.2.2.1 *Discussion—In this practice, displacement,* v, is the total displacement measured by clip gages or other devices spanning the crack faces.

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

3.2.4 *crack-extension force, G* $[FL^{-1}$ or $FLL^{-2}]$, *n*—the elastic energy per unit of new separation area that is made available at the front of an ideal crack in an elastic solid during a virtual increment of forward crack extension.

3.2.5 *crack size, a [L], n*—a lineal 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, and is often also termed crack size or depth.

3.2.5.1 *Discussion*—In practice, the value of *a* is obtained from procedures for measurement of physical crack size, a_p, original crack size, a_o, and effective crack size, a_e, as appropriate to the situation being considered.

3.2.6 *crack-tip opening displacement (CTOD),* δ *[L], n*—the crack displacement due to elastic and plastic deformation at variously defined locations near the original crack tip.

[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.

Current edition approved Dec. 1, 2008. Published January 2009. Originally approved in 1996. Last previous edition approved in 2008 as E 1820 – 08.

[2] 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.

3.2.6.1 *Discussion—In this test method*, CTOD is the displacement of the crack surfaces normal to the original (unloaded) crack plane at the tip of the fatigue precrack, a_o. In this test method, CTOD is calculated at the original crack size, a_o, from measurements made from the force versus displacement record.

3.2.6.2 *Discussion—In CTOD testing*, δ_{Ic} [*L*] is a value of CTOD near the onset of slow stable crack extension, here defined as occurring at $\Delta a_p = 0.2$ mm (0.008 in.) + $0.7\delta_{Ic}$.

3.2.6.3 *Discussion—In CTOD testing*, δ_c [*L*] is the value of CTOD at the onset of unstable crack extension (see 3.2.28) or pop-in (see 3.2.17) when Δa_p<0.2 mm (0.008 in.) + $0.7\delta_c$. The δ_c corresponds to the force P_c and clip-gage displacement v_c (see Fig. 1). It may be size-dependent and a function of test specimen geometry.

3.2.6.4 *Discussion—In CTOD testing*, δ_u [*L*] is the value of CTOD at the onset of unstable crack extension (see 3.2.28) or pop-in (see 3.2.17) when the event is preceded by Δa_p >0.2 mm (0.008 in.) + $0.7\delta_u$. The δ_u corresponds to the force P_u and the clip gage displacement v_u (see Fig. 1). It may be size-dependent and a function of test specimen geometry. It can be useful to define limits on ductile fracture behavior.

3.2.6.5 *Discussion—In CTOD testing,* δ_c^**[L]* characterizes the CTOD fracture toughness of materials at fracture instability prior to the onset of significant stable tearing crack extension. The value of δ_c^* determined by this test method represents a measure of fracture toughness at instability without significant stable crack extension that is independent of in-plane dimensions. However, there may be a dependence of toughness on thickness (length of crack front).

3.2.7 *effective thickness, B_e [L], n*—for side-grooved specimens $B_e = B - (B - B_N)^2/B$. This is used for the elastic unloading compliance measurement of crack size.

3.2.7.1 *Discussion*—This definition is different from the definition of effective thickness in Test Method E 813.

3.2.8 *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.

3.2.8.1 *Discussion*—It is calculated as the average of the 0.2 % offset yield strength σ_{YS}, and the ultimate tensile strength, σ_{TS} as follows:

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

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

3.2.9 *J-integral, J [FL^{-1}], n*—a mathematical expression, a line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the local stress-strain field around the crack front.

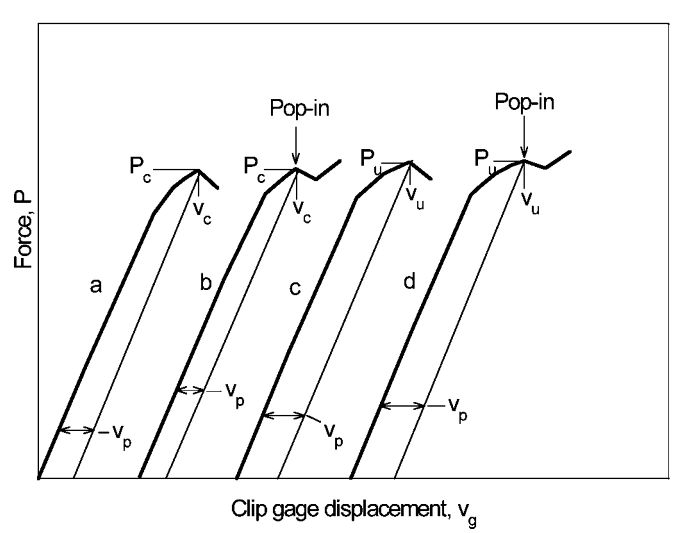
3.2.9.1 *Discussion*—The *J*-integral expression for a two-dimensional crack, in the *x-z* plane with the crack front parallel to the *z*-axis, is the line integral as follows:

$$J = \int_{\Gamma} \left(W dy - \bar{T} \cdot \frac{\partial \bar{u}}{\partial x} ds \right) \quad (2)$$

where:

W	=	loading work per unit volume or, for elastic bodies, strain energy density,
Γ	=	path of the integral, that encloses (that is, contains) the crack tip,
ds	=	increment of the contour path,
$\bar{T}$	=	outward traction vector on *ds*,
$\bar{u}$	=	displacement vector at *ds*,
x, y, z	=	rectangular coordinates, and
$\bar{T} \cdot \frac{\partial \bar{u}}{\partial x} ds$	=	rate of work input from the stress field into the area enclosed by Γ.

3.2.9.2 *Discussion*—The value of *J* obtained from this equation is taken to be path-independent in test specimens commonly used, but in service components (and perhaps in test specimens) caution is needed to adequately consider loading



NOTE 1—Construction lines drawn parallel to the elastic loading slope to give v_p, the plastic component of total displacement, v_g.

NOTE 2—In curves b and d, the behavior after pop-in is a function of machine/specimen compliance, instrument response, etc.

FIG. 1 Types of Force versus Clip Gage Displacement Records

interior to Γ such as from rapid motion of the crack or the service component, and from residual or thermal stress.

3.2.9.3 *Discussion*—In elastic (linear or nonlinear) solids, the *J*-integral equals the crack-extension force, *G*. (See *crack extension force.*)

3.2.10 J_c *[FL^{-1}]*—The property J_c determined by this test method characterizes the fracture toughness of materials at fracture instability prior to the onset of significant stable tearing crack extension. The value of J_c determined by this test method represents a measure of fracture toughness at instability without significant stable crack extension that is independent of in-plane dimensions; however, there may be a dependence of toughness on thickness (length of crack front).

3.2.11 J_u *[FL^{-1}]*—The quantity J_u determined by this test method measures fracture instability after the onset of significant stable tearing crack extension. It may be size-dependent and a function of test specimen geometry. It can be useful to define limits on ductile fracture behavior.

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

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

3.2.13.1 *Discussion*—In this test method, a_{oq} is used to denote original crack size estimated from compliance.

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

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

3.2.16 *plane-strain fracture toughness,* K_{Ic} $[FL^{-3/2}]$, J_{Ic} $[FL^{-1}]$, K_{JIc} $[FL^{-3/2}]$, *n*—the crack-extension resistance under conditions of crack-tip plane-strain.

3.2.16.1 *Discussion*—For example, in Mode I for slow rates of loading and negligible plastic-zone adjustment, plane-strain fracture toughness is the value of the stress-intensity factor designated K_{Ic} $[FL^{-3/2}]$ as measured using the operational procedure (and satisfying all of the qualification requirements) specified in this test method, which provides for the measurement of crack-extension resistance at the start of crack extension and provides operational definitions of crack-tip sharpness, start of crack extension, and crack-tip plane-strain.

3.2.16.2 *Discussion*—For example, in Mode I for slow rates of loading and substantial plastic deformation, plane-strain fracture toughness is the value of the *J*-integral designated J_{Ic} $[FL^{-1}]$ as measured using the operational procedure (and satisfying all of the qualification requirements) specified in this test method, that provides for the measurement of crack-extension resistance near the onset of stable crack extension.

3.2.16.3 *Discussion*—For example, in Mode I for slow rates of loading, plane-strain fracture toughness is the value of the stress intensity designated $K_{JIc}[FL^{-3/2}]$ calculated from J_{Ic} using the equation (and satisfying all of the qualification requirements) specified in this test method, that provides for the measurement of crack-extension resistance near the onset of stable crack extension under dominant elastic conditions.(**1**)[3]

3.2.17 *pop-in*, *n*—a discontinuity in the force versus clip gage displacement record. The record of a pop-in shows a sudden increase in displacement and, generally a decrease in force. Subsequently, the displacement and force increase to above their respective values at pop-in.

3.2.18 *R-curve or J-R curve*, *n*—a plot of crack extension resistance as a function of stable crack extension, Δa_p or Δa_e.

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

3.2.19 *remaining ligament, b [L]*, *n*—distance from the physical crack front to the back edge of the specimen, that is ($b = W - a_p$).

3.2.20 *specimen center of pin hole distance, H* [L]*, *n*—the distance between the center of the pin holes on a pin-loaded specimen.

3.2.21 *specimen gage length, d [L]*, *n*—the distance between the points of displacement measure (for example, clip gage, gage length).

3.2.22 *specimen span, S [L]*, *n*—the distance between specimen supports.

3.2.23 *specimen thickness, B [L]*, *n*—the side-to-side dimension of the specimen being tested.

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

3.2.25 *stable crack extension [L]*, *n*—a displacement-controlled crack extension beyond the stretch-zone width (see 3.2.27). The extension stops when the applied displacement is held constant.

3.2.26 *stress-intensity factor,* K, K_1, K_2, K_3, K_I, K_{II}, K_{III} $[FL^{-3/2}]$, *n*—the magnitude of the ideal-crack-tip stress field (stress-field singularity) for a particular mode in a homogeneous, linear-elastic body.

3.2.26.1 *Discussion*—Values of *K* for the Modes 1, 2, and 3 are given by the following equations:

$$K_1 = \lim_{r\to 0}[\sigma_{yy}(2\pi r)^{1/2}] \quad (3)$$

$$K_2 = \lim_{r\to 0}[\tau_{xy}(2\pi r)^{1/2}] \quad (4)$$

$$K_3 = \lim_{r\to 0}[\tau_{yz}(2\pi r)^{1/2}] \quad (5)$$

where r = distance directly forward from the crack tip to a location where the significant stress is calculated.

3.2.26.2 *Discussion*—In this test method, Mode 1 or Mode I is assumed. See Terminology E 1823 for definition of mode.

3.2.27 *stretch-zone width, SZW [L]*, *n*—the length of crack extension that occurs during crack-tip blunting, for example, prior to the onset of unstable brittle crack extension, pop-in, or slow stable crack extension. The SZW is in the same plane as

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

the original (unloaded) fatigue precrack and refers to an extension beyond the original crack size.

3.2.28 *unstable crack extension [L], n*—an abrupt crack extension that occurs with or without prior stable crack extension in a standard test specimen under crosshead or clip gage displacement control.

4. Summary of Test Method

4.1 The objective of this test method is to load a fatigue precracked test specimen to induce either or both of the following responses (*1*) unstable crack extension, including significant pop-in, referred to as "fracture instability" in this test method; (*2*) stable crack extension, referred to as "stable tearing" in this test method. Fracture instability results in a single point-value of fracture toughness determined at the point of instability. Stable tearing results in a continuous fracture toughness versus crack-extension relationship (*R*-curve) from which significant point-values may be determined. Stable tearing interrupted by fracture instability results in an *R*-curve up to the point of instability.

4.2 This test method requires continuous measurement of force versus load-line displacement and crack mouth opening displacement. If any stable tearing response occurs, then an *R*-curve is developed and the amount of slow-stable crack extension shall be measured.

4.3 Two alternative procedures for measuring crack extension are presented, the basic procedure and the resistance curve procedure. The basic procedure involves physical marking of the crack advance and multiple specimens used to develop a plot from which a single point initiation toughness value can be evaluated. The resistance curve procedure is an elastic-compliance method where multiple points are determined from a single specimen. In the latter case, high precision of signal resolution is required. These data can also be used to develop an *R*-curve. Other procedures for measuring crack extension are allowed.

4.4 The commonality of instrumentation and recommended testing procedure contained herein permits the application of data to more than one method of evaluating fracture toughness. Annex A4-Annex A11 define the various data treatment options that are available, and these should be reviewed to optimize data transferability.

4.5 Data that are generated following the procedures and guidelines contained in this test method are labeled qualified data. Data that meet the size criteria in Annex A4-Annex A11 are insensitive to in-plane dimensions.

4.6 Supplementary information about the background of this test method and rationale for many of the technical requirements of this test method are contained in (**2**). The formulas presented in this test method are applicable over the range of crack size and specimen sizes within the scope of this test method.

5. Significance and Use

5.1 Assuming the presence of a preexisting, sharp, fatigue crack, the material fracture toughness values identified by this test method characterize its resistance to: *(1)* fracture of a stationary crack, *(2)* fracture after some stable tearing, *(3)* stable tearing onset, and *(4)* sustained stable tearing. This test method is particularly useful when the material response cannot be anticipated before the test. Application of procedures in Test Method E 1921 is recommended for testing ferritic steels that undergo cleavage fracture in the ductile-to-brittle transition.

5.1.1 These fracture toughness values may serve as a basis for material comparison, selection, and quality assurance. Fracture toughness can be used to rank materials within a similar yield strength range.

5.1.2 These fracture toughness values may serve as a basis for structural flaw tolerance assessment. Awareness of differences that may exist between laboratory test and field conditions is required to make proper flaw tolerance assessment.

5.2 The following cautionary statements are based on some observations.

5.2.1 Particular care must be exercised in applying to structural flaw tolerance assessment the fracture toughness value associated with fracture after some stable tearing has occurred. This response is characteristic of ferritic steel in the transition regime. This response is especially sensitive to material inhomogeneity and to constraint variations that may be induced by planar geometry, thickness differences, mode of loading, and structural details.

5.2.2 The *J-R* curve from bend-type specimens recommended by this test method (SE(B), C(T), and DC(T)) has been observed to be conservative with respect to results from tensile loading configurations.

5.2.3 The values of δ_c, δ_u, J_c, and J_u may be affected by specimen dimensions.

6. Apparatus

6.1 Apparatus is required for measurement of applied force, load-line displacement, and crack-mouth opening displacement. Force versus load-line displacement and force versus crack-mouth opening displacement may be recorded digitally for processing by computer or autographically with an *x-y* plotter. Test fixtures for each specimen type are described in the applicable Annex.

6.2 *Displacement Gages*:

6.2.1 Displacement measurements are needed for the following purposes: to evaluate P_Q in the K_{Ic} evaluation, J from the area under the force versus load-line displacement record, CTOD from the force versus crack-mouth opening displacement record and, for the elastic compliance method, to infer crack extension, Δa_p, from elastic compliance calculations.

6.2.2 The recommended 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. 2 may be used. When a greater working range is needed, an enlarged gage such as the one shown in Fig. 3 is recommended. Accuracy shall be within ±1 % of the full working range. In calibration, the maximum deviation of the individual data points from a fit (linear or curve) to the data shall be less than ±0.2 % of the working range of the gage when using the elastic compliance method and ±1 % otherwise. Knife edges are required for seating the gage. Parallel alignment of the knife edges shall be maintained to within 1°. Direct methods for load-line displacement are described in Refs (**2-5**).

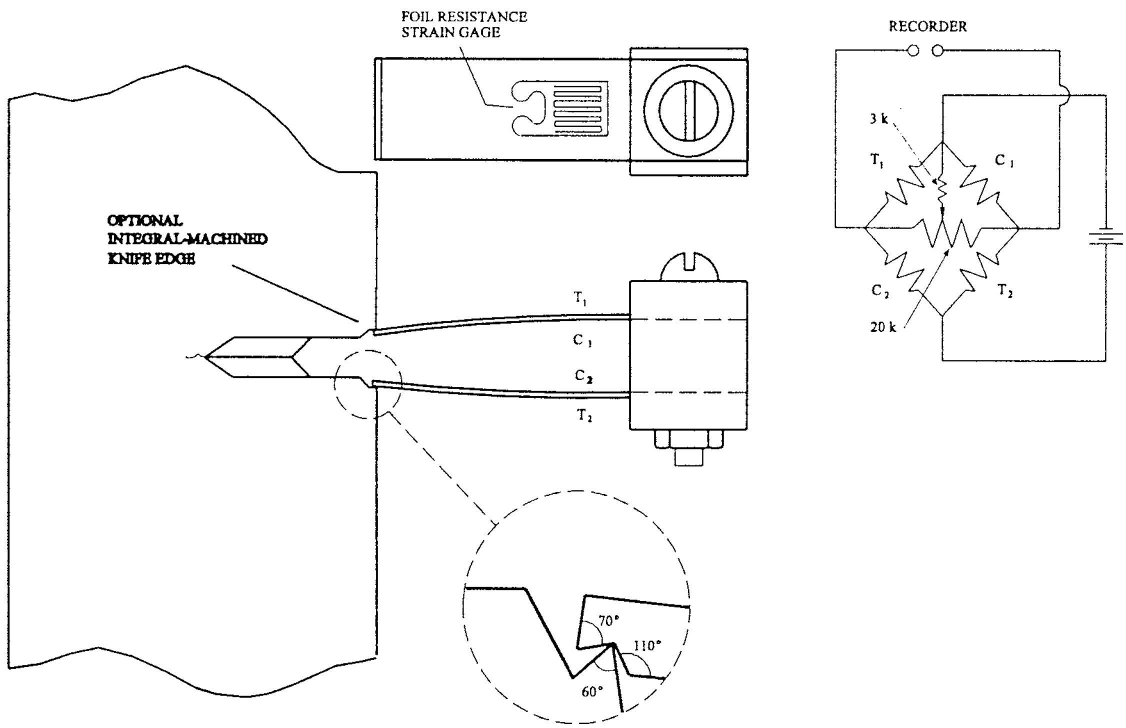
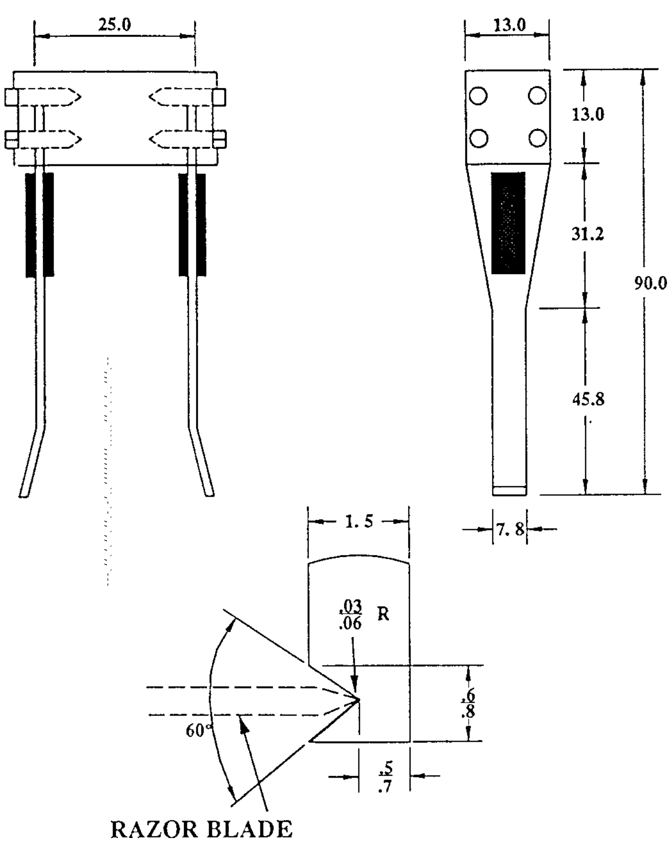


FIG. 2 Double-Cantilever Clip-In Displacement Gage Mounted by Means of Integral Knife Edges



NOTE 1—All dimensions are in millimeters.

FIG. 3 Clip Gage Design for 8.0 mm (0.3 in.) and More Working Range

6.2.2.1 *Gage Attachment Methods*—The specimen shall be provided with a pair of accurately machined knife edges that support the gage arms and serve as the displacement reference points. These knife edges can be machined integral with the specimen or they may be attached separately. Experience has shown that razor blades serve as effective attachable knife edges. The knife edges shall be positively attached to the specimen to prevent shifting of the knife edges during the test method. Experience has shown that machine screws or spot welds are satisfactory attachment methods.

6.2.3 For the elastic compliance method, the recommended signal resolution for displacement should be at least 1 part in 32 000 of the transducer signal range, and signal stability should be ±4 parts in 32 000 of the transducer signal range measured over a 10-min period. Signal noise should be less than ±2 parts in 32 000 of the transducer signal range.

6.2.4 Gages other than those recommended in 6.2 are permissible if the required accuracy and precision can be met or exceeded.

6.3 *Force Transducers*:

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

6.3.2 For the elastic compliance method, the signal resolution on force should be at least 1 part in 4000 of the transducer signal range and signal stability should be ±4 parts in 4000 of the transducer signal range measured over a 10-min period.

Recommended maximum signal noise should be less than ±2 parts in 4000 of the transducer signal range.

6.4 *System Verification*—It is recommended that the performance of the force and displacement measuring systems should be verified before beginning a series of continuous tests. Calibration accuracy of displacement transducers shall be verified with due consideration for the temperature and environment of the test. Force calibrations shall be conducted periodically and documented in accordance with the latest revision of Practices E 4.

6.5 *Fixtures*:

6.5.1 *Bend-Test Fixture*—The general principles of the bend-test fixture are illustrated in Fig. 4. This fixture is designed to minimize frictional effects by allowing the support rollers to rotate and move apart slightly as the specimen is loaded, thus permitting rolling contact. Thus, the support rollers are allowed limited motion along plane surfaces parallel to the notched side of the specimen, but are initially positively positioned against stops that set the span length and are held in place by low-tension springs (such as rubber bands). Fixtures and rolls shall be made of high hardness (greater than 40 HRC) steels.

6.5.2 *Tension Testing Clevis*:

6.5.2.1 A loading clevis suitable for testing compact specimens is shown in Fig. 5. Both ends of the specimen are held in such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. In order to provide rolling contact between the loading pins and the clevis holes, these holes are provided with small flats on the loading surfaces. Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown. Clevises and pins should be fabricated from steels of sufficient strength (greater than 40 HRC) to elastically resist indentation of the clevises or pins.

6.5.2.2 The critical tolerances and suggested proportions of the clevis and pins are given in Fig. 5. These proportions are based on specimens having $W/B = 2$ for $B > 12.7$ mm (0.5 in.) and $W/B = 4$ for $B \leq 12.7$ mm. If a 1930-MPa (280 000-psi) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained. If lower-strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio, then heavier grips will be required. As indicated in Fig. 5 the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 9.5 mm (0.375 in.) thick.

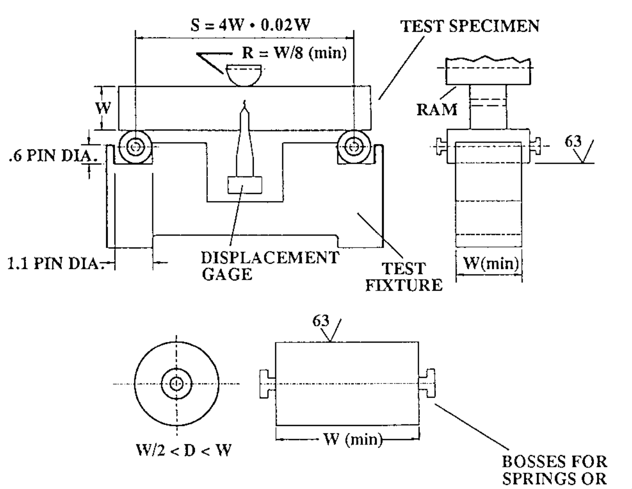


FIG. 4 Bend Test Fixture Design

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

7. Specimen Size, Configuration, and Preparation

7.1 *Specimen Configurations*—The configurations of the standard specimens are shown in Annex A1-Annex A3.

7.2 *Crack Plane Orientation*—The crack plane orientation shall be considered in preparing the test specimen. This is discussed in Terminology E 1823.

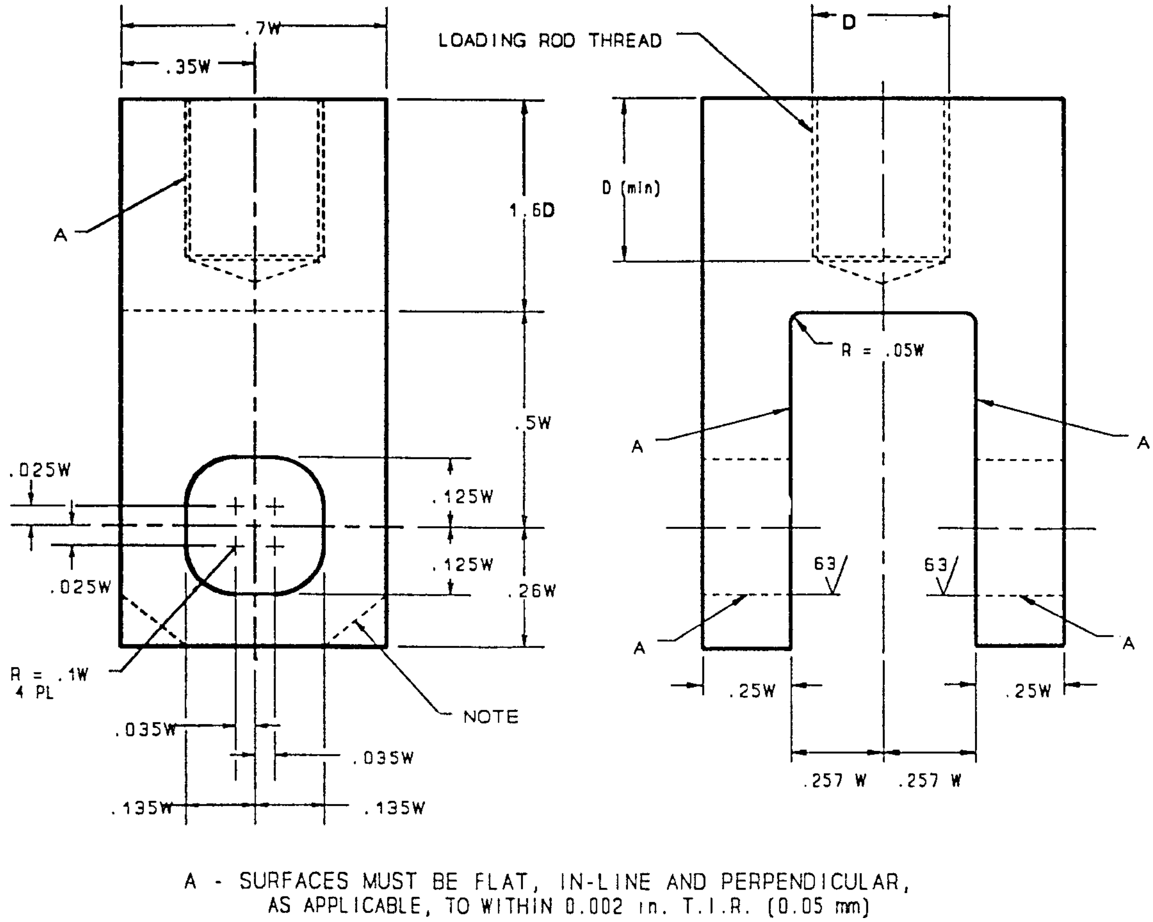
7.3 *Alternative Specimens*—In certain cases, it may be desirable to use specimens having W/B ratios other than two. Suggested alternative proportions for the single-edge bend specimen are $1 \leq W/B \leq 4$ and for the compact (and diskshaped compact) specimen are $2 \leq W/B \leq 4$, however, any thickness can be used as long as the qualification requirements are met.

7.4 *Specimen Precracking*—All specimens shall be precracked 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 precrack. (A fatigue precrack 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 precrack, and the sharpness of the precrack 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*—Three forms of fatigue crack starter notches are shown in Fig. 6. To facilitate fatigue cracking at low stress intensity levels, the root radius for a straight-through slot terminating in a *V*-notch should be 0.08 mm (0.003 in.) or less. If a chevron form of notch is used, the root radius may be 0.25 mm (0.010 in.) or less. In the case of a slot tipped with a hole it will be necessary to provide a sharp stress raiser at the end of the hole.

7.4.2 *Fatigue Crack Size*—The crack size (total average length of the crack starter configuration plus the fatigue crack) shall be between 0.45 and 0.70 W for J and δ determination, but is restricted to the range from 0.45 to 0.55 for K_{Ic} determination.

7.4.3 *Equipment*—The equipment for fatigue cracking should be such that the stress distribution is uniform through the specimen thickness; otherwise the crack will not grow uniformly. The stress distribution should also be symmetrical about the plane of the prospective crack; otherwise the crack



NOTE 1—Corners may be removed as necessary to accommodate the clip gage.

FIG. 5 Tension Testing Clevis Design

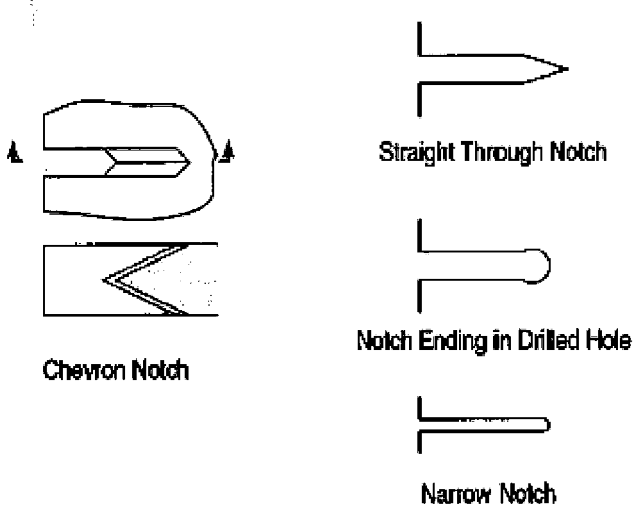
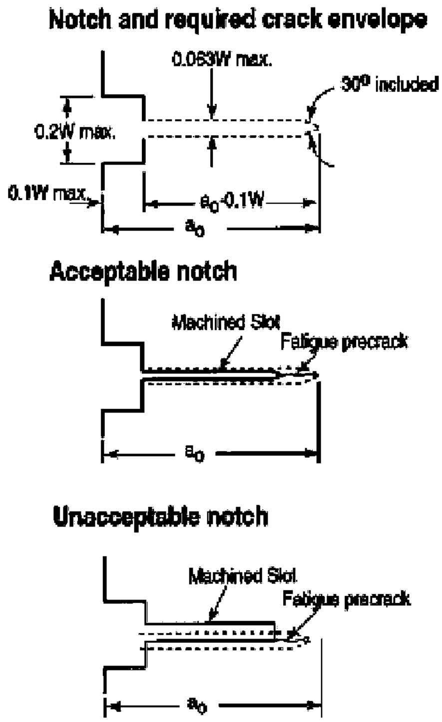


FIG. 6 Fatigue Crack Starter Notch Configurations

may deviate from that plane and the test result can be significantly affected. The K calibration for the specimen, if it is different from the one given in this test method, shall be known with an uncertainty of less than 5 %. Fixtures used for precracking should be machined with the same tolerances as those used for testing.

7.4.4 *Fatigue Loading Requirements*—Allowable fatigue force values are limited to keep the maximum stress intensity applied during precracking, K_{MAX}, well below the material fracture toughness measured during the subsequent test. The fatigue precracking shall be conducted with the specimen fully heat-treated to the condition in which it is to be tested. No intermediate treatments between precracking and testing are allowed. The combination of starter notch and fatigue precrack shall conform to the requirements shown in Fig. 7. There are several ways of promoting early crack initiation: *(1)* by providing a very sharp notch tip, *(2)* by using a chevron notch (Fig. 6), *(3)* by statically preloading the specimen in such a way that the notch tip is compressed in a direction normal to the intended crack plane (to a force not to exceed P_m), and *(4)* by using a negative fatigue force ratio; for a given maximum fatigue force, the more negative the force ratio, the earlier crack initiation is likely to occur. The peak compressive force shall not exceed P_m as defined in Annex A1-Annex A3.

7.4.5 *Fatigue Precracking Procedure*—Fatigue precracking can be conducted under either force control or displacement control. If the force cycle is maintained constant, the maximum K and the K range will increase with crack size; if the displacement cycle is maintained constant, the reverse will



Notch and precrack configurations

	Wide Notch	Narrow Notch
maximum notch height	0.063W	0.01W
maximum notch angle	60°	as machined
minimum precrack length	0.05B	0.025B

NOTE 1—The crack-starter notch shall be centered between the top and bottom specimen edges within 0.005 W.

FIG. 7 Envelope of Fatigue Crack and Crack Starter Notches

happen. The initial value of the maximum fatigue force should be less than P_m. The specimen shall be accurately located in the loading fixture. Fatigue cycling is then begun, usually with a sinusoidal waveform and near to the highest practical frequency. There is no known marked frequency effect on fatigue precrack formation up to at least 100 Hz in the absence of adverse environments. The specimen should be carefully monitored until crack initiation is observed on one side. If crack initiation is not observed on the other side before appreciable growth is observed on the first, then fatigue cycling should be stopped to try to determine the cause and find a remedy for the unsymmetrical behavior. Sometimes, simply turning the specimen around in relation to the fixture will solve the problem.

7.4.5.1 The length of the fatigue precrack extension from the machined notch shall not be less than 0.05*B*, and not less than 1.3 mm (0.05 in.) for the wide notch, see Fig. 7, nor less than 0.025*B* or less than 0.6 mm (0.024 in.) for the narrow notch. Precracking shall be accomplished in at least two steps. For the first step the maximum stress intensity applied to the specimen shall be limited by:

$$K_{MAX} = \left(\frac{\sigma^f_{YS}}{\sigma^T_{YS}}\right)(0.063\sigma^f_{YS}\,\text{MPa}\sqrt{\text{m}}) \tag{6}$$

or

$$K_{MAX} = \left(\frac{\sigma^f_{YS}}{\sigma^T_{YS}}\right)(0.4\sigma^f_{YS}\,\text{ksi}\sqrt{\text{in.}})$$

where:

$\sigma_{YS}{}^f$ and $\sigma_{YS}{}^T$ = the material yield stresses at the fatigue precrack and test temperatures respectively.

7.4.5.2 It is generally most effective to use $R = P_{MIN}/P_{MAX} = 0.1$. The accuracy of the maximum force values shall be known within ±5 %.

Precracking should be conducted at as low as a K_{MAX} as practical. For some aluminum alloys and high strength steels the above K_{MAX} relationship can give very high precracking forces. This is especially true if precracking and testing are conducted at the same temperature. It is suggested that the user start with approximately 0.7 K_{MAX} given by the above relationship, and if the precrack does not grow after 10^5 cycles the loading can be incrementally increased until the crack begins to extend.

For the second precracking step, which shall include at least the final 50 % of the fatigue precrack or 1.3 mm (0.05 in.) for the wide notch or 0.6 mm (0.024 in.) for the narrow notch, whichever is less, the maximum stress intensity that may be applied to the specimen shall be given by:

$$K_{MAX} = 0.6\frac{\sigma^{f}_{YS}}{\sigma^{T}_{YS}} K_F \quad (7)$$

where:

K_F = K_Q, K_{JQ}, K_{JQc} or K_{JQu} depending on the result of the test, and K_F is calculated from the corresponding J_F using the relationship that:

$$K_F = \sqrt{\frac{EJ_F}{(1-\nu^2)}} \quad (8)$$

7.4.5.3 To transition between steps, intermediate levels of force shedding can be used if desired.

7.5 *Side Grooves*—Side grooves are highly recommended when the compliance method of crack size prediction is used. The specimen may also need side grooves to ensure a straight crack front as specified in Annex A4-Annex A7. The total thickness reduction shall not exceed 0.25*B*. A total reduction of 0.20*B* has been found to work well for many materials. Any included angle of side groove less than 90° is allowed. Root radius shall be 0.5 ± 0.2 mm (0.02 ± 0.01 in.). In order to produce nearly straight fatigue precrack fronts, the precracking should be performed prior to the side-grooving operation. B_N is the minimum thickness measured at the roots of the side grooves. The root of the side groove should be located along the specimen centerline.

8. Procedure

8.1 *Objective and Overview*:

8.1.1 The overall objective of the test method is to develop a force-displacement record that can be used to evaluate *K, J,* or CTOD. Two procedures can be used: *(1)* a basic procedure directed toward evaluation of a single *K, J,* or CTOD value without the use of crack extension measurement equipment, or *(2)* a procedure directed toward evaluation of a complete fracture toughness resistance curve using crack extension measurement equipment. This also includes the evaluation of single-point toughness values.

8.1.2 The basic procedure utilizes a force versus displacement plot and is directed toward obtaining a single fracture toughness value such as K_{Ic}, J_c, or δ_c. Optical crack measurements are utilized to obtain both the initial and final physical crack sizes in this procedure. Multiple specimens can be used to evaluate *J* at the initiation of ductile cracking, J_{Ic} or δ_{Ic}.

8.1.3 The resistance curve procedure utilizes an elastic unloading procedure or equivalent procedure to obtain a *J*- or CTOD-based resistance curve from a single specimen. Crack size is measured from compliance in this procedure and verified by posttest optical crack size measurements. An alternative procedure using the normalization method is presented in Annex A15: Normalization Data Reduction Technique.

8.1.4 Three or more determinations of the fracture toughness parameter are suggested to ascertain the effects of material and test system variability. If fracture occurs by cleavage of ferritic steel, the testing and analysis procedure of Test Method E 1921 is recommended.

8.2 *System and Specimen Preparation*:

8.2.1 *Specimen Measurement*—Measure the dimensions, B_N, *B, W, H*,* and *d* to the nearest 0.050 mm (0.002 in.) or 0.5 %, whichever is larger.

8.2.2 *Specimen Temperature*:

8.2.2.1 The temperature of the specimen shall be stable and uniform during the test. Hold the specimen at test temperature ±3°C for ½ h/25 mm of specimen thickness.

8.2.2.2 Measure the temperature of the specimen during the test to an accuracy of ±3°C, where the temperature is measured on the specimen surface within *W*/4 from the crack tip. (See Test Methods E 21 for suggestions on temperature measurement.)

8.2.2.3 For the duration of the test, the difference between the indicated temperature and the nominal test temperature shall not exceed ±3°C.

8.2.2.4 The term "indicated temperature" means the temperature that is indicated by the temperature measuring device using good-quality pyrometric practice.

NOTE 2—It is recognized that specimen temperature may vary more than the indicated temperature. The permissible indicated temperature variations in 8.2.2.3 are not to be construed as minimizing the importance of good pyrometric practice and precise temperature control. All laboratories should keep both indicated and specimen temperature variations as small as practicable. It is well recognized, in view of the dependency of fracture toughness of materials on temperature, that close temperature control is necessary. The limits prescribed represent ranges that are common practice.

8.3 *Alignment*:

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

8.3.1.1 When the load-line displacement is referenced from the loading jig there is potential for introduction of error from two sources. They are the elastic compression of the fixture as the force increases and indentation of the specimen at the loading points. Direct methods for load-line displacement measurement are described in Refs (**3-6**). If a remote transducer is used for load-line displacement measurement, take care to exclude the elastic displacement of the load-train measurement and brinelling displacements at the load points (**7**).

8.3.2 *Compact Testing*—Loading pin friction and eccentricity of loading can lead to errors in fracture toughness determination. The centerline of the upper and lower loading rods should be coincident within 0.25 mm (0.01 in.). Center the specimen with respect to the clevis opening within 0.76 mm (0.03 in.). Seat the displacement gage in the knife edges firmly by wiggling the gage lightly.

8.4 *Basic Procedure*—Load all specimens under displacement gage or machine crosshead or actuator displacement control. If a loading rate that exceeds that specified here is desired, please refer to Annex A14: Special Requirements for Rapid-Load J-Integral Fracture Toughness Testing.

8.4.1 The basic procedure involves loading a specimen to a selected displacement level and determining the amount of crack extension that occurred during loading.

8.4.2 Load specimens at a constant rate such that the time taken to reach the force P_m lies between 0.3 to 3 min.

8.4.3 If the test ends by a fracture instability, measure the initial crack size and any ductile crack extension by the procedure in 9. Ductile crack extension may be difficult to distinguish but should be defined on one side by the fatigue precrack and on the other by the brittle region. Proceed to 9 to evaluate fracture toughness in terms of K, J, or CTOD.

8.4.4 If stable tearing occurs, test additional specimens to evaluate an initiation value of the toughness. Use the procedure in 8.5 to evaluate the amount of stable tearing that has occurred and thus determine the displacement levels needed in the additional tests. Five or more points favorably positioned are required to generate an R curve for evaluating an initiation point. See Annex A9 and Annex A11 to see how points shall be positioned for evaluating an initiation toughness value.

8.5 *Optical Crack Size Measurement*:

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

8.5.2 Break the specimen to expose the crack, with care taken to minimize additional deformation. Cooling ferritic steel specimens to ensure brittle behavior may be helpful. Cooling nonferritic materials may help to minimize deformation during final fracture.

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

8.5.4 None of the nine measurements of original crack size and final physical crack size may differ by more than 0.05B from the average physical crack size defined in 8.5.3.

8.6 *Resistance Curve Procedure*:

8.6.1 The resistance curve procedure involves using an elastic compliance technique or other technique to obtain the J or CTOD resistance curve from a single specimen test. The elastic compliance technique is described here, while the normalization technique is described in Annex A15.

8.6.2 Load the specimens under the displacement gage or machine crosshead or actuator displacement control. Load the specimens at a rate such that the time taken to reach the force P_m lies between 0.3 and 3.0 min. The time to perform an unload/reload sequence should be as needed to accurately estimate crack size, but not more than 10 min. If a higher loading rate is desired, please refer to Annex A14: Special Requirements for Rapid-Load J-Integral Fracture Toughness Testing.

8.6.3 Take each specimen individually through the following steps:

8.6.3.1 Measure compliance to estimate the original crack size, a_o, using unloading/reloading sequences in a force range from 0.5 to 1.0 times the maximum precracking force. Estimate a provisional initial crack size, a_{oq}, from at least three unloading/reloading sequences. No individual value shall differ from the mean by more than ±0.002 W.

8.6.3.2 Proceed with the test using unload/reload sequences that produce crack extension measurements at intervals prescribed by the applicable data analysis section of Annex A8 or Annex A10. Note that at least eight data points are required before specimen achieves maximum force. If fracture instability is an expected response, then it may be helpful to load the specimen monotonically over the range $P_m < P < P_Q$. (See Annex A5 for a definition of P_Q). If crack size values change negatively by more than 0.005 a_o(backup), stop the test and check the alignment of the loading train. Crack size values determined at forces lower than the maximum precracking force should be ignored.

8.6.3.3 For many materials, load relaxation may occur prior to conducting compliance measurements, causing a time-dependent nonlinearity in the unloading slope. One method that may be used to remedy this effect is to hold the specimen for a period of time until the force becomes stable at a constant displacement prior to initiating the unloading.

8.6.3.4 The maximum recommended range of unload/reload for crack extension measurement should not exceed either 50 % of P_m or 50 % of the current force, whichever is smaller.

8.6.3.5 After completing the final unloading cycle, return the force to zero without additional crosshead displacement beyond the then current maximum displacement.

8.6.3.6 After unloading the specimen, use the procedure in 8.5 to optically measure the crack sizes.

8.7 *Alternative Methods*:

8.7.1 Alternative methods of measuring crack extension, such as the electric potential drop method, are allowed. Methods shall meet the qualification criteria given in 9.1.5.2. If an alternative method is used to obtain J_{Ic}, at least one additional, confirmatory specimen shall be tested at the same test rate and under the same test conditions. From the alternative method the load line displacement corresponding to a ductile crack extension of 0.5 mm shall be estimated. The additional specimen shall then be loaded to this load line displacement level, marked, broken open and the ductile crack growth measured. The measured crack extension shall be 0.5 ± 0.25 mm in order for these results, and hence the J_{Ic} value, to be qualified according to this method.

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

9. Analysis of Results

9.1 *Qualification of Data*—The data shall meet the following requirements to be qualified according to this test method. If the data do not pass these requirements, no fracture toughness measures can be determined in accordance with this test method.

NOTE 3—This section contains the requirements for qualification that are common for all tests. Additional qualification requirements are given with each type of test in the Annexes as well as requirements for determining whether the fracture toughness parameter developed is insensitive to in-plane dimensions.

9.1.1 All requirements on the test equipment in Section 6 shall be met.

9.1.2 All requirements on machining tolerance and precracking in Section 7 shall be met.

9.1.3 All requirements on fixture alignment, test rate, and temperature stability and accuracy in Section 8 shall be met.

9.1.4 The following crack size requirements shall be met in all tests.

9.1.4.1 *Original Crack Size*—None of the nine physical measurements of initial crack size defined in 8.5.3 shall differ by more than 0.05B from the average a_o.

9.1.4.2 *Final Crack Size*—None of the nine physical measurements of final physical crack size, a_p, defined in 8.5.3 shall differ by more than 0.05B from the average a_p. In subsequent tests, the side-groove configuration may be modified within the requirements of 7.5 to facilitate meeting this requirement.

9.1.5 The following crack size requirements shall be met in the tests using the resistance curve procedure of 8.6.

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

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

9.2 *Fracture Instability*—When the test terminates with a fracture instability, evaluate whether the fracture occurred before stable tearing or after stable tearing. The beginning of stable tearing is defined in A6.3 and A7.3. For fracture instability occurring before stable tearing proceed to Annex A5, Annex A6, and Annex A7 to evaluate the toughness values in terms of K, J, or CTOD. For fracture instability occurring after stable tearing, proceed to Annex A5, Annex A6, and Annex A7 to evaluate toughness values and then go to 9.3 to evaluate stable tearing.

9.3 *Stable Tearing*:

9.3.1 *Basic Procedure*—When the basic procedure is used, only an initiation toughness can be evaluated. Proceed to Annex A9 and Annex A11 to evaluate initiation toughness values.

9.3.2 *Resistance Curve Procedure*—When the resistance curve procedure is used, refer to Annex A8 and Annex A10 to develop the R-curves. Proceed to Annex A9 and Annex A11 to develop initiation values of toughness.

10. Report

10.1 A recommended table for reporting results is given Fig. 8 and Fig. 9.

10.2 Report the following information for each fracture toughness 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), material product form (plate, forging, casting, and so forth), and material yield and tensile strength (at test temperatures),

10.2.3 Specimen dimensions (8.2.1), Thickness B and B_N, and Width W,

10.2.4 Test temperature (8.2.2), loading rate (8.4.2 and 8.6.2), and type of loading control,

10.2.5 Fatigue precracking conditions (7.4), K_{max}, ΔK range, and fatigue precrack size (average),

10.2.6 Load-displacement record and associated calculations (Section 9),

10.2.7 If the loading rate is other than quasi-static, report the applied dK/dt,

10.2.8 Original measured crack size, a_o (8.5), original predicted crack size, a_{oq}, final measured crack size, a_p, final predicted crack extension, $\Delta a_{predicted}$, physical crack extension during test, Δa_p, crack front appearance—straightness and planarity, and fracture appearance,

10.2.9 Qualification of fracture toughness measurement (Annex A4-Annex A7 and Annex A8-Annex A11), based on size requirements, and based on crack extension, and

10.2.10 Qualified values of fracture toughness, including R-curve values.

11. Precision and Bias

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

11.2 *Precision*—The precision of any of the various fracture toughness determinations cited in this test method is a function of the precision and bias of the various measurements of linear dimensions of the specimen and testing fixtures, the precision of the displacement measurement, the bias of the force measurement as well as the bias of the recording devices used to produce the force-displacement record, and the precision of the constructions made on this record. It is not possible to make meaningful statements concerning precision and bias for all these measurements. However, it is possible to derive useful information concerning the precision of fracture toughness measurements in a global sense from interlaboratory test programs. Most of the measures of fracture toughness that can be determined by this procedure have been evaluated by an interlaboratory test program. The K_{Ic} was evaluated in **(8)**, J_{Ic} was evaluated in **(9)**, the J-R curve was evaluated in **(10)**, and

Basic Test Information
Loading Rate, time to P_m = [min]
Test temperature = [°C]

Crack Size Information
Initial measured crack size, a_o = [mm]
Initial predicted crack size, a_{oq} = [mm]
Final measured crack size, a_f = [mm]
Final Δa_p = [mm]
Final $\Delta a_{predicted}$ = [mm]

Analysis of Results
Fracture type = (Fracture instability or stable tearing)

K Based Fracture
K_{Ic} = [MPa-m$^{1/2}$]
K_{JIc} = [MPa-m$^{1/2}$]

J Based Fracture
J_c = [kJ/m^2]
J_{Ic} = [kJ/m^2]
J_u = [kJ/m^2]

δ Based Results
δ_c^* = [mm]
δ_{Ic} = [mm]
δ_c = [mm]
δ_u = [mm]

Final $\Delta a/b$ =
Final J_{max}/σ_{YS} = [mm]

Specimen Information
Type =
Identification =
Orientation =

Basic dimensions
B = [mm]
B_N = [mm]
W = [mm]
a_N(Notch Length) = [mm]

Particular dimensions
C(T) H = [mm]
SE(B) S = [mm]
DC(T) D = [mm]

Material
Material designation =
Form =

Tensile Properties
E (Young's modulus) = [MPa]
ν (Poisson's ratio) =
σ_{YS} (Yield Strength) = [MPa]
σ_{TS} (Ultimate Strength) = [MPa]

Precracking Information
Final P_{max} = [N]
Final P_{min} = [N]
P_m = [N]
Final $\Delta K/E$ = [MPa-m$^{1/2}$]
Fatigue temperature = [°C]
Fatigue crack growth information

FIG. 8 Suggested Data Reporting Format

δ_c was evaluated in a research report.[4] In addition, the overall analysis procedures of this test method were evaluated in an interlaboratory test program.

12. Keywords

12.1 crack initiation; crack-tip opening displacement; CTOD; ductile fracture; elastic-plastic fracture toughness; fracture instability; J-integral; K_{Ic}; plane-strain fracture toughness; resistance curve; stable crack growth

[4] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR: E24-1013.

Test Information				Specimen ID:		Date	
Test Record Information			Operator:				
Event	P [N]	v [mm]	a [mm]	Δa [mm]	K [MPa-m$^{1/2}$]	J [kJ/m^2]	δ [mm]

FIG. 9 Suggested Data Reporting Format

ANNEXES

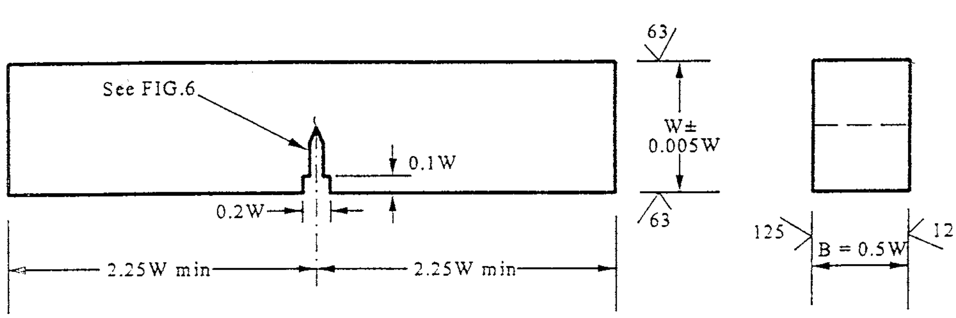
(Mandatory Information)

A1. SPECIAL REQUIREMENTS FOR TESTING SINGLE EDGE BEND SPECIMENS

NOTE A1.1—Annex A1-Annex A3 cover specimen information.

A1.1 Specimen

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



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

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

FIG. A1.1 Recommended Single Edge Bend [SE(B)] Specimen

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

A1.2 Apparatus

A1.2.1 For generally applicable specifications concerning the bend-test fixture and displacement gage see 6.5.1 and 6.2.

A1.3 *Specimen Preparation:*

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

A1.3.2 All specimens shall be precracked in three-point bending fatigue based upon the force P_m, as follows:

$$P_m = \frac{0.5Bb_o^2\sigma_Y}{S} \tag{A1.1}$$

See 7.4.5 for fatigue precracking requirements.

A1.4 Calculation

A1.4.1 *Calculation of K*—For the bend specimen at a force, $P_{(i)}$, calculate K as follows:

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

where:

$$f\left(\frac{a_i}{W}\right) = \tag{A1.3}$$

$$\frac{3\left(\frac{a_i}{W}\right)^{1/2}\left[1.99 - \left(\frac{a_i}{W}\right)\left(1 - \frac{a_i}{W}\right)\left(2.15 - 3.93\left(\frac{a_i}{W}\right) + 2.7\left(\frac{a_i}{W}\right)^2\right)\right]}{2\left(1 + 2\frac{a_i}{W}\right)\left(1 - \frac{a_i}{W}\right)^{3/2}}$$

A1.4.2 *Calculation of J:*

NOTE A1.2—In the calculation of J for the bend specimen a load-line displacement is required. For evaluating crack size, a crack mouth displacement is used.

For the single edge bend specimen, calculate J as follows:

$$J = J_{el} + J_{pl} \tag{A1.4}$$

where:

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

A1.4.2.1 *J Calculations for the Basic Test Method*—At a point corresponding to v and P on the specimen force versus displacement record, calculate the J integral as follows:

$$J = \frac{K^2(1 - \nu^2)}{E} + J_{pl} \tag{A1.5}$$

where K is from A1.4.1 with $a = a_o$, and

$$J_{pl} = \frac{\eta_{pl} A_{pl}}{B_N b_o} \tag{A1.6}$$

where:

A_{pl} = area under force versus displacement record as shown in Fig. A1.2,
η_{pl} = 1.9 if the load-line displacement is used for A_{pl},
= $3.667 - 2.199(a_o/W) + 0.437(a_o/W)^2$ if the crack mouth opening displacement record is used for A_{pl}, (11)
B_N = net specimen thickness ($B_N = B$ if no side grooves are present), and
b_o = $W - a_o$.

All basic test method J integral values shall be corrected for crack growth using the procedure of Annex A16.

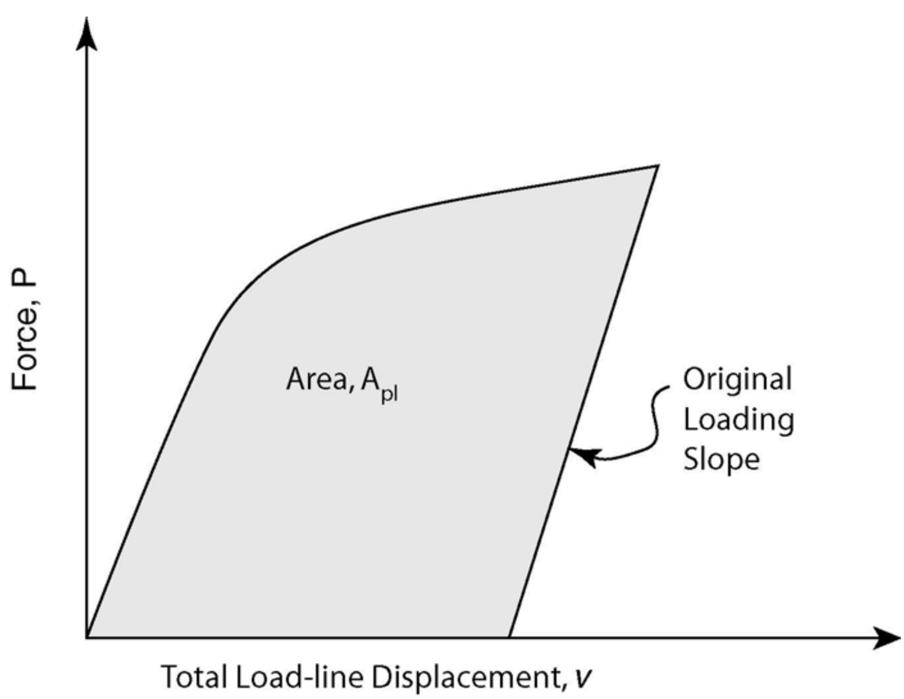


FIG. A1.2 Definition of Area for *J* Calculation Using the Basic Method

A1.4.2.2 *J Calculations for the Resistance Curve Test Method*—At a point corresponding to $a_{(i)}$, $v_{(i)}$, and $P_{(i)}$ on the specimen force versus load-line displacement record, calculate the J integral as follows:

$$J_{(i)} = \frac{(K_{(i)})^2 (1 - \nu^2)}{E} + J_{pl(i)} \quad (A1.7)$$

where $K_{(i)}$ is from A1.4.1, and

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{pl}}{b_{(i-1)}} \right) \left(\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N} \right) \right] \left[1 - \gamma_{pl} \frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}} \right] \quad (A1.8)$$

Where:
ηpl = 1.9 and
γpl = 0.9;

In Eq A1.8, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the force versus load-line displacement record between lines of constant displacement at points i−1 and i shown in Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic J at point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the Eq A1.8 relationship requires small and uniform crack growth increments consistent with the suggested elastic compliance spacing of Annex A8 and Annex A10. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + [P_{(i)} + P_{(i-1)}][v_{pl(i)} - v_{pl(i-1)}]/2 \quad (A1.9)$$

where:
$v_{pl(i)}$ = plastic part of the load-line displacement = $\nu_{(i)} - (P_{(i)} C_{LL(i)})$, and
$C_{LL(i)}$ = experimental compliance, $(\Delta v/\Delta P)_{(i)}$, corresponding to the current crack size, a_i.

For test methods that do not evaluate an experimental load-line elastic compliance, the load line displacement $C_{LL(i)}$ *can be determined from the following equation:*

$$C_{LL(i)} = \frac{1}{EB_e} \left(\frac{S}{W - a_i} \right)^2 \left[1.193 - 1.98 \left(\frac{a_i}{W} \right) + 4.478 \left(\frac{a_i}{W} \right)^2 - 4.443 \left(\frac{a_i}{W} \right)^3 + 1.739 \left(\frac{a_i}{W} \right)^4 \right] \quad (A1.10)$$

where:
$B_e = B - (B - B_N)^2/B$

The compliance estimated using Eq A1.10 should be verified by calibrating against the initial experimental load versus load line displacement data to assure the integrity of the load line displacement measurement system.

A1.4.2.3 *J Calculations for the Resistance Curve Test Method—Crack Mouth Opening Displacement*—At a point corresponding to a_i, $\nu_{(i)}$, and $P_{(i)}$ on the specimen force versus crack mouth opening displacement record calculate the J integral as follows:

$$J_{(i)} = \frac{(K_{(i)})^2 (1 - \nu^2)}{E} + J_{pl(i)} \quad (A1.11)$$

where $K_{(i)}$ is from A1.4.1, and

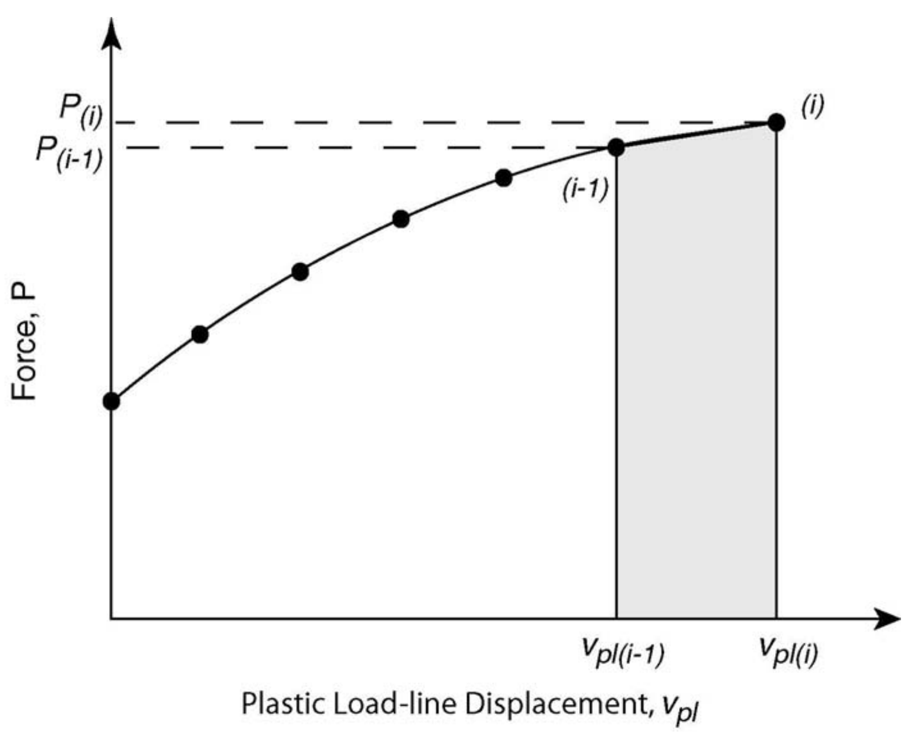


FIG. A1.3 Definition of Plastic Area for Resistance Curve *J* Calculation

$$J_{pl} = \frac{\eta_{pl(i)} A_{pl(i)}}{B_N b_i} \quad (A1.12)$$

where:

A_{pl} = area under load versus crack mouth opening displacement record to $\nu_{(i)}$ as shown in Fig. A1.2,
$\eta_{pl(i)}$ = $3.667 - 2.199(a_i/W) + 0.437(a_i/W)^2$(**11**), and
b_i = $W - a_i$.

J integral values calculated according to Eq A1.11 and A1.12 shall be corrected for crack growth using the procedure of Annex A16.

A1.4.3 *Calculation of Crack Size*—For a resistance curve test method using an elastic compliance technique on single edge bend specimens with crack opening displacements measured at the notched edge, the crack size is given as follows:

$$\frac{a_i}{W} = [0.999748 - 3.9504u + 2.9821u^2 - 3.21408u^3 + 51.51564u^4 - 113.031u^5] \quad (A1.13)$$

where:

$$u = \frac{1}{\left[\frac{B_e W E C_i}{S/4}\right]^{1/2} + 1} \quad (A1.14)$$

C_i = $(\Delta v_m/\Delta P)$ on an unloading/reloading sequence,
v_m = crack opening displacement at notched edge,
B_e = $B - (B - B_N)^2/B$.

NOTE A1.3—Crack size on a single edge bend specimen is normally determined from crack opening compliance. It can be determined from load-line compliance if the correct calibration is available.

A1.4.4 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

A1.4.5 *Calculation of CTOD*:

A1.4.5.1 *Calculation of CTOD for the Basic Test Method*—For the basic test method, calculations of CTOD for any point on the force-displacement curve are made from the following expression:

$$\delta = \frac{J}{m\sigma_Y} \quad (A1.15)$$

where: J is defined in A1.4.2.1 with $a = a_o$, the original crack size, and then crack growth corrected using Annex A16 and:

$$m = A_0 - A_1^* \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right) + A_2^* \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^2 - A_3^* \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^3 \quad (A1.16)$$

with :
$A_0 = 3.18\text{-}0.22 * (a_o/W)$,
$A_1 = 4.32\text{-}2.23 * (a_o/W)$,
$A_2 = 4.44\text{-}2.29 * (a_o/W)$, and
$A_3 = 2.05\text{-}1.06 * (a_o/W)$.

Calculation of δ requires $\sigma_{YS}/\sigma_{TS} \geq 0.5$.

A1.4.5.2 *Calculations of CTOD for the Resistance Curve Test Method*—For the resistance curve test method, calculations of CTOD for any point on the force-displacement curve are made from the following expression:

$$\delta_i = \frac{J_i}{m_i \sigma_Y} \quad (A1.17)$$

where J_i is defined in A1.4.2.2 or A1.4.2.3 with $a = a_i$, the current crack size and:

$$m = A_0 - A_1^* \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right) + A_2^* \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^2 - A_3^* \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^3 \quad (A1.18)$$

with :
$A_0 = 3.18\text{-}0.22 * (a_i/W)$,
$A_1 = 4.32\text{-}2.23 * (a_i/W)$,
$A_2 = 4.44\text{-}2.29 * (a_i/W)$, and
$A_3 = 2.05\text{-}1.06 * (a_i/W)$.

Calculation of δ_i requires $\sigma_{YS}/\sigma_{TS} \geq 0.5$.

A2. SPECIAL REQUIREMENTS FOR TESTING COMPACT SPECIMENS

A2.1 Specimen

A2.1.1 The standard compact specimen, *C(T)*, is a single edge-notched and fatigue cracked plate loaded in tension. Two specimen geometries which have been used successfully for *J* testing are shown in Fig. A2.1.

A2.1.2 The compact specimen in Fig. A2.2 has generally been used only for K_{Ic} testing; it has no provision for load-line displacement measurement. Do not use this specimen for ductile fracture toughness measurement. Use it only when K_{Ic} behavior is expected.

A2.1.3 Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions.

A2.2 Apparatus

A2.2.1 For generally applicable specifications concerning the loading clevis and displacement gage, see 6.5.2 and 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 precracked in fatigue at a force value based upon the force P_m as follows:

$$P_m = \frac{0.4 B b_o^2 \sigma_Y}{(2W + a_o)} \quad (A2.1)$$

See Section 7 for fatigue precracking requirements.

A2.4 Calculation

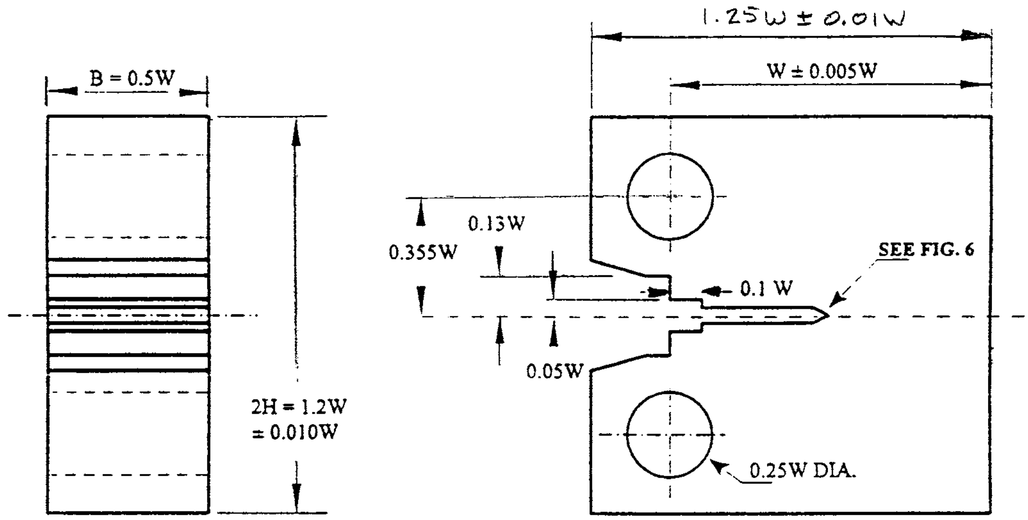
A2.4.1 *Calculation of K*—For the compact specimen at a force $P_{(i)}$, calculate *K* as follows:

$$K_{(i)} = \frac{P_i}{(B B_N W)^{1/2}} f\left(\frac{a_i}{W}\right) \quad (A2.2)$$

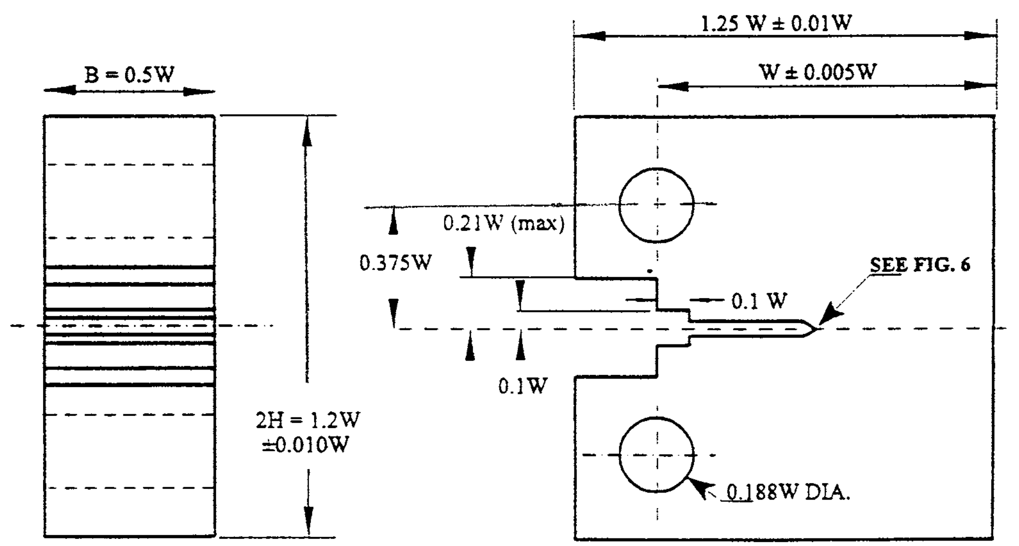
with:

$$f\left(\frac{a_i}{W}\right) = \quad (A2.3)$$

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



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



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

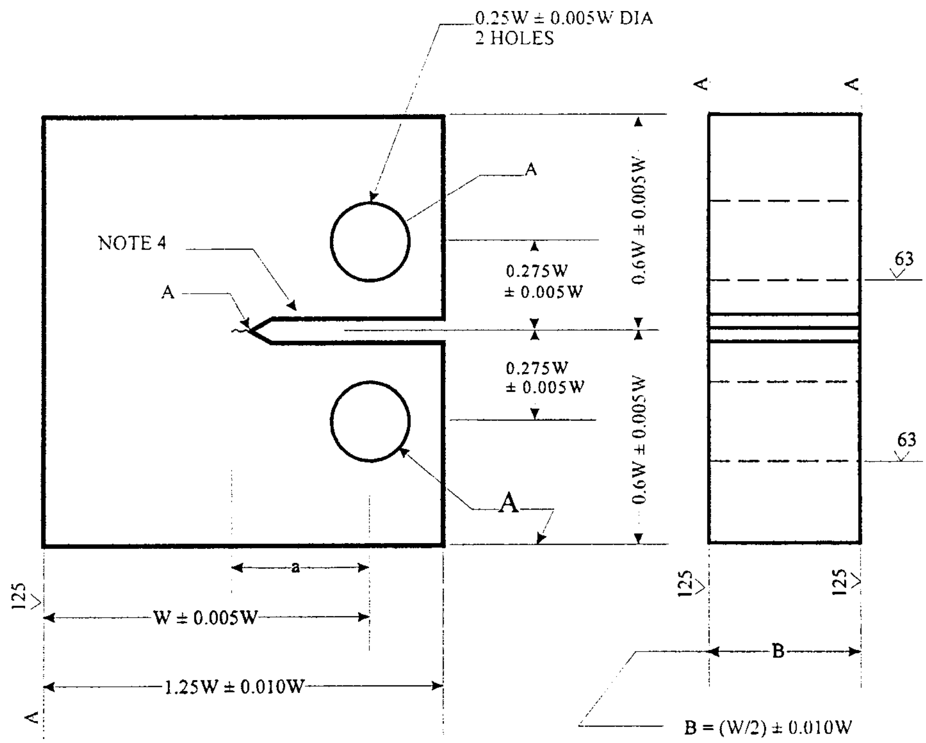
FIG. A2.1 Two Compact Specimen Designs That Have Been Used Successfully for Fracture Toughness Testing

A2.4.2 *Calculation of J*—For the compact specimen calculate J as follows:

$$J = J_{el} + J_{pl} \quad (A2.4)$$

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

The load line compliance estimated using Eq A1.10 should be verified by calibrating against the initial experimental compliance to assure the integrity of the load line displacement measurement system.



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

NOTE 2—The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen within 0.005 W.

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

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

FIG. A2.2 Compact Specimen for K_{Ic} Testing

A2.4.2.1 *J Calculations for the Basic Test Method*—For the compact specimen at a point corresponding to v, P on the specimen force versus load-line displacement record calculate as follows:

$$J = \frac{K^2(1 - \nu^2)}{E} + J_{pl} \tag{A2.5}$$

where:
K is from A2.4.1 with $a = a_o$, and

$$J_{pl} = \frac{\eta A_{pl}}{B_N b_o} \tag{A2.6}$$

where:
A_{pl} = Area A as shown in Fig. A1.2,
B_N = net specimen thickness ($B_N = B$ if no side grooves are present),
b_o = uncracked ligament, ($W - a_o$), and
η = $2 + 0.522 b_o/W$.

All basic test method J integral values shall be corrected for crack growth using the procedure of Annex A16.

A2.4.2.2 *J Calculation for the Resistance Curve Test Method*—For the C(T)specimen at a point corresponding $a_{(i)}$, $v_{(i)}$, and $P_{(i)}$ on the specimen force versus load-line displacement record calculate as follows:

$$J_{(i)} = \frac{(K_{(i)})^2 (1 - \nu^2)}{E} + J_{pl(i)} \tag{A2.7}$$

where $K_{(i)}$ is from A2.4.1, and:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{(i-1)}}{b_{(i-1)}}\right) \frac{A_{pl(i)} - A_{pl(i-1)}}{B_N} \right] \left[1 - \gamma_{(i-1)} \frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}} \right] \tag{A2.8}$$

where:
$\eta_{(i-1)}$ = $2.0 + 0.522\, b_{(i-1)}/W$, and
$\gamma_{(i-1)}$ = $1.0 + 0.76\, b_{(i-1)}/W$.

In Eq A2.8, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the force versus plastic load-line displacement record between lines of constant displacement at points $i-1$ and i shown in Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic J at point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the above relationship requires small and uniform crack growth increments consistent with the suggested elastic compliance spacing of Annex A8 and Annex A10. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + \frac{[P_{(i)} + P_{(i-1)}]\,[v_{pl(i)} - v_{pl(i-1)}]}{2} \tag{A2.9}$$

where:

$v_{pl(i)}$ = plastic part of the load-line displacement, $v_i - (P_{(i)}C_{LL(i)})$, and

$C_{LL(i)}$ = experimental compliance, $(\Delta v/\Delta P)_i$ corresponding to the current crack size, a_i.

For test methods that do not evaluate an experimental elastic compliance, $C_{LL(i)}$ can be determined from the following equation:

$$C_{LL(i)} = \frac{1}{EB_e}\left(\frac{W + a_i}{W - a_i}\right)^2 [2.1630 + 12.219\left(\frac{a_i}{W}\right) - 20.065\left(\frac{a_i}{W}\right)^2 - 0.9925\left(\frac{a_i}{W}\right)^3 + 20.609\left(\frac{a_i}{W}\right)^4 - 9.9314\left(\frac{a_i}{W}\right)^5] \quad \text{(A2.10)}$$

where:

$$B_e = B - \frac{(B - B_N)^2}{B} \quad \text{(A2.11)}$$

In an elastic compliance test, the rotation corrected compliance, $C_c(i)$, described in A2.4.4 shall be used instead of $C_{LL\ (i)}$ in Eq A2.10.

A2.4.3 *Calculation of Crack Size*—For a single specimen test method using an elastic compliance technique on the compact specimen with crack opening displacements measured on the load line, the crack size is given as follows:

$$a_i/W = [1.000196 - 4.06319u + 11.242u^2 - 106.043u^3 + 464.335u^4 - 650.677u^5] \quad \text{(A2.12)}$$

where:

$$u = \frac{1}{[B_eEC_{c(i)}]^{1/2} + 1} \quad \text{(A2.13)}$$

$C_{c(i)}$ = specimen load-line crack opening elastic compliance $(\Delta v/\Delta\ P)$ on an unloading/reloading sequence corrected for rotation (see A2.4.4),

B_e = $B - (B - B_N)^2/B$.

A2.4.4 To account for crack opening displacement in *C(T)* specimens, the crack size estimation shall be corrected for rotation. Compliance is corrected as follows:

$$C_{c(i)} = \frac{C_i}{\left[\frac{H^*}{R}\sin\theta_i - \cos\theta_i\right]\left[\frac{D}{R}\sin\theta_i - \cos\theta_i\right]} \quad \text{(A2.14)}$$

where (Fig. A2.3):

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

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

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

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

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

$$\theta = \sin^{-1}\left[\frac{\left(\frac{d_m}{2} + D\right)}{(D^2 + R^2)^{1/2}}\right] - \tan^{-1}\left(\frac{D}{R}\right), \text{ and} \quad \text{(A2.15)}$$

d_m = total measured load-line displacement.

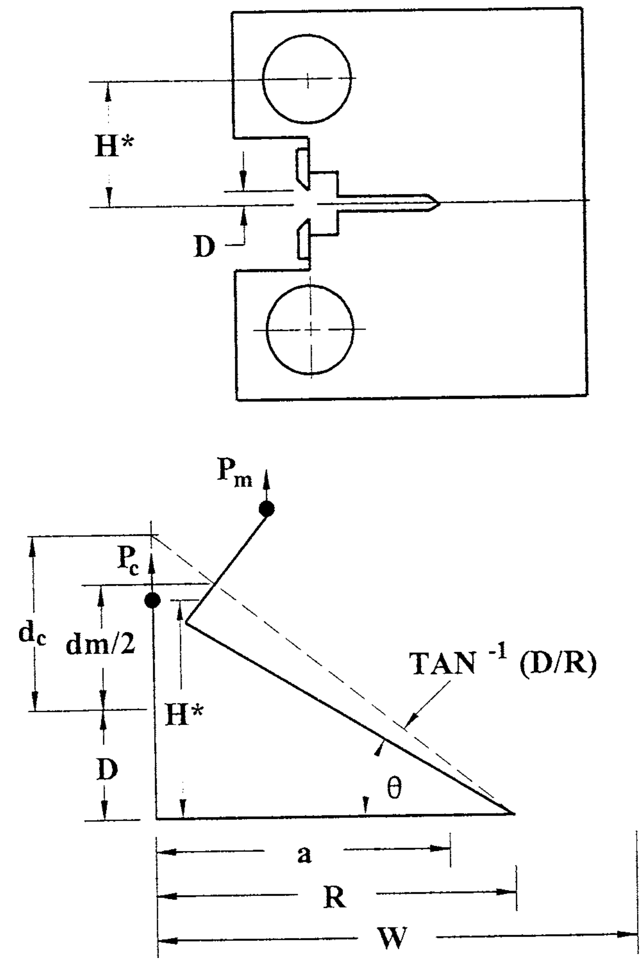


FIG. A2.3 Elastic Compliance Correction for Specimen Rotation

A2.4.5 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

A2.4.6 *Calculation of CTOD*:

A2.4.6.1 *Calculation of CTOD for the Basic Test Method*—For the basic test method, calculations of CTOD for any point on the force-displacement curve are made from the following expression:

$$\delta = \frac{J}{m\sigma_Y} \quad \text{(A2.16)}$$

Where J is defined in A2.4.2.1 with $a = a_o$, the original crack size and then crack growth corrected using Annex A16 and:

$$m = A_0 - A_1{*}\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right) + A_2{*}\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^2 - A_3{*}\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^3 \quad \text{(A2.17)}$$

with: A_0=3.62, A_1= 4.21, A_2=4.33, and A_3=2.00. Calculation of δ requires $\sigma_{YS}/\sigma_{TS} \geq 0.5$.

A2.4.6.2 *Calculation of CTOD for the Resistance Curve Test Method*—For the resistance curve test method, calculations of CTOD for any point on the force-displacement curve are made from the following expression:

$$\delta_i = \frac{J_i}{m\sigma_Y} \quad \text{(A2.18)}$$

Where J is defined in A2.4.2.2 with $a = a_i$, the current crack size and,

$$m = A_0 – A_1 * \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right) + A_2 * \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^2 – A_3 * \left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^3 \quad \text{(A2.19)}$$

with: A_0=3.62, A_1= 4.21, A_2=4.33, and A_3=2.00. Calculation of δ_i requires $\sigma_{YS}/\sigma_{TS} \geq 0.5$.

A3. SPECIAL REQUIREMENTS FOR TESTING DISK-SHAPED COMPACT SPECIMENS

A3.1 Specimen

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

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

A3.2 Apparatus

A3.2.1 For generally applicable specifications concerning the loading clevis and displacement gage see 6.5.2 and 6.2.

A3.3 Specimen Preparation

A3.3.1 For generally applicable specifications concerning specimen size and preparation, see Section 7.

A3.3.2 All specimens shall be precracked in fatigue at a force value based upon the force P_m as follows:

$$P_m = \frac{0.4Bb_o^2\sigma_Y}{(2W + a_o)} \quad \text{(A3.1)}$$

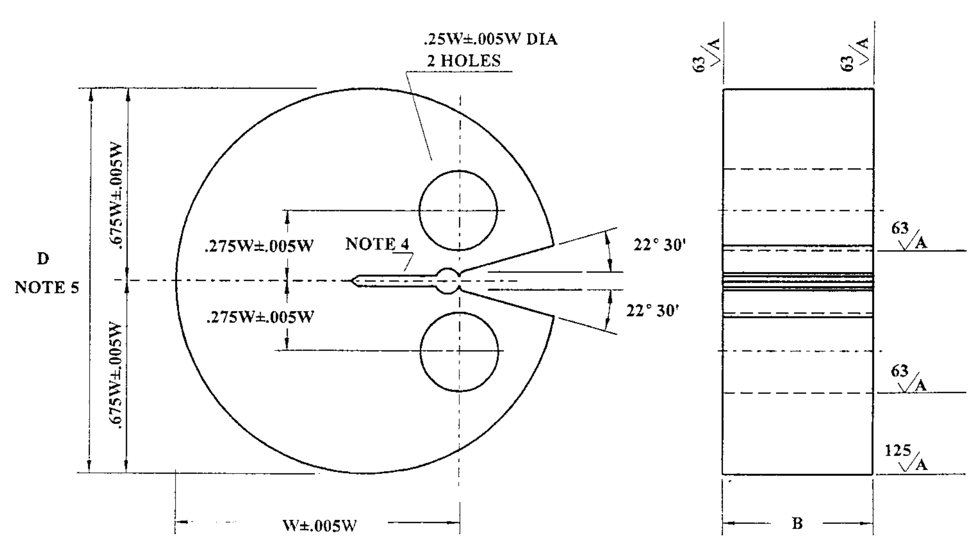
See section 7.4 for precracking requirements.

A3.4 Procedure

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

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

A3.4.1.2 Measure the width, W, and the crack size, a, from the plane of the centerline of the loading holes (the notched edge is a convenient reference line but the distance from the centerline of the holes to the notched edge must be subtracted to determine W and a). Measure the width, W, to the nearest 0.05 mm (0.002 in.) or 0.5 %, whichever is larger.



NOTE 1—All surfaces shall be perpendicular and parallel as applicable within 0.002 W TIR.

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

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

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

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

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

A3.5 Calculation

A3.5.1 *Calculation of K*—For the DC(T) specimen at a force $P_{(i)}$, calculate K as follows:

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

where:

$$f\left(\frac{a_i}{W}\right) = \frac{\left[\left(2+\frac{a_i}{W}\right)\left(0.76+4.8\left(\frac{a_i}{W}\right)-11.58\left(\frac{a_i}{W}\right)^2+11.43\left(\frac{a_i}{W}\right)^3-4.08\left(\frac{a_i}{W}\right)^4\right)\right]}{\left(1-\frac{a_i}{W}\right)^{3/2}} \tag{A3.3}$$

A3.5.2 *Calculation of J*—For the DC(T) specimen, calculate J as follows:

$$J = J_{el} + J_{pl} \tag{A3.4}$$

where:

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

A3.5.2.1 *J Calculation for the Basic Test Method*—For the DC(T) specimen at a point corresponding to $\nu_{(i)}$, $P_{(i)}$ on the specimen force versus load-line displacement record calculate as follows:

$$J = \frac{K^2(1-\nu^2)}{E} + J_{pl} \tag{A3.5}$$

where K is from A3.5.1 with $a = a_o$, and

$$J_{pl} = \frac{\eta A_{pl}}{B_N b_o} \tag{A3.6}$$

where:

A_{pl} = Area A as shown in Fig. A1.2,
B_N = net specimen thickness ($B_N = B$ if no side grooves are present),
b_o = uncracked ligament, ($W - a_o$), and
η = $2 + 0.522 b_o/W$.

All basic test method J integral values shall be corrected for crack growth using the procedure of Annex A16.

A3.5.2.2 *J Calculation for the Resistance Curve Test Method*—For the DC(T) specimen at a point corresponding to a_i, v_i, and P_i on the specimen force versus load-line displacement record, calculate as follows:

$$J_{(i)} = \frac{(K_{(i)})^2(1-\nu^2)}{E} + J_{pl(i)} \tag{A3.7}$$

where $K_{(i)}$ is from A3.5.1 and:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{(i-1)}}{b_{(i-1)}}\right)\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right]\left[1 - \gamma_{(i-1)}\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right] \tag{A3.8}$$

where:

$\eta_{(i-1)}$ = $2.0 + 0.522\, b_{(i-1)}/W$, and
$\gamma_{(i-1)}$ = $1.0 + 0.76\, b_{(i-1)}/W$.

In the preceding equation, the quantity $A_{pl(i)} - A_{pl(i-1)}$ is the increment of plastic area under the force versus load-line displacement record between lines of constant displacement at points i–1 and i shown in Fig. A1.3. The quantity $J_{pl(i)}$ represents the total crack growth corrected plastic J at Point i and is obtained in two steps by first incrementing the existing $J_{pl(i-1)}$ and then by modifying the total accumulated result to account for the crack growth increment. Accurate evaluation of $J_{pl(i)}$ from the preceding relationship requires small and uniform crack growth increments consistent with the suggested elastic compliance spacing of Annex A8 and Annex A10. The quantity $A_{pl(i)}$ can be calculated from the following equation:

$$A_{pl(i)} = A_{pl(i-1)} + \frac{[P_{(i)} + P_{(i-1)}][\nu_{pl(i)} - \nu_{pl(i-1)}]}{2} \tag{A3.9}$$

where:

$\nu_{pl(i)}$ = plastic part of the load-line displacement, $\nu_i - (P_i C_{LL(i)})$, and
$C_{LL(i)}$ = experimental compliance, $(\Delta\nu/\Delta P)_i$ corresponding to the current crack size, a_i.

For test methods that do not evaluate an experimental elastic compliance, $C_{LL(i)}$ can be determined from the following equation:

$$C_{LL(i)} = \frac{1}{EB_e}\left(\frac{1+\frac{a_{(i)}}{W}}{1-\frac{a_{(i)}}{W}}\right)^2 \times \left[2.0462 + 9.6496\left(\frac{a_{(i)}}{W}\right) - 13.7346\left(\frac{a_{(i)}}{W}\right)^2 + 6.1748\left(\frac{a_{(i)}}{W}\right)^3\right] \tag{A3.10}$$

where:

B_e = $B - (B - B_N)^2/B$.

The compliance estimated using Eq A1.10 should be verified by calibrating against the initial experimental compliance to assure the integrity of the load line displacement measurement system.

In an elastic compliance test, the rotation corrected compliance, $C_c(i)$, described in A3.5.4 shall be used instead of $C_{LL(i)}$ given above.

A3.5.3 *Calculation of Crack Size*—For a single-specimen test method using an elastic compliance technique on DC(T) specimens with crack opening displacements measured at the load-line, the crack size is given as follows:

$$\frac{a_{(i)}}{W} = 0.998193 - 3.88087u + 0.187106u^2 + 20.3714u^3 - 45.2125u^4 + 44.5270u^5 \tag{A3.11}$$

where:

$$u = \frac{1}{[(B_e E C_{c(i)})^{1/2} + 1]} \tag{A3.12}$$

where:

$C_{c(i)}$ = specimen crack opening compliance ($\Delta v/\Delta P$) on an unloading/reloading sequence, corrected for rotation (see A3.5.4),
B_e = $B - (B - B_N)^2/B$.

A3.5.4 To account for crack opening displacement in DC(T) specimens, the crack size estimation shall be corrected for rotation. Compliance shall be corrected as follows:

$$C_{c(i)} = \frac{C_i}{\left[\frac{H^*}{R}\sin\theta_i - \cos\theta_i\right]\left[\frac{D}{R}\sin\theta_i - \cos\theta_i\right]} \tag{A3.13}$$

where (Fig. A2.3):

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

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

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

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

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

$$\theta = \sin^{-1}\left[\frac{\left(\frac{d_m}{2} + D\right)}{(D^2 + R^2)^{1/2}}\right] - \tan^{-1}\left(\frac{D}{R}\right), \text{ and} \quad (A3.14)$$

d_m = total measured load-line displacement.

A3.5.5 Other compliance equations are acceptable if the resulting accuracy is equal to or greater than those described and the accuracy has been verified experimentally.

A3.5.6 *Calculation of CTOD*:

A3.5.6.1 *Calculation of CTOD for the Basic Test Method*—For the basic test method calculations of CTOD for any point on the force-displacement curve are made from the following expression:

$$\delta = \frac{J}{m\sigma_Y} \quad (A3.15)$$

where J is defined in A3.5.2.1 with a = a_o, the original crack size and then crack growth corrected using Annex A16 and:

$$m = A_0 - A_1^*\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right) + A_2^*\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^2 - A_3^*\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^3 \quad (A3.16)$$

with: A_0=3.62, A_1= 4.21, A=4.33, and A_3=2.00. Calculation of δ requires $\sigma_{YS}/\sigma_{TS} \geq 0.5$.

A3.5.6.2 *Calculation of CTOD for the Resistance Curve Test Method*—For the resistance curve test method, calculations of CTOD for any point on the force-displacement curve are made from the following expression:

$$\delta = \frac{J_i}{m\sigma_Y} \quad (A3.17)$$

where J is defined in A3.5.2.2 with a = a_i, the current crack size and,

$$m = A_0 - A_1^*\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right) + A_2^*\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^2 - A_3^*\left(\frac{\sigma_{YS}}{\sigma_{TS}}\right)^3 \quad (A3.18)$$

with: A_0=3.62, A_1= 4.21, A_2=4.33, and A_3=2.00. Calculation of δ requires $\sigma_{YS}/\sigma_{TS} \geq 0.5$.

A4. METHODS FOR EVALUATING INSTABILITY AND POP-IN

A4.1 *Assessment of Force/Clip Gage Displacement Records*—The applied force-displacement record obtained from a fracture test on a notched specimen will usually be one of the four types shown in Fig. A4.1.

A4.1.1 In the case of a smooth continuous record in which the applied force rises with increasing displacement up to the onset of unstable brittle crack extension or pop-in, and where no significant slow stable crack growth has occurred (see 3.2 and Fig. A4.1a and Fig. A4.1b), the critical CTOD, δ_c shall be determined from the force and plastic component of clip gage displacement, ν_p, corresponding to the points P_c and ν_c. If failure occurs close to the linear range, apply the procedure of Annex A5 to test whether a valid K_{Ic} measurement can be made.

A4.1.2 In the event that significant slow stable crack extension precedes either unstable brittle crack extension or pop-in, or a maximum force plateau occurs, the force-displacement curves will be of the types shown in Fig. A4.1c, Fig. A4.1d, respectively. These figures illustrate the values of P and ν to be used in the calculation of δ_u.

A4.1.3 If the pop-in is attributed to an arrested unstable brittle crack extension in the plane of the fatigue precrack, the result must be considered as a characteristic of the material tested.

NOTE A4.1—Splits and delaminations can result in pop-ins with no arrested brittle crack extension in the plane of the fatigue precrack.

For this test method, pop-in crack extension in the plane of the fatigue precrack can be assessed by a specific change in compliance. The following procedure may be used to assess the significance of small pop-ins (see Fig. A4.1b and Fig. A4.1d). Referring to Fig. A4.1 and Fig. A4.2, measure the values of P_c and ν_c or P_u and ν_u from the test record at points corresponding to: *(a)* the earliest significant pop-in fracture, that is, for which $F > 0.05$ and *(b)* fracture, when pop-ins prior to fracture may be ignored, that is, for which $F < 0.05$ as follows:

$$F = 1 - \frac{\nu_1}{P_1} \cdot \left(\frac{P_n - y_n}{\nu_n + x_n}\right) \quad (A4.1)$$

where:

F = factor representing the accumulated increase in compliance and crack size due to all stable crack extensions, or pop-ins, or both, prior to and including the nth pop-in, and

n = sequential number (see Fig. A4.2) of the last of the particular series of pop-ins being assessed.

NOTE A4.2—When only one pop-in occurs, n = 1. When multiple pop-ins occur it may be necessary to make successive assessments of F with n = 1, 2, 3, or more.

ν_1 = elastic displacement at pop-in No. 1 (see Fig. A4.2),

P_n = force at the nth pop-in, and

ν_n = elastic displacement at the nth pop-in.

NOTE A4.3—ν_n may be determined graphically or analytically (see Fig. A4.2).

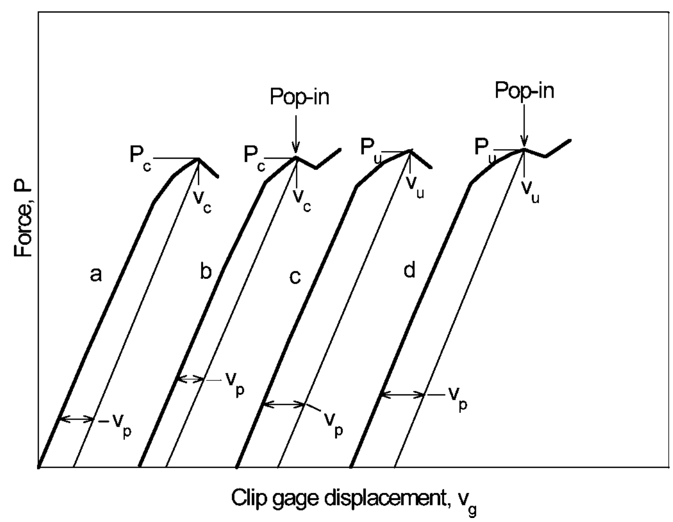
y_n = force drop at the nth pop-in, and

x_n = displacement increase at the nth pop-in

NOTE A4.4—Although an individual pop-in may be ignored on the basis of these criteria, this does not necessarily mean that the lower bound of fracture toughness has been measured. For instance, in an inhomogeneous material such as a weld, a small pop-in may be recorded because of fortuitous positioning of the fatigue precrack tip. Thus, a slightly different fatigue precrack position may give a larger pop-in, which could not be ignored. In such circumstances the specimens should be sectioned after testing, and examined metallographically to ensure that the crack tips have sampled the weld or base metal region of interest (26).

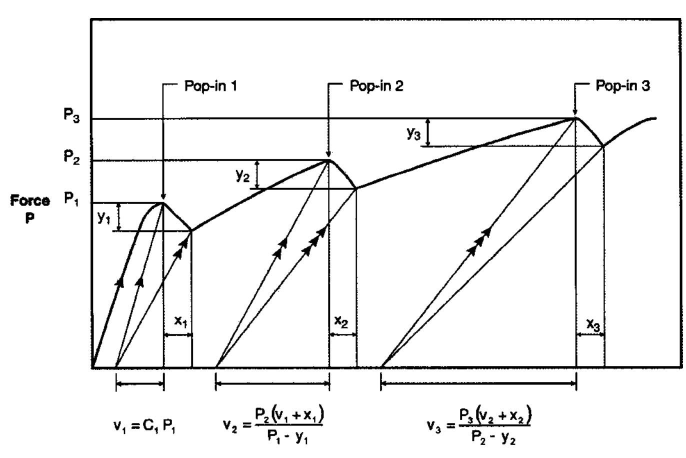
A4.1.4 The initial compliance C_1 shall be determined by constructing the tangent OA to the initial portion of the force-clip gage displacement curve as shown in Fig. A4.3. The initial compliance C_1 is the inverse of the slope of the tangent line OA:

$$C_1 = \frac{\Delta v_g}{\Delta P} \tag{A4.2}$$



NOTE 1—Construction lines drawn parallel to the elastic loading slope to give v_p, the plastic component of total displacement, v_g.
NOTE 2—In curves b and d, the behavior after pop-in is a function of machine/specimen compliance, instrument response, etc.

FIG. A4.1 Types of Force versus Clip Gage Displacement Records



NOTE 1—C_1 is the initial compliance.
NOTE 2—The pop-ins have been exaggerated for clarity.

FIG. A4.2 Significance of Pop-In

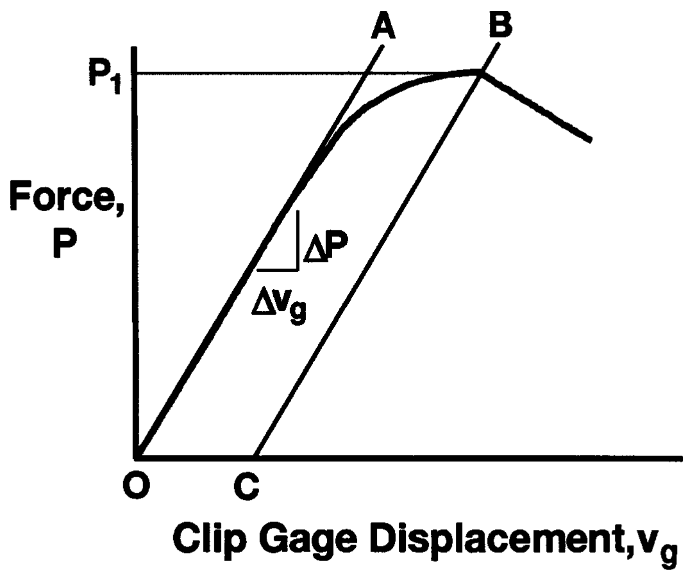


FIG. A4.3 Determination of Initial Compliance

A5. METHOD FOR K_{Ic} DETERMINATION

A5.1 This annex describes the methods and calculations required to determine the linear elastic, plane-strain fracture toughness, K_{Ic}, and the associated requirements for qualifying the data according to this test method. Data meeting all of the qualification requirements of 9.1 and those of this annex result in a size-insensitive K_{Ic} value.

A5.2 *Test Record*—Conduct the test following the procedure in Section 8, recording a force versus crack mouth opening displacement as shown in Fig. A5.1. Digital data is recommended.

A5.3 *Calculation of Results*—In order to determine K_{Ic} in accordance with this test method, it is necessary first to calculate a conditional result, K_Q, which involves a construction on the test record, and then to determine whether this result is consistent with size and yield strength requirements. The procedure is as follows:

A5.3.1 Construct a secant line as shown on Fig. A5.1 with a slope $(P/v)_5 = 0.95(P/v)_o$ where $(P/v)_o$ is the slope of the

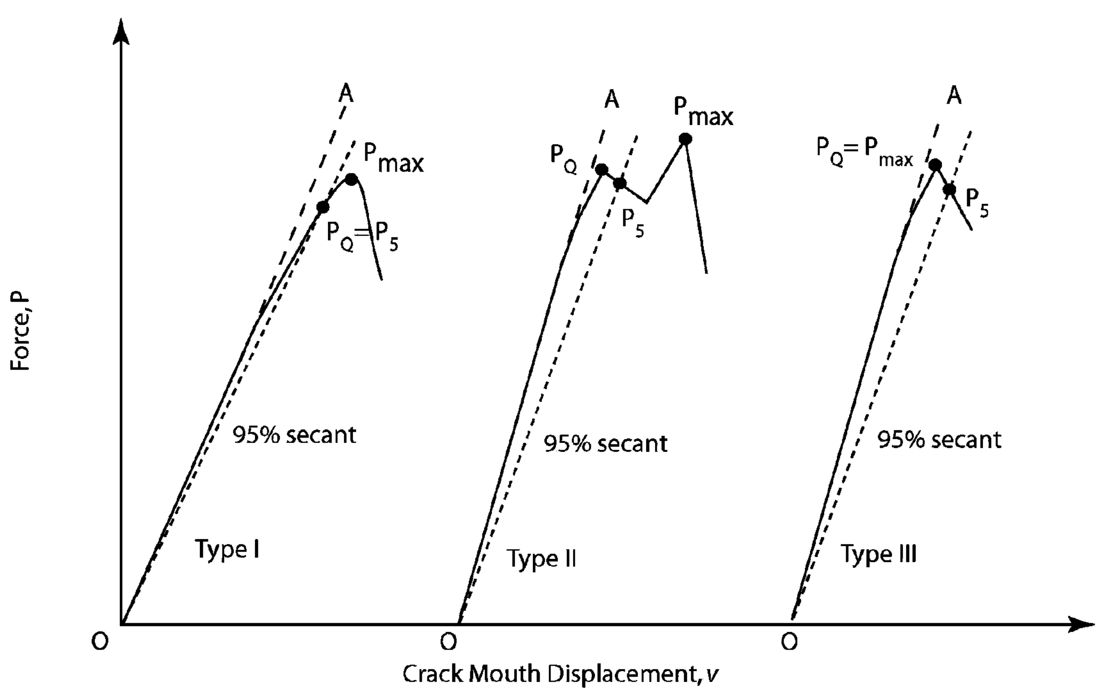


FIG. A5.1 Principal Types of Force-Displacement Records tangent *OA* to the initial portion of the data record. This slope can be obtained from a slope calculation using digital data or fit to an autographic record as desired.

NOTE A5.1—Slight nonlinearity often occurs at the very beginning of a record and should be ignored. However, it is important to establish the initial slope of the record with high precision and therefore it is advisable to minimize this nonlinearity by a preliminary loading and unloading with the maximum force not producing a stress intensity level exceeding that used in the final stage of fatigue cracking.

The force P_Q is then defined as follows: if the force at every point on the record that precedes P_5 is lower than P_5, then P_5 is P_Q (Fig. A5.1, Type I); if, however, there is a maximum force preceding P_5 that exceeds it, then this maximum force is P_Q (Fig. A5.1, Types II and III).

NOTE A5.2—For the Annex A1-Annex A3 specimens over the range $0.45 \leq a/W \leq 0.55$, the 95 % offset criterion corresponds to an increase in elastic compliance equivalent to that caused by a crack extension of approximately 2 % of the original remaining ligament, b_o or the original crack size, a_o.

A5.3.2 Calculate K_Q using the appropriate expression from A12.1.1 with $P = P_Q$.

A5.4 *Qualification of K_Q as K_{Ic}:*

A5.4.1 For K_Q to be qualified as a K_{Ic} value according to this method it must meet the qualification requirements of 9.1 and the following requirements:

A5.4.2 Calculate the ratio P_{max}/P_Q, where P_{max} is the maximum force the specimen was able to sustain (see Fig. A5.1). The ratio P_{max}/P_Q must be ≤ 1.10 in order for K_Q to be equal to K_{Ic}. The use of side grooved specimens is recommended to keep $P_{max}/P_Q \leq 1.10$.

A5.4.3 Calculate $2.5\,(K_Q/\sigma_{YS})^2$ where σ_{YS} is the 0.2 % offset yield strength in tension (see Test Methods E 8). This quantity must be less than the length of the initial uncracked ligament, b_o, in order for K_Q to be equal to K_{Ic}. Otherwise, the test is not a qualified K_{Ic} test according to this standard.

A5.4.4 If the test result fails to meet the qualification requirements in 9.1 or in A5.4, or both, it will be necessary to use a larger specimen to determine K_{Ic}. The dimensions of the larger specimen can be estimated on the basis of K_Q but generally will be at least 1.5 times those of the specimen that failed to yield a K_{Ic} value qualified according to this method. A test result that fails to meet the qualification requirements in A5.4 generally corresponds to a specimen size that is to small for the 95 % secant method to correspond to the point on the force versus crack opening displacement record adequately close to the onset of crack extension. In this instance a fracture toughness measurement cannot be based on force and crack size measurements alone. The unqualified K_{Ic} test specimen record can be evaluated by the methods of Annex A4-Annex A7 and Annex A8-Annex A11 to determine whether other measures of fracture toughness can be developed from this test. The normalization method of Annex A15 might also be useful to obtain other fracture toughness measures from this test.

A5.5 *Significance of K_{Ic}*—The property K_{Ic} determined by this test method characterizes the resistance of a material to fracture in a neutral environment in the presence of a sharp crack under severe tensile constraint, such that the state of stress near the crack front approaches plane-strain, and the crack-tip plastic region is small compared to both the crack size and thickness.

A5.5.1 Variation in the value of K_{Ic} can be expected within the allowable range of specimen proportions, *a/W* and *W/B*. K_{Ic} may also be expected to rise with increasing ligament size. Notwithstanding these variations, however, K_{Ic} is believed to represent a lower limiting value of fracture toughness (for 2 % apparent crack extension) in the environment and at the speed and temperature of the test.

A5.5.2 Lower values of K_{Ic} can be obtained for materials that fail by cleavage fracture; for example, ferritic steels in the ductile-to-brittle transition region or below, where the crack front length affects the measurement in a stochastic manner independent of crack front constraint. The present test method does not apply to such materials and the user is referred to Test Method E 1921 and **(25)** for applicable guidance. Likewise, K_{Ic}, as a measure of fracture toughness does not apply to high toughness or high tearing resistance materials whose failure is accompanied by appreciable amounts of plasticity. Procedures for characterizing the fracture toughness of elastic-plastic materials are given in Annex A6-Annex A11.

A6. FRACTURE INSTABILITY TOUGHNESS DETERMINATION USING *J*

A6.1 This annex describes the method for characterizing fracture toughness values based on *J*, J_c, or J_u, for a fracture instability and the associated requirements for qualifying the data according to this test method. Data meeting all of the qualification requirements of 9.1 and those of this annex result in qualified values of J_c or J_u. Data meeting the size requirement result in a value of J_c that is insensitive to the in-plane dimensions of the specimen.

A6.2 *Fracture Instability Before Stable Tearing*—When fracture occurs before stable tearing a single-point toughness value may be obtained labeled J_c.

A6.2.1 *J* is calculated at the final point, instability, using the *J* formulas for the basic method including the crack growth correction in Annex A16. This point is labeled J_{Qc}, a provisional J_c value.

A6.2.2 *Qualification of J_{Qc} as J_c*—$J_{Qc} = J_c$, a measure of fracture toughness at instability without significant stable crack extension that is independent of in-plane dimensions, provided the following two conditions are both met: (*1*) $B,\ b_o \geq 100\ J_Q/\sigma_Y$, and (*2*) crack extension $\Delta a_p < 0.2\ \text{mm} + J_Q/M\sigma_Y$ where

$M = 2$, or an alternative value can be determined from the test data, see A9.8. Note that even if these conditions are met, J_c may be dependent on thickness (length of crack front).

A6.3 *Fracture Instability After Stable Tearing*—When fracture occurs after stable tearing crack extension Δa_p >0.2 mm (0.008 in.) + $J_{Qc}/M\sigma_Y$, a single-point fracture toughness value may be obtained, labeled J_{Qu}. In addition, part of an *R*-curve may be developed or the final point may be used in the evaluation of an initiation toughness value J_{Ic} (these are described in Annex A8-Annex A11).

A6.3.1 *J* is calculated at the final point where instability occurs using the *J* formulas for the basic method including the crack growth correction of Annex A16. This point is a J_u value.

A6.3.2 *Qualification of* J_{Qu} *as* J_u—$J_{Qu} = J_u$ if crack extension $\Delta a_p \geq 0.2$ mm (0.008 in.) + $J_Q/M\sigma_Y$.

A6.4 *Significance of* J_c *and* J_u—Values of J_{Qc} that meet the size criteria are labeled J_c and are considered to be insensitive to the in-plane dimensions of the specimen. For ferritic steel specimens that have failed unstably by cleavage in the ductile to brittle transition, the analysis procedure of Test Method E 1921 is recommended. Values of J_{Qc} that do not meet validity remain J_{Qc} and may be size-dependent. J_u is not considered to be a size-insensitive property and therefore is not subject to a size criterion. It is a characteristic of the material and specimen geometry and size. It signifies that at the test temperature the material is not completely ductile and can sustain only limited *R*-curve behavior.

A7. FRACTURE INSTABILITY TOUGHNESS DETERMINATION USING CTOD (δ)

A7.1 This annex describes the method for characterizing fracture toughness values based on δ, δ_c, or δ_u for a fracture instability and the associated requirements for qualifying the data according to this test method. Data meeting all of the qualification requirements of 9.1 and those in this annex result in qualified values of δ_c or δ_u. Data meeting the size requirement result in a value of δ_c^* that is insensitive to in-plane dimensions of the specimen.

A7.2 *Fracture Instability Before Stable Tearing*—When fracture occurs before stable tearing a single-point toughness value may be obtained labeled δ_c, the force P_c and the clip gage displacement υ_c, for δ_c are indicated in Fig. 1.

A7.2.1 δ is calculated at the final point, instability, using the δ formulas from Annex A1-Annex A3. This point is labeled δ_{Qc}, a provisional δ_c value.

A7.2.2 *Qualification of* δ_{Qc} *as* δ_c^*—A fracture toughness value that is insensitive to the in-plane dimensions of the specimen, if the following two conditions are met: (*1*) $\delta_{Qc} = \delta_c^*$ if $B, b_o \geq 300\ \delta_{Qc}$, and (*2*) crack extension $\Delta a_p < 0.2$ mm (0.008 in.) + δ_{Qc}/M_δ where $M_\delta = 1.4$ or an alternative value determined from the test data, see A11.3. Data that fail to meet the size criterion based on *B* or b_o, but still meet the restriction on crack extension, are labeled δ_c.

A7.3 *Fracture Instability After Stable Tearing*—When fracture occurs after stable tearing, crack extension $\Delta a_p \geq 0.2$ mm (0.008 in.) + δ_{Qc}/M_δ, where $M_\delta = 1.4$ or an alternative value determined from the test data, see A11.3, a single-point fracture toughness value may be obtained, labeled δ_u. In addition, part of an *R* curve may be developed or the final point may be used in the evaluation of an initiation toughness value (these are described in Annex A8-Annex A11).

A7.3.1 δ is calculated at the final point where instability occurs, using the δ formulas for the basic method. This point is labeled δ_{Qu}, a provisional δ_u value.

A7.3.2 *Qualification of* δ_{Qu} *as* δ_u—$\delta_{Qu} = \delta_u$, if crack extension, $\Delta a_p > 0.2$ mm (0.008 in.) + δ_{Qu}/M_δ where $M_\delta = 1.4$ or an alternative value can be determined from the test data, see A11.3.

A7.3.3 *Significance of* δ_c *and* δ_u—Values of δ_{Qc} that meet the qualification requirements are labeled δ_c^* and are considered to be insensitive to the in-plane dimensions of the specimen. Values of δ_{Qc} that do not meet the size requirement are labeled δ_c and may be size-dependent. δ_u is not considered to be a size-insensitive property and, therefore, is not subject to a size criterion. It is a characteristic of the material and specimen geometry and size. It signifies that at the test temperature the material is not completely ductile and can sustain only limited *R*-curve behavior.

A8. *J-R* CURVE DETERMINATION

NOTE A8.1—Annex A8-Annex A11 cover methods for evaluating toughness for stable tearing.

A8.1 This method describes a single-specimen technique for determining the *J-R* curve of metallic materials. The *J-R* curve consists of a plot of *J* versus crack extension in the region of *J* controlled growth. The *J-R* curve is qualified provided that the criteria of 9.1 and A8.3 are satisfied.

A8.2 *J Calculation:*

A8.2.1 *J* can be calculated at any point on the force versus load-line displacement record using the equations suggested in the calculation section of Annex A1-Annex A3 for the different specimen geometries.

A8.2.2 If the basic method is used, *J* values must be crack growth corrected using the procedure of Annex A16. In this case crack size values are obtained from direct optical measurements from the specimen fracture surfaces using the procedure of 8.5.

A8.2.3 If a resistance curve method is used, the values of crack size are calculated using the compliance equations described in Annex A1-Annex A3 (or an alternative method for measuring crack size). The rotation correction shall be applied to account for geometry changes due to deformation for the compact, C(T) and disk-shaped compact DC(T) specimens.

A8.2.4 If an elastic compliance method is used, the unload/reload sequences should be spaced with the displacement interval not to exceed $0.01W$, the average being about $0.005W$. If an initiation value of toughness is being evaluated more unload/reload sequences may be necessary in the early region of the *J-R* curve.

A8.3 *Measurement Capacity of Specimen:*

A8.3.1 The maximum *J*-integral capacity for a specimen is given by the smaller of the following:

$$J_{max} = b_o \sigma_Y / 10, \text{ or}$$

$$J_{max} = B \sigma_Y / 10.$$

A8.3.2 The maximum crack extension capacity for a specimen is given by the following:

$$\Delta a_{max} = 0.25\, b_o$$

A8.4 *Constructing the J-R Curve:*

A8.4.1 The *J*-integral values and the corresponding crack extension values must be plotted as shown in Fig. A8.1. If an elastic compliance method is used, shift the *J-R* curve according to the procedure described in A9.3. The *J-R* curve is defined as the data in a region bounded by the coordinate axes and the J_{max} and Δa_{max} limits given in A8.3.1 and A8.3.2.

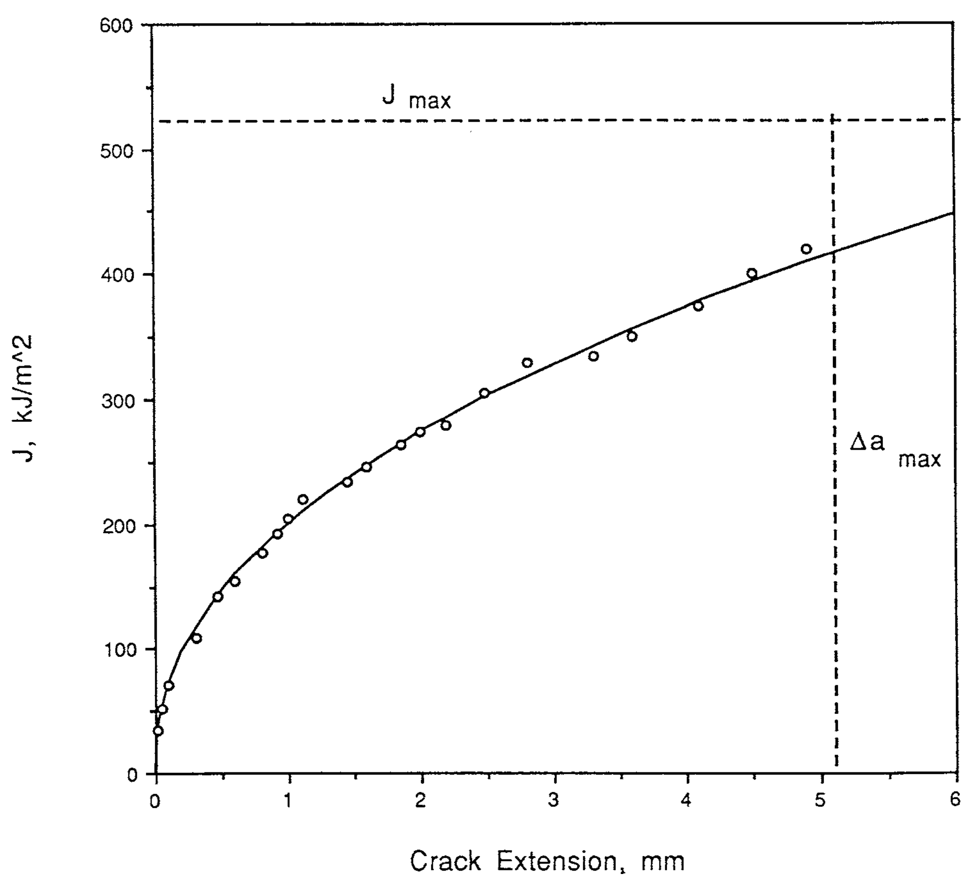


FIG. A8.1 Typical *J-R* Curve

A9. J_{Ic} and K_{JIc} EVALUATION

A9.1 *Significance*—The property J_{Ic} determined by this method characterizes the toughness of a material near the onset of crack extension from a preexisting fatigue crack. The J_{Ic} value marks the beginning stage of material crack growth resistance development, the full extent of which is covered in Annex A8. J_{Ic} is qualified provided that the criteria of 9.1 and A9.8 and A9.9 are satisfied.

A9.2 *J Calculation*—Calculations of the *J* integral are made using the equations in Annex A1-Annex A3.

A9.3 *Corrections and Adjustments to Data:*

A9.3.1 If the basic method is used, calculate crack growth corrected J values using the procedure of Annex A16.

A9.3.2 If an elastic compliance method is used, a correction is applied to the estimated Δa_i data values to obtain an improved a_{oq}. This correction is intended to obtain the best value of a_{oq}, based on the initial set of crack size estimates, a_i, data. For data generated using the basic procedure of 8.4, no adjustments to the crack size and crack extension data are necessary. To evaluate J_{Ic} using data from the basic procedure, proceed to A9.6.

A9.3.3 A modified construction line slope, M, can be calculated from a fit to the initial J_i and a_i data, and used for the calculation of J_{Ic}.

A9.3.4 *Adjustment of* a_{oq}—The value of J_Q is very dependent on the a_{oq} used to calculate the Δa_i quantities. The value obtained for a_{oq} in A9.3.4.1 might not be the correct value and the following adjustment procedure is required.

A9.3.4.1 Identify all J_i and a_i pairs that were determined before the specimen reached the maximum force for the test. Use this data set of points to calculate a revised a_{oq} from the following equation:

$$a = a_{oq} + \frac{J}{2\sigma_Y} + BJ^2 + CJ^3 \quad \text{(A9.1)}$$

The coefficients of this equation shall be found using a least squares fit procedure, see Appendix X1.

A9.3.4.2 If the number of points used in A9.3.4.1 to determine a_{oq} is less than 8 or of these 8 there are less than 3 between 0.4 J_Q and J_Q or the correlation coefficient of this fit is less than 0.96, the data set is not adequate to evaluate any toughness measures in accordance with this test method.

A9.4 If the optically measured crack size, a_o, differs from a_{oq} by more than 0.01W, the data set is not adequate according to this test method.

A9.5 Evaluate the final J_i values using the adjusted a_{oq} of A9.3.4 and the equations of the applicable Annex A1, Annex A2, or Annex A3.

A9.6 *Calculation of an Interim* J_Q:

A9.6.1 *Basic Procedure*—For each specimen, calculate Δa as follows:

$$\Delta a = a_p - a_o \quad \text{(A9.2)}$$

Resistance Curve Procedure—For each a_i value, calculate a corresponding Δa_i as follows:

$$\Delta a_i = a_i - a_{0q} \quad \text{(A9.3)}$$

Plot J versus Δa as shown in Fig. A9.1. Determine a construction line in accordance with the following equation:

$$J = M\sigma_Y\Delta a \quad \text{(A9.4)}$$

where M = 2 or M can be determined from the test data. In some cases the initial slope of the J-R curve is steeper than $2\sigma_Y$, for example with austenitic stainless steels. For these materials, it is recommended that a J_Q value be determined using M = 2 such that an experimental M can then be evaluated and verified according to A9.7. An improved J_Q can then be evaluated. Under no circumstances can a value of M less than 2 be used for J_Q evaluation.

A9.6.2 Plot the construction line, then draw an exclusion line parallel to the construction line intersecting the abscissa at 0.15 mm (0.006 in.). Draw a second exclusion line parallel to the construction line intersecting the abscissa at 1.5 mm (0.06 in.). Plot all $J - \Delta a$ data points that fall inside the area enclosed by these two parallel lines and capped by $J_{limit} = b_o\sigma_Y / 7.5$.

A9.6.3 Plot a line parallel to the construction and exclusion lines at an offset value of 0.2 mm (0.008 in.).

A9.6.4 At least one J–Δa point shall lie between the 0.15-mm (0.006-in.) exclusion line and a parallel line with an offset of 0.5 mm (0.02 in.) from the construction line as shown in Fig. A9.2. At least one $J-\Delta a$ point shall lie between this 0.5-mm offset line and the 1.5-mm (0.06-in.) exclusion line. Acceptable data are shown in Fig. A9.2. The other $J-\Delta a$ pairs can be anywhere inside the exclusion zone.

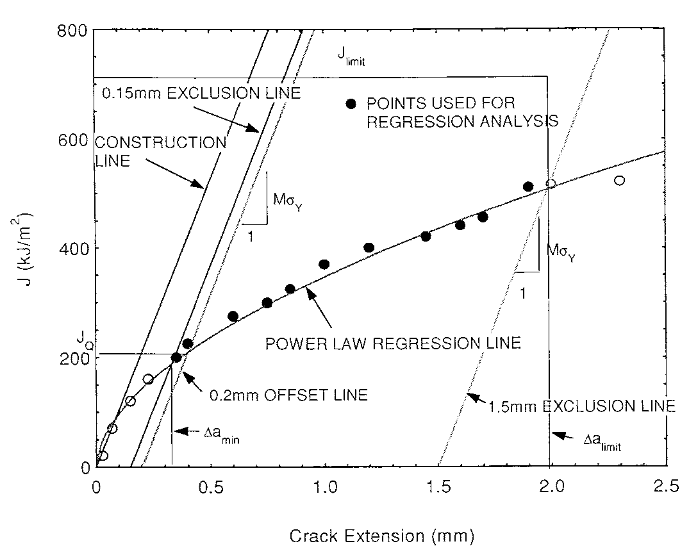


FIG. A9.1 Definition of Construction Lines for Data Qualification

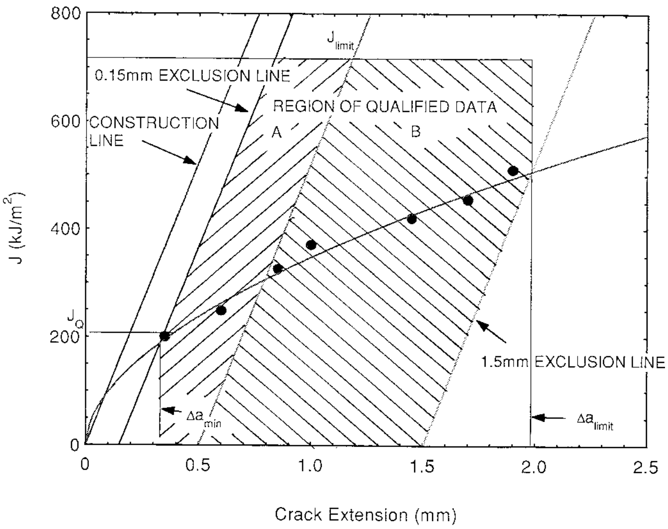


FIG. A9.2 Definition of Regions for Data Qualification

A9.6.5 Using the method of least squares, determine a linear regression line of the following form:

$$\ln J = \ln C_1 + C_2 \ln\left(\frac{\Delta a}{k}\right) \quad \text{(A9.5)}$$

where k = 1.0 mm or 0.0394 in. Use only the data which conform to the requirements stated in the previous sections. Draw the regression line as illustrated in Fig. A9.1.

A9.6.6 The intersection of the regression line of A9.6.5 with the 0.2-mm offset line defines J_Q and Δa_Q. To determine this intersection the following procedure is recommended.

A9.6.6.1 As a starting point estimate an interim $J_{Q(1)} = J_{Q(i)}$ value from the data plot of Fig. A9.1.

A9.6.6.2 Evaluate $\Delta a_{(i)}$ from the following:

$$\Delta a_{(i)} = \frac{J_{Q(i)}}{M\sigma_Y} + 0.2 \text{ mm } (0.008 \text{ in.}) \quad \text{(A9.6)}$$

A9.6.6.3 Evaluate an interim $J_{Q(i+1)}$ from the following power law relationship:

$$J_{Q(i+1)} = C_1 \left(\frac{\Delta a_{(i)}}{k}\right)^{C_2} \quad \text{(A9.7)}$$

where k = 1.0 mm or 0.0394 in.

A9.6.6.4 Increment i and return to A9.6.6.2 and A9.6.6.3 to get $\Delta a_{(i)}$ and interim $J_{Q(i+1)}$ until the interim J_Q values converge to within ±2 %.

A9.6.6.5 Project the intercepts of the power law curve with the 0.15-mm (0.006-in.) and the 1.5-mm (0.06-in.) exclusion lines vertically down to the abscissa. This indicates Δa_{min} and Δa_{limit}, respectively. Eliminate all data points that do not fall between Δa_{min} and Δa_{limit} as shown in Fig. A9.1. Also eliminate all data points which lie above the limiting J capacity where $J_{limit} = b_o\sigma_Y / 7.5$. The region of qualified data is shown in Fig. A9.2.

A9.6.6.6 At least five data points must remain between Δa_{min} and Δa_{limit} and J_{limit}. Data point spacing must meet the requirements of A9.6.4. If these data points are different from those used in A9.6.6 to evaluate J_Q, obtain a new value of J_Q based only on qualified data.

A9.7 An alternative construction line slope, M, can be calculated by fitting the least squares linear regression line to the initial J-R curve data for data in the region $0.2\ J_Q \leq J_i \leq 0.6 J_Q$ as evaluated with $M = 2$. A minimum of 6 data points are required in the evaluation region to allow an experimental value of M. Only values of $M \geq 2$ are allowed by this method. A revised J_Q can now be evaluated using this M by returning to A9.6.1-A9.6.6.

A9.8 *Qualification of Data*—The data shall satisfy the requirements of 9.1 and all of the following requirements to be qualified according to this test method. If the data do not pass these requirements no fracture toughness values can be determined according to this test method.

A9.8.1 The power coefficient C_2 of A9.6.5 shall be less than 1.0.

A9.8.2 For the *Resistance Curve Procedure* the following additional requirements must be satisfied:

A9.8.2.1 If an elastic compliance method is used, a_{oq} shall not differ from a_o by more than the larger of $0.01W$ or 0.5 mm.

A9.8.2.2 The number of data available to calculate a_{oq} shall be ≥8; the number of data between $0.4J_Q$ and J_Q shall be ≥ 3; and the correlation coefficient of the least squares fit of A9.3.4.1 shall be greater than 0.96.

A9.8.2.3 If an experimental value of M is determined, at least 6 data points are required in the region $0.2J_Q \leq J_i \leq 0.6J_Q$. Only $M \geq 2.0$ can be used in the method.

A9.9 *Qualification of J_Q as J_{Ic}*—$J_Q = J_{Ic}$, a size-independent value of fracture toughness, if:

A9.9.1 Thickness $B > 10\ J_Q / \sigma_Y$,

A9.9.2 Initial ligament, $b_o > 10\ J_Q / \sigma_Y$,

A9.9.3 *Regression Line Slope*—The slope of the power law regression line, dJ/da, evaluated at Δa_Q is less than σ_Y.

A9.10 *Evaluation of K_{JIc}*—Calculate $K_{JIc} = \sqrt{(E' J_{Ic})}$ using $E' = E/(1-\nu^2)$ and the qualified J_{Ic} of A9.9.

A10. METHOD FOR δ-*R* CURVE DETERMINATION

A10.1 This annex describes a single-specimen technique for determining the δ-*R* curve of metallic materials. The δ-*R* curve consists of a plot of δ versus crack extension. To measure the δ-*R* curve the resistance curve procedure of 8.6 must be used. The δ-*R* curve is qualified provided that the criteria of 9.1 and A10.3 are satisfied.

A10.2 δ *Calculation:*

A10.2.1 The δ calculation can be evaluated at any point along the force versus load-line displacement record using the equations suggested in the calculation section of Annex A1-Annex A3 for the different specimen geometries.

A10.2.2 The values of crack size are calculated using the compliance equations described in Annex A1-Annex A3. The rotation correction shall be applied to account for geometry changes due to deformation for the compact, C(T) and disk-shaped compact DC(T) specimens.

A10.2.3 The unload/reload sequences should be spaced with the displacement interval less than 0.01 *W*, the average being about 0.005 *W*. If an initiation value of toughness is being evaluated more unload/reload sequences may be necessary in the early region of the δ-*R* Curve.

A10.3 *Measurement Capacity of a Specimen:*

A10.3.1 The maximum δ capacity for a specimen is given as follows:

$$\delta_{max} = b_o / 10m$$

Where *m* is defined in Annex A1 through Annex A3 for the different specimen geometries.

A10.3.2 The maximum crack extension capacity for a specimen is given as follows:

$$\Delta a_{max} = 0.25\, b_o.$$

A10.4 *Constructing the δ-R Curve:*

A10.4.1 The δ values and the corresponding crack extension values must be plotted as shown in Fig. A10.1. A δ-*R* curve is established by smoothly fitting the data points in the region bounded by the coordinate axes and the δ_{max} and Δa_{max} limits.

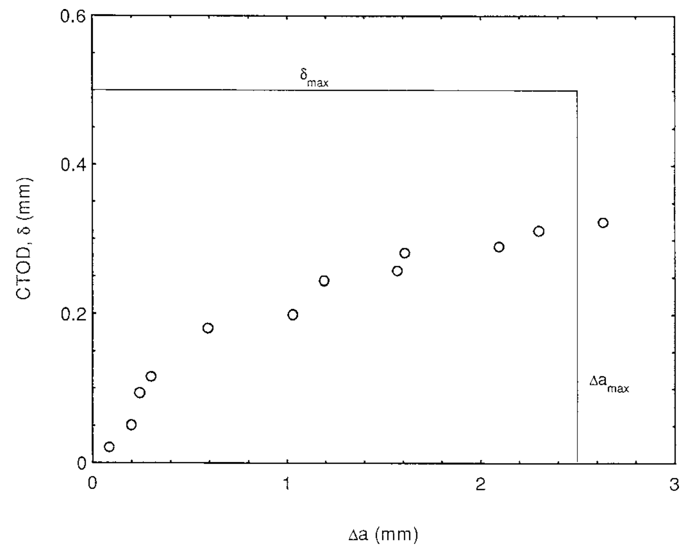


FIG. A10.1 Typical δ-*R* Curve

A11. METHOD FOR δ_{Ic} DETERMINATION

A11.1 *Significance*—The value of CTOD, δ_{Ic}, determined by this method characterizes the fracture toughness of materials near the onset of stable crack extension from a preexisting fatigue crack. δ_{Ic} is qualified provided that the criteria of 9.1 and A11.8 and A11.9 are satisfied.

A11.2 δ *Calculation*—Calculations of δ are made using the equations in Annex A1-Annex A3.

A11.3 *Corrections and Adjustments to Data:*

A11.3.1 A correction is applied to the estimated a_i data values to obtain an improved a_{oq}. This correction is intended to obtain the best value of a_{oq}, based on the initial set of crack size estimates, a_i, data. For data generated using the basic procedure of 8.4, no adjustments to the data are necessary. To evaluate δ_{Ic} using data from the basic procedure, proceed to A11.7.

A11.3.2 A modified construction line slope, M_δ, can be calculated from a fit to the initial δ_i and a_i data, and used for the calculation of δ_{Ic}.

A11.3.3 *Adjustment of* a_{oq}—The value of δ_Q is very dependent on the a_{oq} used to calculate the Δa_i quantities. The value obtained for a_{oq} in 8.6.3.1 might not be the correct value, and the following adjustment procedure is required.

A11.3.3.1 Identify all δ_i and a_i pairs that were determined before the specimen reached the maximum force for the test. Use this data set of points to calculate a revised a_{oq} from the following equation:

$$a = a_{oq} + \frac{\delta}{1.4} + B\delta^2 + C\delta^3 \qquad \text{(A11.1)}$$

The coefficients of this equation shall be found using a least squares fit procedure, see Appendix X1.

A11.3.3.2 If the number of points used in A11.3.3.1 to calculate a_{oq} is less than 8, or of these 8 there are less than 3 between $0.4\delta_Q$ and δ_Q, or the correlation coefficient of this fit is < 0.96, the data set is not adequate to evaluate any toughness measures in accordance with this method.

A11.4 If the optically measured crack size, a_o, differs from a_{oq} by more than 0.01 W, the data set is not adequate in accordance with this method.

A11.5 Evaluate the final δ_i values using the adjusted a_{oq} of A11.3.3.1 and the equations of the applicable Annex A1, Annex A2, or Annex A3.

A11.6 *Calculation of an Interim* δ_Q*:*

A11.6.1 *Basic Procedure*—for each specimen, calculate Δa as follows:

$$\Delta a = a_p - a_o \qquad \text{(A11.2)}$$

Resistance Curve Procedure—for each a_i value, calculate a corresponding Δa_i as follows:

$$\Delta a_i = a_i - a_{0q} \qquad \text{(A11.3)}$$

Plot δ versus Δa as shown in Fig. A11.1. Draw a construction line in accordance with the following equation:

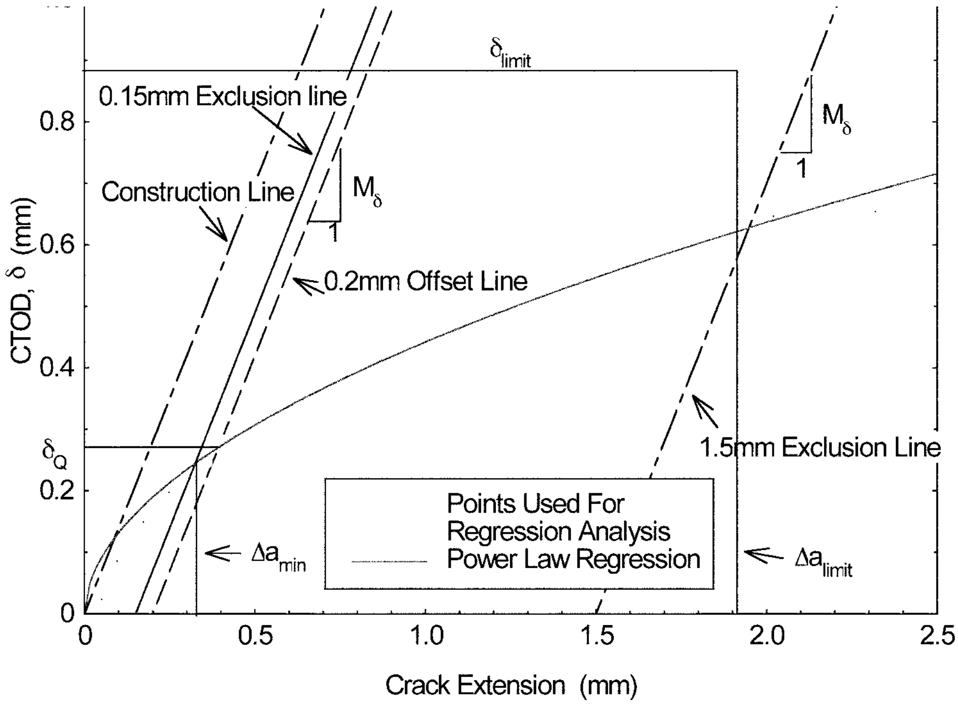


FIG. A11.1 Definition of Construction Lines for Data Qualification

$$\delta = M_\delta \, \Delta a \tag{A11.4}$$

where M_δ = 1.4 or M_δ can be determined from the test data. In some cases the initial slope of the δ-*R* curve is steeper than 1.4. For these materials it is recommended that a δ_Q value be determined using M_δ = 1.4 such that an experimental M_δ can then be evaluated and verified according to A11.7. An improved δ_Q can then be evaluated. Under no circumstances can a value of M_δ less than 1.4 be used for δ_Q evaluation.

A11.6.2 Plot the construction line on suitable graph paper. Draw an exclusion line parallel to the construction line intersecting the abscissa at 0.15 mm (0.006 in.) as shown in Fig. A11.1. Draw a second exclusion line intersecting the abscissa at 1.5-mm (0.06-in.). Plot all δ-Δa_p data points that fall inside the area enclosed by these two parallel lines and capped by $\delta_{limit} = b_o / 7.5m$ where, *m* is defined in Annex A1 through Annex A3 for the different specimen geometries.

A11.6.3 One δ-Δa_p point must lie between the 0.15-mm (0.006-in.) exclusion line and a parallel line with an offset of 0.5 mm (0.02 in.) from the construction line. One δ-Δa_p point must lie between a line parallel to the construction line at an offset of 0.5 mm (0.020 in.) and the 1.5-mm exclusion line. Acceptable data is shown in Fig. A11.2 with one point in Zone A and one point in Zone B. The other δ-Δa_p pairs can be placed anywhere inside the exclusion zone.

A11.6.4 Plot a line parallel to the construction line and exclusion lines at an offset value of 0.2 mm (0.008 in.).

A11.6.5 To establish a crack initiation measurement point under dominant slow-stable crack growth, a power law curve fitting procedure shall be used. This has the following form:

$$\delta_Q = C_1 \left(\frac{\Delta a}{k}\right)^{C_2} \tag{A11.5}$$

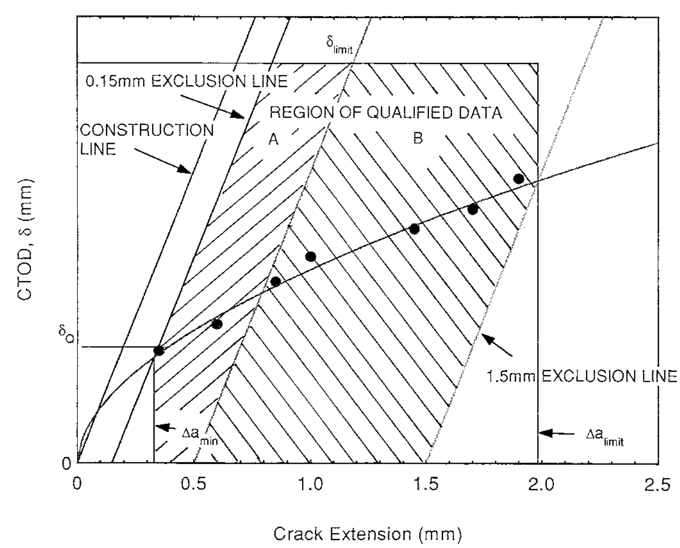


FIG. A11.2 Definition of Regions for Data Qualification

where *k* = 1 mm (or 0.0394 in.) depending upon units used. This power law can be determined by using a method of least squares to determine a linear regression line of the following form:

$$\ln\delta = \ln C_1 + C_2 \ln\left(\frac{\Delta a}{k}\right) \tag{A11.6}$$

Use only the data that conform to the criteria stated in the previous sections. Plot the regression line as illustrated in Fig. A11.1.

A11.6.6 The intersection of the regression line of A11.6.4 with the offset line of A11.6.5 defines δ_Q and Δa_Q. To determine this intersection the following procedure is recommended:

A11.6.6.1 Estimate a $\delta_{Q(1)}$ value from the data plot of Fig. A11.1.

A11.6.6.2 Evaluate $\Delta a_{p(1)}$ from the following:

$$\Delta a_{p(1)} = \frac{\delta_{Q(1)}}{M_\delta} + 0.2 \text{ mm (0.008 in.)} \quad (A11.7)$$

A11.6.6.3 Evaluate

$$\delta_{Q(1)} = C_1 \left(\frac{\Delta a_{p(1)}}{k}\right)^{C_2} \quad (A11.8)$$

A11.6.6.4 Return to A11.6.6.2 and A11.6.6.3 to get $\Delta a_{(i)}$ and $\delta_{Q(i+1)}$ until the δ_Q values converge to within 2 %.

A11.6.6.5 Project the intercepts of the power law curve with the 0.15-mm (0.006-in.) and the 1.5-mm (0.06-in.) exclusion lines vertically down to the abscissa. This indicates Δa_{min} and Δa_{limit}, respectively. Eliminate all data points that do not fall between Δa_{min} and Δa_{limit} as shown in Fig. A11.1. Also eliminate all data points which lie above the limiting δ capacity where $\delta_{limit} = b_o / 7.5\text{m}$. Where, m is defined in Annex A1 through Annex A3 for the different specimen geometries.

A11.6.6.6 At least five data points must remain between Δa_{min} and Δa_{limit} and δ_{limit}. Data point spacing must meet the requirements of A11.6.3. If these data points are different from those used in A11.6.6 to evaluate δ_Q, obtain a new value of δ_Q based only on qualified data.

A11.7 An alternative construction line slope, M_δ, can be calculated by fitting the least squares linear regression line to the initial *J-R* curve data for data in the region $0.2\delta_Q \leq \delta_i \leq 0.6\delta_Q$ as evaluated with $M_\delta = 1.4$. A minimum of 6 data points are required in the evaluation region to allow an experimental value of M_δ. Only values of $M_\delta \geq 1.4$ are allowed by this method. A revised δ_Q can now be evaluated using this M_δ by returning to A11.6.1-A11.6.6.

A11.8 *Qualification of Data*—The data shall satisfy the requirements of 9.1 and all of the following requirements to be qualified according to this method. If the data do not pass these requirements, no fracture toughness values can be determined according to this method.

A11.8.1 The power coefficient C_2 of A11.6.5 shall be less than 1.0.

A11.8.2 For the *Resistance Curve Procedure* the following additional requirements must be satisfied:

A11.8.2.1 a_{oq} shall not differ from a_o by more than the greater of $0.01W$ or 0.5 mm.

A11.8.2.2 The number of data available to calculate a_{oq} shall be ≥ 8; the number of data between $0.4\delta_Q$ and δ_Q shall be ≥ 3; and the correlation coefficient of the least squares fit of A11.6.5 shall be greater than 0.96.

A11.8.2.3 If an experimental value of M_δ is determined, at least 6 data points are required in the region $0.2\delta_Q \leq \delta_i \leq 0.6\delta_Q$. Only $M_\delta \leq 1.4$ can be used by this method.

A11.9 *Qualification of* δ_Q as δ_{Ic}:

$\delta_Q = \delta_{Ic}$, a size-independent value of fracture toughness, if:

A11.9.1 The initial ligament, $b_o \geq 10\text{m}\delta_Q$.

Where m is defined in Annex A1 through Annex A3 for the different specimen geometries.

A11.9.2 The slope of the power law regression line, $d\delta/da$, evaluated at Δa_Q must be less than 1.

A12. COMMON EXPRESSIONS

NOTE A12.1—Annex A12 and Annex A13 cover miscellaneous information.

A12.1 *Stress-Intensity Factor:*

A12.1.1 The elastic stress intensity factor for a specimen is expressed as follows:

$$K = \frac{Pf(a/W)}{(BB_N W)^{1/2}} \quad (A12.1)$$

where:

$$f\left(\frac{a}{W}\right) = \left(\frac{\xi}{\zeta}\right)\left[C_0 + C_1\left(\frac{a}{W}\right) + C_2\left(\frac{a}{W}\right)^2 + C_3\left(\frac{a}{W}\right)^3 + C_4\left(\frac{a}{W}\right)^4\right]$$

A12.1.2 The parameters for *f(a/W)* are listed in Table A12.1.

A12.2 *Compliance from Crack Size:*

A12.2.1 Compliance, C , of a specimen is expressed as a function of crack size as follows:

$$C = \frac{v}{P} = \quad (A12.2)$$

$$\frac{Y^2}{B_e E'}\left[A_0 + A_1(a/W) + A_2(a/W)^2 + A_3(a/W)^3 + A_4(a/W)^4 + A_5(a/W)^5\right]$$

A12.2.2 $B_e = B - (B - B_N)^2/B$ and $E' = E/(1 - \nu^2)$ for all cases and the other parameters for compliance are listed in Table A12.2.

TABLE A12.1 Parameters for Stress-Intensity Factors

	Specimens		
	SE(B)	C(T)	DC(T)
ξ	$3(S/W)\,(a/W)^{1/2}$	$2 + a/W$	$2 + a/W$
ζ	$2(1 + 2a/W)\,(1 - a/W)^{3/2}$	$(1 - a/W)^{3/2}$	$(1 - a/W)^{3/2}$
C_0	1.99	0.886	0.76
C_1	−2.15	4.64	4.8
C_2	6.08	−13.32	−11.58
C_3	−6.63	14.72	11.43
C_4	2.7	−5.6	−4.08
Limits	$0 \le a/W \le 1$	$0.2 \le a/W \le 1$	$0.2 \le a/W \le 1$
	$S/W = 4$	$H/W = 0.6$	$D/W = 1.35$
Refs	**(10)**	**(10)**, **(11)**	**(12)**

TABLE A12.2 Parameters for Compliance Expressions

Specimen	SE(B)	C(T)	DC(T)
Location	v_{LL}	v_{LL}	v_{LL}
Y	$S/(W - a)$	$(W + a)/(W - a)$	$(W + a)/(W - a)$
A_0	1.193	2.163	2.0462
A_1	−1.980	12.219	9.6496
A_2	4.478	−20.065	−13.7346
A_3	−4.433	−0.9925	6.1748
A_4	1.739	20.609	0
A_5	0	−9.9314	0
Limits	$0 \le a/W \le 1$	$0.2 \le a/W \le$ 0.975	$0.2 \le a/W \le$ 0.8
Refs	**(13)**	**(14)**	**(15)**

A13. METHOD FOR RAPID LOADING K_{Ic} DETERMINATION

A13.1 This annex describes the determination of plane-strain fracture toughness (K_{Ic}) properties of metallic materials under conditions where the loading rates exceed those for conventional (static) testing [2.5 ksi·in.$^{1/2}$/s (2.75 MPa·m$^{1/2}$/s)].

A13.2 *Summary of Requirements*—Special requirements are necessary for plane-strain fracture toughness testing at loading rates exceeding those of conventional (static) plane-strain fracture toughness testing. This description of these requirements does not include impact or quasi-impact testing (free-falling or swinging masses). Conventional fracture toughness test specimens are prepared as described in this method, tested under rapid-load conditions, and a fracture toughness value is calculated. Load-deflection, load-time, and deflection-time curves are recorded for each test. The load-deflection curves resulting from these tests are analyzed to ensure that the initial linear portion of the force-displacement record is sufficiently well-defined that P_Q can be determined unambiguously. In addition, a test time (t), restricted to not less than one millisecond is determined. This test time and an optionally calculated average stress intensity factor rate, dK/dt, characterize the rapid load test. The yield strength of the material must be determined or estimated for the loading time of the fracture test and is used in the analysis of the fracture test data. All of the criteria for static K_{Ic} determination apply to the rapid-load plane-strain fracture toughness test. The toughness property is denoted by K_{Ic}( ) where the time to reach the force corresponding to K_Q in milliseconds is indicated in the parentheses ( ).

A13.3 *Significance and Use*—The significance of the conventional (static) K_{Ic} properties applies also to the case of rapid loading. The plane-strain fracture toughness of certain materials is sensitive to the loading rate and substantial decreases in toughness may be noted as the loading rate increases. Generally, such materials also show a pronounced dependence of K_{Ic} on test temperature. For example, the loading rate sensitivity of structural grade steels has required the development of a lower bound K_{IR} curve, given in Appendix G of Division III of the ASME Boiler and Pressure Vessel Code,[5] for the fracture-safe design of heavy-wall nuclear pressure vessels. Additionally, K_{Ic} values for steels tested at various temperatures and loading rates are required for correlation with small-scale production control tests (such as the Charpy V-notch test) for setting material specifications and fracture-safe design procedures.

A13.4 *Apparatus:*

A13.4.1 *Loading*—Generally, hydraulic machines with rapid-acting servo controlled valves are used. Depending on the compliance of the loading system and the pump capacity, an accumulator may be required.

A13.4.2 *Fixtures*—The fixtures used for static plane-strain fracture toughness tests are generally suitable for rapid-load tests. However, consideration should be given to the possibility that the toughness of the fixture material may be reduced by rapid loading.

[5] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990, http://www.asme.org.

A13.4.3 *Force and Displacement Transducers*—The transducers used for static plane-strain fracture toughness tests are generally suitable for rapid-load tests. However, these transducers must have response characteristics that will ensure that inertial effects will not influence the force and displacement signals.

NOTE A13.1—While not required, the resonant frequencies of these transducers may be determined by suitably exciting them and observing the wave characteristic on an oscilloscope. If ringing (high-frequency oscillation) is observed within the time period required to reach the P_Q force, the stiffness of the transducers should be increased or their mass reduced. Force cells are quite stiff and should provide no problem at the minimum loading time of 1 ms. The displacement transducer might be cause for concern depending on its design. The cantilever beam displacement gage described in Section 6 has been used successfully at loading times slightly lower than 1 ms. The resonant frequency of this gage when mounted in a specimen in a conventional manner and excited by tapping is about 3300 Hz. The free-arm resonant frequency is about 750 Hz. Other gages of the same type but having different dimensions should operate satisfactorily if their free-arm resonance is at least 750 Hz. The following equation may be used to estimate the free-arm resonant frequency of such a gage:

$$f = RC\left[\frac{B^2Eg}{\rho l^4}\right] \tag{A13.1}$$

where:

RC = 51.7,
f = resonant frequency, Hz,
B = arm thickness, m,
E = elastic modulus of the arms, MPa,
g = gravitational acceleration, 9.804 m/s^2,
ρ = density of the arm material, kg/m^3, and
l = length of the uniform thickness section of the arms, m.

The coefficient RC becomes 0.162 if inch-pound units are used where B is in inches, E is in pound-force per square inch, g is 386 in./s^2, ρ is pounds per cubic inch, and l is in inches.

A13.4.4 *Signal Conditioners*—Amplification or filtering of the transducer signals may be necessary. Such signal conditioning units should have a frequency response from dc to at least 20/t (kilohertz) where t is the test time in milliseconds as defined in A13.6.3. As described in A13.4.3, conventional mechanical recording devices may not have sufficient frequency response to permit direct plotting of the force versus time and the displacement versus time signals.

A13.5 *Procedure:*

A13.5.1 *Loading Rate*—The rate of loading is optional with the investigator, but the time to reach the force corresponding to K_Q shall not be less than 1 ms. Use a preload to eliminate ringing in the force or displacement transducers associated with clearances in the load train being suddenly taken up by the start of rapid loading.

A13.5.2 For each test conducted, a force versus time, a displacement versus time, and a force versus displacement record shall be obtained. The time scale of these records shall be accurately determined since the time is used to characterize the test. Examine the time-dependent records for the presence of ringing before reaching the P_Q force. Such ringing can result from inertial effects as described in Note A13.2. The special record analysis procedure described in A13.6 may be helpful in assessing the magnitude of such effects.

NOTE A13.2—It should be recognized that some materials may exhibit a burst of crack extension at forces less than P_Q that is sufficiently abrupt to produce ringing in the displacement transducer signal. Such an abrupt advance of the crack may be associated with material inhomogeneities local to the fatigue crack tip. If the ringing is severe it may not be possible to unambiguously determine a value for P_Q. The presence of such bursts of crack extension should be recorded for those tests having analyzable force versus displacement records.

NOTE A13.3—The test data may be directly recorded if the recording devices have sufficient frequency response. Generally, it is advantageous to use a storage device that will capture the data and permit playing it out at a sufficiently slow speed that a pen recorder can be used in producing the required records. Such storage devices are commonly available in the form of digital storage oscilloscopes having pen recorder outputs. Separate storage instruments are also available. In general these digital storage devices have performance characteristics that are more than adequate to capture, store, and replay the transducer signals from a 1-ms test. For example, calculations show that for a typical fracture test, the crack-mouth displacement resolution would be about 0.76 mm/sample (0.030 mil/sample) and the force resolution would be about 712 N/sample (160 lbf/sample). It should be possible to obtain at least 1000 simultaneous samples of force and displacement during such a test. A digital storage scope capable of at least this performance would have the following characteristics: maximum digitizing rate of 1 MHz, maximum sensitivity of ±100 mV, resolution of 0.025 %, and memory of 4096 words by 12 bits. It may be necessary to amplify the output of the clip gage moderately and possibly that of the force cell depending on its capacity in terms of the range required. These values of resolution are based on a total noise figure of about 50 mV.

A13.6 *Calculation and Interpretation of Results:*

A13.6.1 Special requirements are placed on the analysis of the force versus displacement record. These take into account the fact that experience **(18)** has shown force versus displacement records from rapid-load fracture toughness tests are not always as smooth in the linear range as those obtained from static tests. The special requirements of this annex are designed to ensure that an unambiguous value of P_Q can be determined. The test time must be determined from the force versus time record.

A13.6.2 The additional analysis of the force versus displacement record is illustrated in Fig. A13.1. The procedure is as follows: Construct the straight line OA best representing the initial portion of the test record that ideally should be linear but may not be smooth. Then construct the line OP_5 as described in Annex A5 and determine P_Q. Draw a vertical line at v_p passing through P_Q and define P_v at the point of intersection of this line with the line OA. Determine 5 % of P_v and construct two lines BC and DE parallel to OA with BC passing through $P_v + 0.05\ P_v$ and DE passing through P_Q ($P_v - 0.05\ P_v$). Draw a horizontal line at $P = 0.5\ P_Q$. For the test to be valid that recorded force versus displacement curve up to P_Q must lie within the envelope described by these parallel lines for the portion of the record with $P \leq 0.5\ P_Q$.

A13.6.3 The test time t in milliseconds is determined from the record of force versus time as indicated in Fig. A13.2. Construct the best straight line OA through the most linear portion of the record. The value t is then determined from the point of intersection of this line with the time axis to the time corresponding to P_Q. This time, t is shown in the parentheses

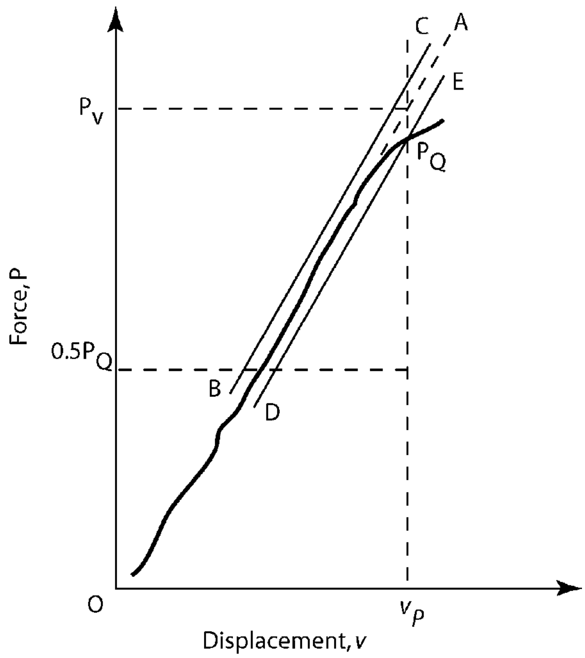


FIG. A13.1 Special Requirements for Analysis of Force versus Displacement Records (5 % Secant Line Not Shown)

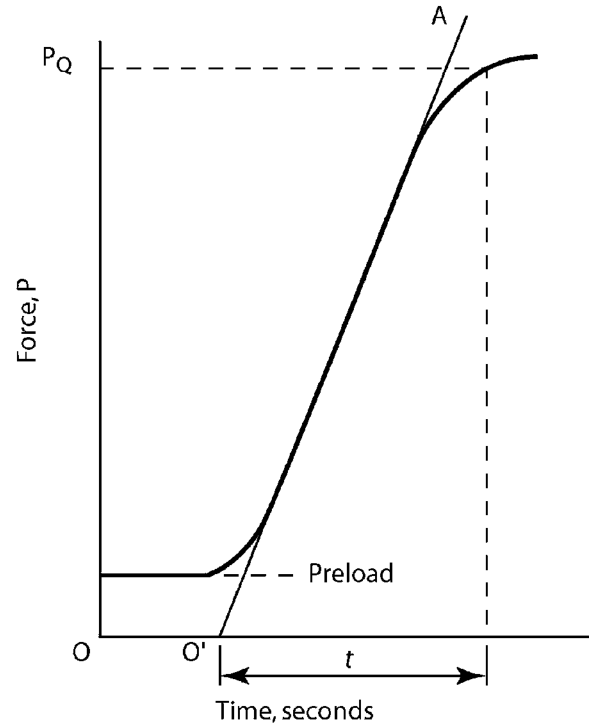


FIG. A13.2 Determination of Test Time from Force versus Time Record

( ) following K_{Ic}. An average stress intensity rate, dK/dt, may be calculated by dividing K_Q or K_{Ic} by t with the result being expressed in ksi·in.$^{1/2}$/s or MPa·m$^{1/2}$/s. It should be recognized that minor errors in determining the loading time are not significant because significant changes in the toughness require a change of several orders of magnitude in loading rate.

A13.6.4 The 0.2 % offset tensile yield strength σ_{YS} is used in determining the specimen size requirements for a valid test as described in Annex A5. If the rapid force value of K_Q is valid using a static yield strength value determined at a temperature at or above that of the rapid-load test, no further yield strength considerations are necessary.

A13.6.5 If the test is invalid using such a yield strength, a tension test should be conducted on the test material at the temperature and loading time of the rapid-load toughness test with the time to reach the yield load in the tension test approximately equal to the time t defined in A13.6.3.

A13.6.6 In the absence of σ_{YS} values as defined in A13.6.5, the dynamic yield strength σ_{YD} of certain steels may be estimated using the following equation:

$$\sigma_{YD} = \sigma_{YD} + \frac{A}{T_x \log_{10}(2 \times 10^7 t)} - B \qquad \text{(A13.2)}$$

where:

σ_{YS} = 0.2 % offset room temperature static yield strength,
t = loading time, ms, and
Tx = temperature of the rapid-load toughness test.

Units:

If σ_{YS} is in megapascals, then A = 1 198 860, B = 187.4 MPa,
If σ_{YS} is in pound force per square inch, then
A = 174 000, B = 27.2 ksi,
If the test temperature T is measured in K, then $T_x = 1.8\ T$, and
If the test temperature T is measured in °F, then $T_x = (T + 460)$.

NOTE A13.4—The equation in A13.6.6 has been found useful only in estimating the low-temperature dynamic yield strength of constructional steels having room temperature yield strengths below 480 MPa (70 ksi).

A14. SPECIAL REQUIREMENTS FOR RAPID-LOAD *J*-INTEGRAL FRACTURE TOUGHNESS TESTING[6]

A14.1 Scope

A14.1.1 This annex covers the determination of the rate dependent $J_{Ic}(t)$ and the J-integral versus crack growth resistance curve (J-$R(t)$ curve) for metallic materials under conditions where the loading rate exceeds that allowed for conventional (static) testing, see Section 8.4.2.

A14.2 Summary of Requirements

A14.2.1 Special requirements are necessary for J-integral fracture toughness testing of metallic materials at loading rates exceeding those of conventional (static) testing. Standard fracture toughness test specimens are prepared as described in this method, tested under rapid-load or drop weight conditions,

[6] This test method is an Annex to ASTM E 1820. It is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.08 on Elastic-Plastic and Fracture Mechanics Technology.

and a J-$R(t)$ curve is calculated. From this J-$R(t)$ curve a $J_Q(t)$ can be evaluated using Section 9 of this method. If unstable fracture intervenes, a $J_{Qc}(t)$ can be evaluated at the onset of unstable behavior as in the static case.

A14.2.1.1 Force, load line displacement, and time are recorded for each test. The force versus displacement curve resulting from each test is analyzed to ensure that the initial portion of the curve is sufficiently well defined that an unambiguous curve can be determined from the $J(t)$ versus crack size $(a(t))$ data. In addition a minimum test time is calculated from the specimen stiffness and effective mass that sets a maximum allowed test rate for the material and geometry being tested. At times less than the minimum test time a significant kinetic energy component is present in the specimen relative to the internal energy, and the static J integral equations presented in this method are not accurate. Evaluation of a $J_Q(t)$ or $J_{Qc}(t)$ at a time less than the minimum test time is not allowed by this method.

A14.2.1.2 Evaluation of the J-$R(t)$ curve requires estimation of crack extension as a function of load line displacement or time using the normalization method of Annex A15. An elastic compliance method cannot be used. A multiple specimen method can be used to evaluate $J_Q(t)$ from a series of tests, which can be corrected using Annex A16 and assembled into a J-$R(t)$ curve. The J-$R(t)$ curve is valid if it meets the requirements of this method.

A14.2.1.3 All of the criteria for the static J_{Ic}, J_c, and J-R curve evaluations apply to the rapid load J integral fracture toughness test. The rapid load J integral resistance curve is denoted J-$R(t)$, the stable initiation property $J_{Ic}(t)$, and the unstable initiation property by $J_c(t)$, where the time to reach the instant corresponding to J_Q in milliseconds is indicated in the brackets.

A14.3. Terminology

A14.3.1 *Definitions:*

A14.3.1.1 The definitions given in Terminology E 1823 are applicable to this annex.

A14.3.1.2 The definitions given in Section 3 of this method are applicable.

A14.3.1.3 *Rapid Load*—In J integral fracture testing, any loading rate such that the time taken to reach P_m (see 7.4.4) is less than 0.1 minutes.

A14.3.1.4 *Minimum Test Time, $t_w(t)$*—In J integral fracture testing, the minimum time to the rate dependent $J_Q(t)$ or $J_{Qc}(t)$ accepted by this method (**19**). Test times less than t_w will lead to inaccurate J integral results since large kinetic energy components will be present. In this method:

$$t_w = \frac{2\,\pi}{\sqrt{k_s/M_{eff}}} \qquad \text{(A14.1)}$$

where:

k_s = specimen load line stiffness, (N/m),
M_{eff} = effective mass of the specimen, taken here to be half of the specimen mass (kg).

A14.3.1.5 *Test Time, $t_Q(t)(T)$*—In J integral fracture testing, the observed time to the rate dependent $J_Q(t)$.

A14.3.1.6 $J_c(t)(FL^{-1})$—In J integral fracture testing, the rate dependent J integral at the onset of fracture instability prior to the onset of significant stable tearing crack extension, see Section 3.2.10, as defined in this annex.

A14.3.1.7 $J_{Qc}(t)(FL^{-1})$—In J integral fracture testing, the provisional rate dependent J integral at the onset of fracture instability prior to the onset of significant stable tearing crack extension, as defined in this annex.

A14.3.1.8 $J_u(t)(FL^{-1})$—In J integral testing, the rate dependent J integral at the onset of fracture instability after significant stable tearing crack extension, see section 3.2.11, as defined in this annex.

A14.3.1.9 $J_{Ic}(t)(FL^{-1})$—In J integral testing, the rate dependent J integral at the onset of stable crack extension as defined in this annex.

A14.3.1.10 $J_Q(t)(FL^{-1})$—In J integral fracture toughness testing, the provisional, rate dependent, J integral at the onset of stable crack extension as defined in this annex.

A14.3.1.11 $dJ/dt(FL^{-1}T^{-1})$—In J integral fracture testing, the rate of change of the J integral per unit time. Two loading rate quantities are defined in this method, $(dJ/dt)_I$ measured before $J_Q(t)$, and $(dJ/dt)_T$ measured after $J_Q(t)$, as defined by this annex.

A14.4 Significance and Use

A14.4.1 The significance of the static J-R curve, J_{Ic}, and J_c properties applies also to the case of rapid loading. The J integral fracture toughness of certain metallic materials is sensitive to the loading rate and to the temperature of test. The J-$R(t)$ curve and J_{Ic}(t) properties are usually elevated by higher test rates while J_c(t) can be dramatically lowered by higher test rates.

A14.5 Apparatus

A14.5.1 *Loading*—Two types of high rate loading systems are anticipated. Servohydraulic machines with high flow rate servovalves and high capacity accumulators, or alternatively, drop weight impact machines can be used. On-specimen force measurements are recommended for high rate tests. Remote force cells or other transducers can be used for high rate tests if the requirements of this annex are met. Strain gage bridges are recommended for on-specimen force measurement, as shown in Fig. A14.1 and Fig. A14.2. For each specimen type, four gages are connected to construct a four-arm bridge and calibrated statically before the rapid load test (see A14.5.4). Strain gages with grid patterns of approximately 0.25B are recommended. For SE(B) specimens, gages should be positioned on the specimen mid-plane at the specimen span quarterpoints. For C(T) specimens, the gages should be positioned on the specimen upper and lower surfaces near the specimen mid-plane with the gage edge at least 0.1W behind the initial crack, a_o.

A14.5.2 *Servohydraulic Testing Fixtures*—The fixtures used for static fracture toughness tests generally require some modification for rapid load tests. Slack grip fixtures are often necessary to reduce the applied force oscillation and to allow the actuator to accelerate before force is applied to the specimen. Soft metal absorbers are generally used in drop tower tests to reduce the inertial shock caused by the impact of the test machine striker on the specimen surface.

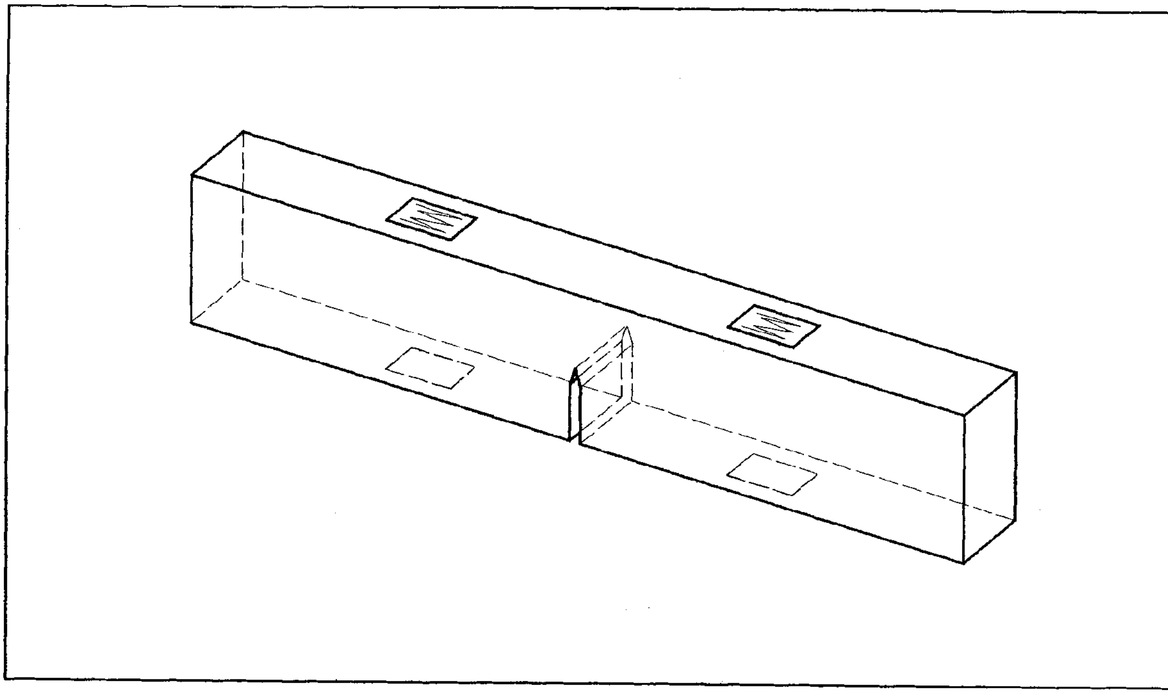


FIG. A14.1 Strain Gages Mounted on SE(B) Specimen for Measurement of Transmitted Force

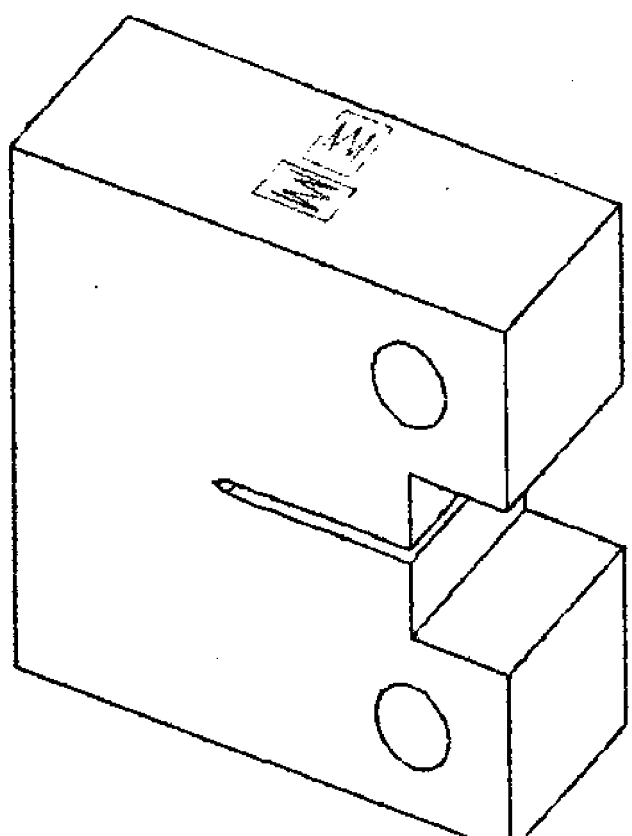


FIG. A14.2 Strain Gages Mounted on C(T) Specimen for Measurement of Transmitted Force

Both initial and final crack sizes are required by the normalization method of *J-R(t)* curve development of Annex A15. The high rate test must be stopped abruptly to obtain a limited specimen deformation and a crack extension increment satisfying the requirement of A15.1.1. Rigid stop block fixtures can be used to obtain the abrupt stop. In some cases a ramp and hold or square wave command signal can be used to obtain limited specimen deformation for the specimen test.

A14.5.3 *Drop Tower Testing Fixtures*—Special fixtures are necessary for drop tower testing according to this standard. Recommended fixtures for SE(B) and C(T) specimens are shown in Figs. A14.3 and A14.4 respectively (**20**). Stop block fixtures are required to obtain a limited extent of stable crack growth for *J-R(t)* curve development. Soft metal absorbers are recommended to reduce the initial shock resulting from the impact of the drop tower striker on the specimen surface. A high frequency load line displacement transducer and signal conditioner is required for drop tower tests.

A14.5.4 *Force Transducers*—If remote force transducers are used, they shall meet the requirements of Practice E 4. Requirements on the measured initial specimen stiffness and on the force and displacement signal smoothness are presented in A14.7.4. Static calibration of the on-specimen strain gage bridge should be done over a force range from 20 to 100 % of the final precracking force. At least five force calibration values shall be used, spaced evenly over this interval, and at least two repeat data sets are required. The applied force shall exceed ¼

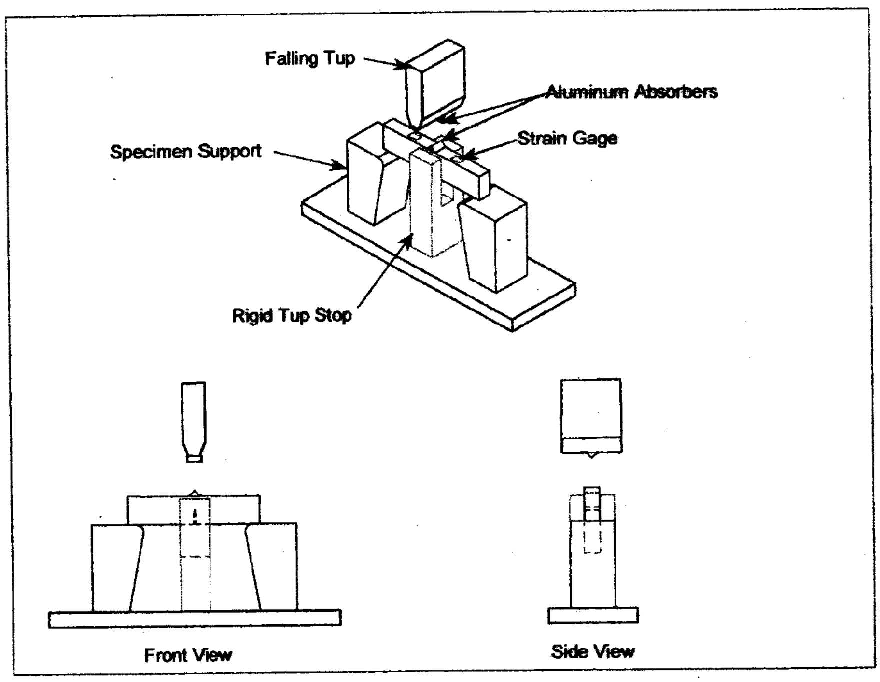


FIG. A14.3 Test Fixture for Drop Tower SE(B) Specimens

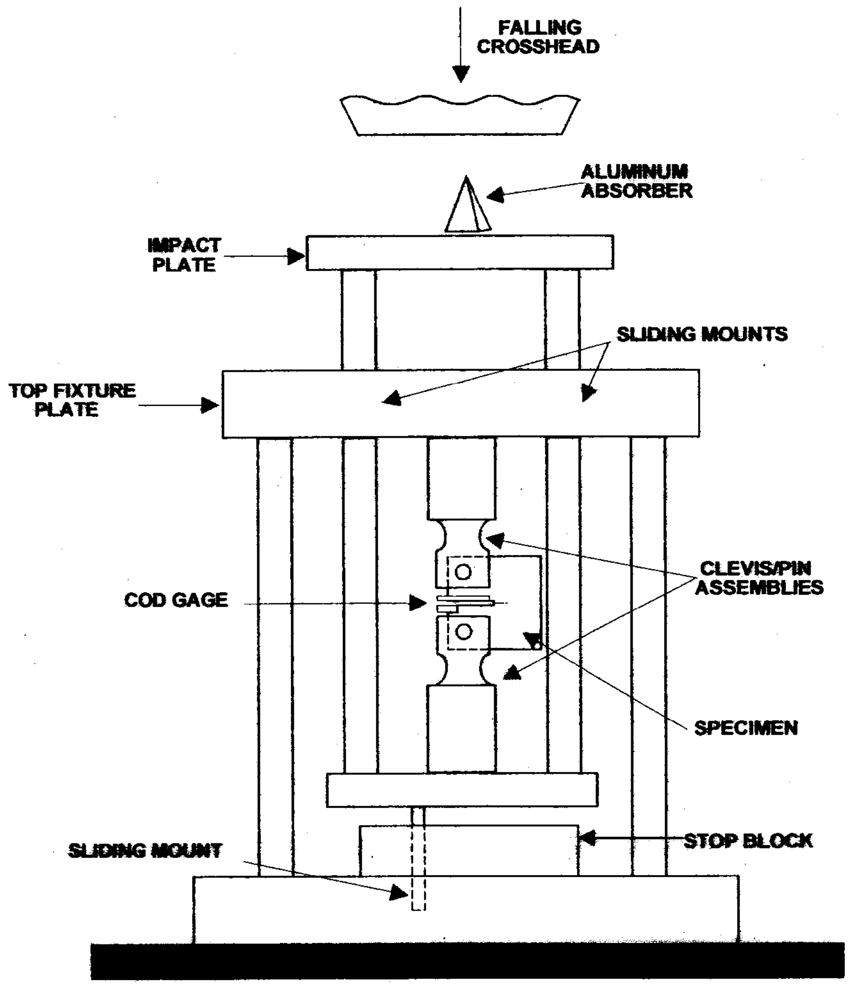


FIG. A14.4 Test Fixtures for Drop Tower C(T) Specimens

of the calibrated range of the reference force cell used. The on-specimen, transmitted force measuring system shall be accurate to within 2 % of the final precracking force over the calibration range.

A14.5.5 *Displacement Transducers*—The transducer shall have response characteristics that allow it to follow the motion of the specimen while not introducing excessive mechanical noise into the measured displacement.

A14.5.5.1 Cantilever beam displacement gages such as those used in static fracture toughness testing may be suitable for rapid-load testing, see A13.4.3. The cantilever beam displacement gage described in Annex A1 of Test Method E 399 has been used successfully at loading times (t_Q) slightly less than 1 ms.

A14.5.5.2 Gap measuring transducers that use either capacitance or optical means to measure displacement have also been used successfully in rapid-load testing (**20**). These transducers have the advantage that they can be rigidly attached to the specimen, and the vibration characteristics of the transducer generally do not affect the measured displacement. The disadvantages are that the output may be non-linear, and the signal conditioners used with these transducers are often the limiting component in frequency response of the displacement measurement system. Capacitive transducers have been designed to fit in the notch of the C(T) specimen as shown in Fig. A14.5. Fiber-optic transducers have been used to measure load line displacement of SE(B) specimens. If the load line displacement is measured relative to the test fixture, care must be taken to account for the effects of fixture compliance and brinnelling on the measured displacement, as discussed in 8.3.1.1.

A14.5.6 *Signal Conditioners*—The user is referred to Guide E 1942 for a detailed discussion of requirements for data acquisitions systems. The signal conditioner must have sufficient bandwidth to capture the transducer signal without introducing distortion.

A14.5.6.1 Signal conditioners shall have a frequency bandwidth in excess of $10/t_Q$ for the force signal and $2/t_Q$ for the displacement signal(s). The more stringent requirement on the force signal is necessary to obtain an accurate measurement of the elastic component of the J integral near crack initiation. No "phase shifting" of transducer signals is allowed by this method. The bandwidth required to accurately capture a signal of that frequency will depend on the type of low-pass filter in the signal conditioner, and the tolerable error. If a low-pass

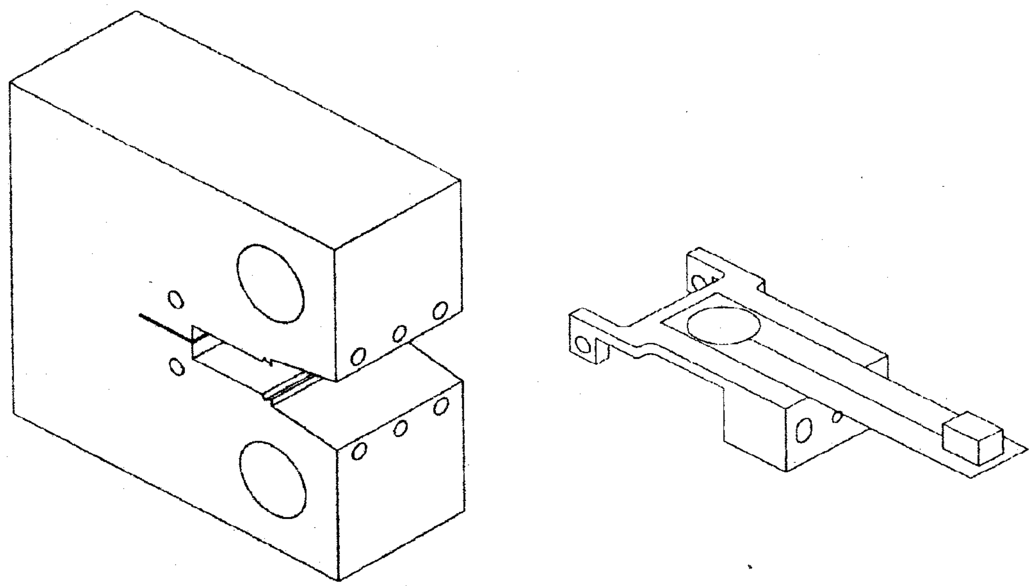


FIG. A14.5 High Rate Capacitance COD Gage and C(T) Specimen with Attachment Holes

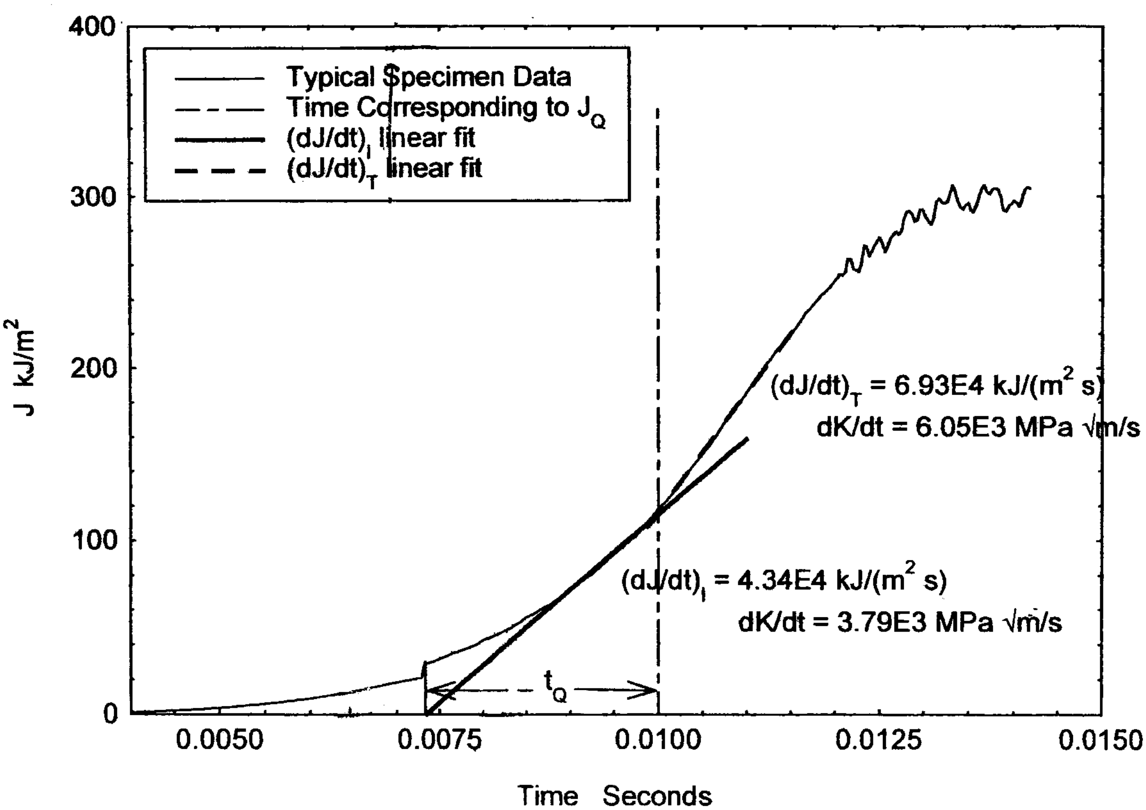


FIG. A14.6 Evaluation of t_Q and the Test Rates $(dJ/dt)_I$ and $(dJ/dt)_T$

filter is present in the measurement system it should not introduce more than 0.5 % measurement error, see Guide E 1942.

A14.5.7 *Data Sampling*—The user is referred to Guide E 1942 for a detailed discussion of requirements for data acquisitions systems. The rate at which an analog signal is sampled to create a digital signal shall be high enough to ensure that the peak value is accurately captured. The rate of data acquisition shall result in the time per data set being less than $t_Q/50$.

A14.6 Procedure

A14.6.1 Follow the procedure of Sections 7 and 8 to prepare and test specimens. The following items are additional steps necessary for high rate testing.

A14.6.2 Calculate t_w, the minimum test time from Eq A14.1. The loading rate is optional but the time to reach $J_Q(t)$ or $J_{Qc}(t)$ shall not be less than t_w.

A14.6.3 For each test, force and load line displacement are required as functions of time. Additional crack opening displacement data, electric potential data, or both, can be acquired as well if desired.

A14.6.4 Install and align the specimen in the test fixtures, establish the test temperature, conduct the test at the desired test rate, collect and store the data required. Remove the test specimen from the fixture and mark the extent of the ductile crack growth according to 8.5.3, break the specimen open according to 8.5.4 to expose the fracture surface, and measure the initial crack size a_o, and the final crack size a_f according to 8.5.4.

A14.6.5 If the specimen is characterized by ductile upper shelf behavior, the normalization method of Annex A15 can be used to develop the *J-R(t)* curve for the test specimen. A multi-specimen method can also be used with J evaluated using the basic method relationships corrected for crack extension using Annex A16. Using Section 9, calculate J_Q (the tentative J_{Ic}) and the corresponding force P_Q and time t_Q. If a ductile instability occurs so that the final stable crack size a_f cannot be determined, the normalization method cannot be used to develop the *J-R(t)* curve or the corresponding J_Q for this test specimen.

A14.6.5.1 If a pop-in is present, refer to Annex A4 to assess its significance. If the pop-in is significant, $J_c(t)$ or $J_u(t)$ values corresponding to the point of onset can be calculated using Annex A6. If fracture instability occurs without significant ductile crack extension, $J_c(t)$ or $J_u(t)$ values corresponding to the point of onset can be calculated as defined in Annex A6. If fracture instability follows significant ductile crack extension, the *J-R(t)* and $J_{Ic}(t)$ can be determined providing that a_f is distinguishable. The validity of the *J-R(t)* curve and $J_{Ic}(t)$ are subject to the requirements of Annex A8, Annex A9, and Section 9.

A14.7 Qualification of the Data

A14.7.1 Test equipment, specimen geometries, specimen fixture alignment, and measured data must meet all requirements of Sections 6, 7, 8, and 9, except as specifically replaced in A14.5. Additional requirements specified here are necessary for high rate testing.

A14.7.2 All of the test equipment requirements of A14.5 shall be met.

A14.7.3 Plot the J integral versus the time as shown in Fig. A14.6. If fracture instability occurs, calculate J based on a_o using the basic analysis procedure and plot the data up to and including $J_{Qc}(t)$ or $J_{Qu}(t)$. Use a linear regression analysis to evaluate $(dJ/dt)_I$ as shown in the example of Fig. A14.5 using the data from $0.5J_Q(t)$ to $J_Q(t)$, from $0.5J_{Qc}(t)$ to $J_{Qc}(t)$, or from $0.5\ J_{Qu}(t)$ to $J_{Qu}(t)$, as the case may be. Extrapolate this line to the abscissa to evaluate the quantity t_Q, as shown in Fig. A14.6.

A14.7.3.1 A second loading rate, $(dJ/dt)_T$, is defined as the slope of the J versus time data beyond maximum force, as shown in Fig. A14.6, over the range from J_Q to $J_Q + 0.5(J_{max}–J_Q)$ or the end of test, if fracture instability occurs.

A14.7.4 Plot force versus load line displacement for the time interval $0 \leq t \leq t_Q$, as shown schematically in Fig. A14.7. Use a linear regression analysis to evaluate the initial specimen stiffness k_s using data over the range from 20 % to 50 % of the maximum force measured in the test. Plot this best fit line on the figure, and also plot two parallel lines of the same slope with the *y*-intercept offset by ±10 % of P_{max} as shown in Fig. A14.7. Locate the final crossover $\Delta_{LL}{}^F$.

A14.7.4.1 For this data set to be qualified according to this method, the compliance, $1/k_s$, shall agree with the predictions of Eq A2.10 for the C(T) specimen and Eq A1.10 for the SE(B) specimen within ±10 %. Additionally, the measured force displacement data in the region between $0.3\Delta_{LL}{}^F$ and $0.8\Delta_{LL}{}^F$ should remain within the bounds of the parallel lines constructed on Fig. A14.7. If these requirements are not met, slack grips or impact absorbers must be added or modified or the test rate reduced to obtain a smoother data set that can be qualified according to this method.

A14.7.5 If $t_Q < t_w$, the test data are not qualified according to this method. A slower loading rate must be used, or the specimen geometry changed to decrease t_w for the test to be qualified according to this method.

A14.7.6 If the normalization method of Annex A15 is used to obtain J_{Ic}, the J resistance curve, or both, at least one confirmatory specimen must be tested at the same test rate and under the same test conditions. From the normalization method the load line displacement corresponding to a ductile crack extension of 0.5 mm shall be estimated. The additional specimen shall then be loaded to this load line displacement level, marked, broken open and the ductile crack growth measured. The measured crack extension shall be 0.5 ± 0.25 mm in order for these results to be qualified according to this method.

A14.8 Qualifying the High Rate Results

A14.8.1 All qualification requirements of 9.1, Annex A6, Annex A8, Annex A9, and A14.7 must be met to qualify the *J-R(t)* curve, $J_Q(t)$ as $J_{Ic}(t)$, or $J_{Qc}(t)$ as $J_c(t)$ according to this method. If the normalization method of Annex A15 is used, the additional requirements of this annex shall also be met.

A14.8.2 The maximum crack extension capacity for a specimen to qualify the *J-R(t)* curve is given by the following:

$$\Delta a_{max} = 0.15 b_o \tag{A14.2}$$

A14.9 Report

A14.9.1 The report shall include all the items of Section 10 as well as the following:

A14.9.1.1 The minimum test time, t_w, according to A14.6.2.

A14.9.1.2 The P_Q and t_Q, corresponding to the calculated $J_Q(t)$ or $J_{Qc}(t)$.

A14.9.1.3 The $(dJ/dt)_I$, $(dJ/dt)_T$ values, or both.

A14.9.1.4 If $J_{Ic}(t)$ is being reported, the final crack extension obtained on the confirmatory specimen of A14.7.6 shall be reported.

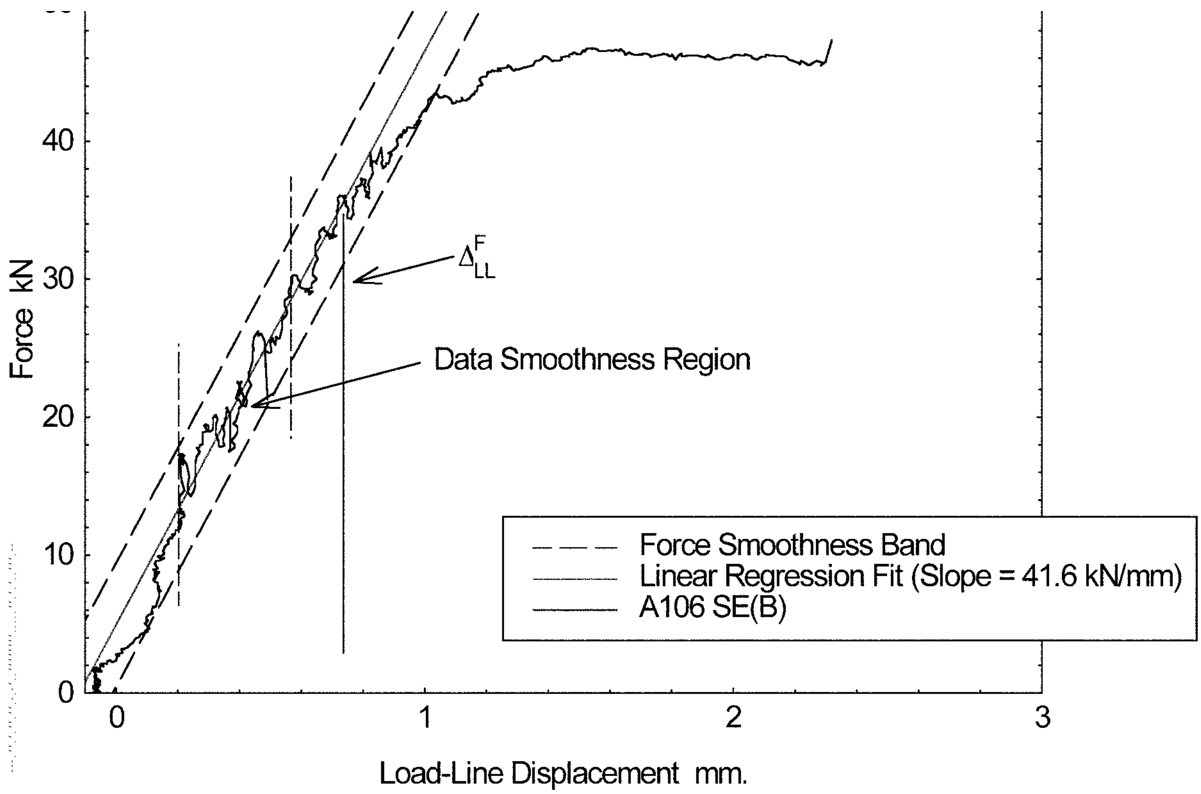


FIG. A14.7 Force Smoothness Verification Schematic

A14.10 Precision and Bias

A14.10.1 *Precision*—The precision of *J* versus crack growth is a function of material variability, the precision of the various measurements of linear dimensions of the specimen and testing fixtures, precision of the displacement measurement, precision of the force measurement, as well as the precision of the recording devices used to produce the force displacement record used to calculate *J* and crack size. For the test rates allowed by this annex, if the procedures outlined in this annex are followed, the force and load-line displacement can be measured with an precision comparable with that of the static loading as described in the main body. If the normalization function method of Annex A15 is used, the crack size and crack extension information must be inferred from initial and final crack size measurements. The requirement for the additional specimen to be tested near to the point of crack initiation has been added to validate the $J_{Ic}(t)$ measurement. A round robin used to evaluate the overall test procedures of this method is reported in (**21**).

A14.10.2 *Bias*—There is no accepted "standard" value for measures of elastic-plastic fracture toughness of any material. In absence of such a true value, any statement concerning bias is not meaningful.

A15. NORMALIZATION DATA REDUCTION TECHNIQUE

A15.1 Scope

A15.1.1 The normalization technique can be used in some cases to obtain a *J-R* curve directly from a force displacement record taken together with initial and final crack size measurements taken from the specimen fracture surface. Additional restrictions are applied (see A14.1.3) which limit the applicability of this method. The normalization technique is described more fully in Herrera and Landes (**22**) and Landes, et al. (**23**), Lee (**24**), and Joyce (**21**). The normalization technique is most valuable for cases where high loading rates are used, or where high temperatures or aggressive environments are being used. In these, and other situations, unloading compliance methods are impractical. The normalization method can be used for statically loaded specimens if the requirements of this section are met. The normalization method is not applicable for low toughness materials tested in large specimen sizes where large amounts of crack extension can occur without measurable plastic force line displacement.

A15.2 Analysis

A15.2.1 The starting point for this analysis is a force versus load point displacement record like that shown in Fig. A15.1. Also required are initial and final physical crack sizes optically measured from the fracture surface. This procedure is applicable only to Test Method E 1820 standard specimen geometries with $0.45 \leq a_o/W \leq 0.70$ and cannot be used if the final physical crack extension exceeds the lesser of 4 mm or 15 % of the initial uncracked ligament.

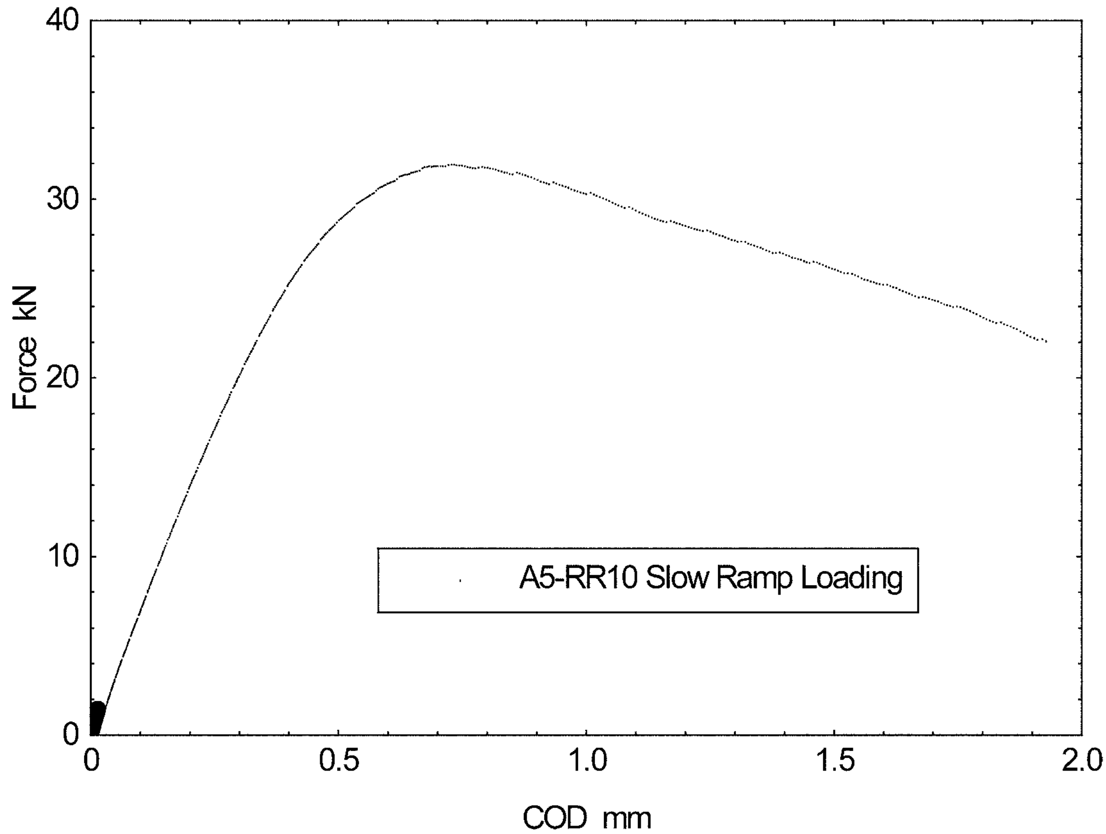


FIG. A15.1 Typical Force versus Displacement Curve

A15.2.2 Each force value P_i up to, but not including the maximum force P_{max}, is normalized using:

$$P_{Ni} = \frac{P_i}{WB\left[\frac{W - a_{bi}}{W}\right]^{\eta_{pl}}} \tag{A15.1}$$

where a_{bi} is the blunting corrected crack size at the ith data point given by:

$$a_{bi} = a_o + \frac{J_i}{2\,\sigma_Y} \tag{A15.2}$$

with J_i calculated from:

$$J_i = \frac{K_i^2\,(1 - \nu^2)}{E} + J_{pli} \tag{A15.3}$$

where K_i, η_{pl}, and J_{pli} are calculated as in Annex A1 and Annex A2 for each specimen type using the crack size a_o.

A15.2.3 Each corresponding load line displacement is normalized to give a normalized plastic displacement:

$$v'_{pli} = \frac{v_{pli}}{W} = \frac{(v_i - P_i\,C_i)}{W} \tag{A15.4}$$

where C_i is the specimen elastic load line compliance based on the crack size a_{bi}, which can be calculated for each specimen type using the equations of Annex A1 and Annex A2.

A15.2.4 The final measured crack size shall correspond to a crack extension of not more than 4 mm or 15 % of the initial uncracked ligament, whichever is less. If this crack extension is exceeded, this specimen can not be analyzed according to this annex.

A15.2.5 The final force displacement pair shall be normalized using the same equations as above except that the final measured crack size, a_f, is used. Typical normalized data are shown in Fig. A15.2.

A15.2.6 A line should be drawn from the final force displacement pair tangent to remaining data as shown in Fig. A15.2. Data to the right of this tangent point shall be excluded from the normalization function fit. Data with $v_{pli}/W \leq 0.001$ shall also be excluded from the normalization function fit.

A15.2.7 If at least ten data pairs conform with A15.2.6, the data of Fig. A15.2 can be fit with the following required analytical normalization function:

$$P_N = \frac{a + b\,v'_{pl} + c\,{v'_{pl}}^2}{d + v'_{pl}} \tag{A15.5}$$

where *a, b, c,* and *d* are fitting coefficients. This function can be fitted to the data of Fig. A15.1 using standard curve fitting packages available as part of computer spreadsheet programs or separately. An example fit for the data of Fig. A15.2 is shown in Fig. A15.3. The normalization function shall fit all the data pairs described above (including the final pair) with a maximum deviation less than 1 % of the P_N at the final point. Data should be evenly spaced between $v_{pli}/W = 0.001$ and the tangency point. If less than ten data pairs are available for this fit, including the final measured data pair, this method cannot be used.

A15.2.8 An iterative procedure is now used to force P_{Ni}, v_{pli}/W, a_i data to lie on Equation A15.5. This involves

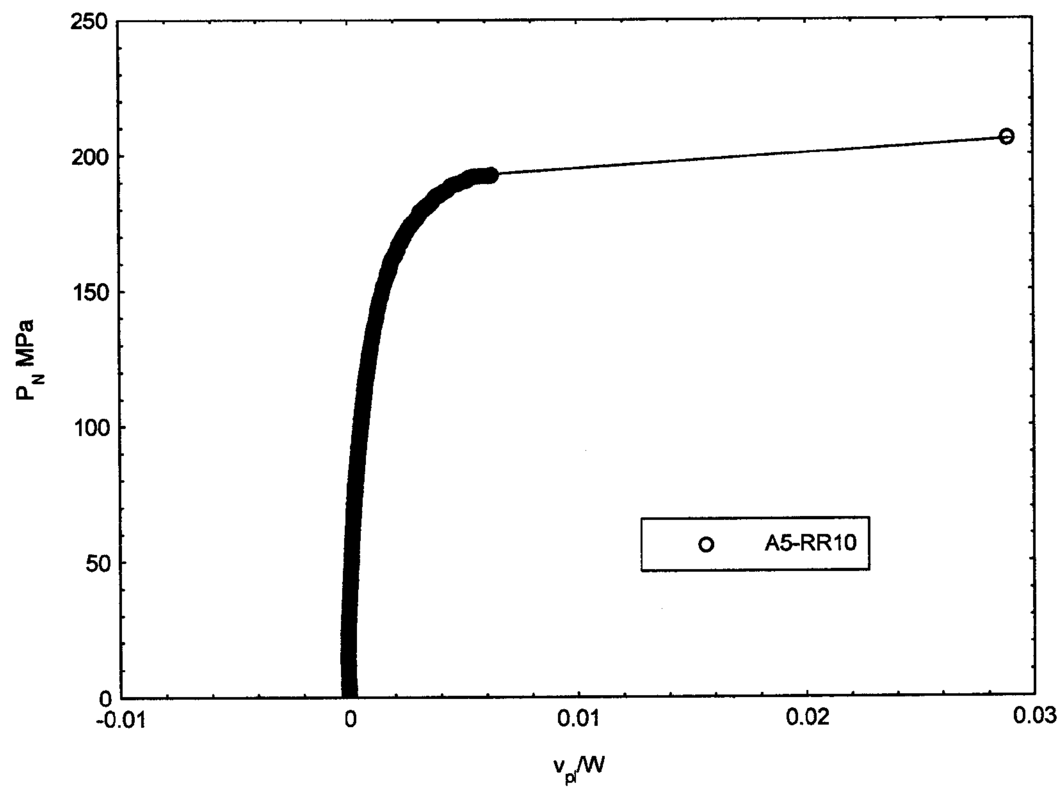


FIG. A15.2 Normalized Force versus Displacement Curve Showing Points up to Maximum Force and the Final Data Point

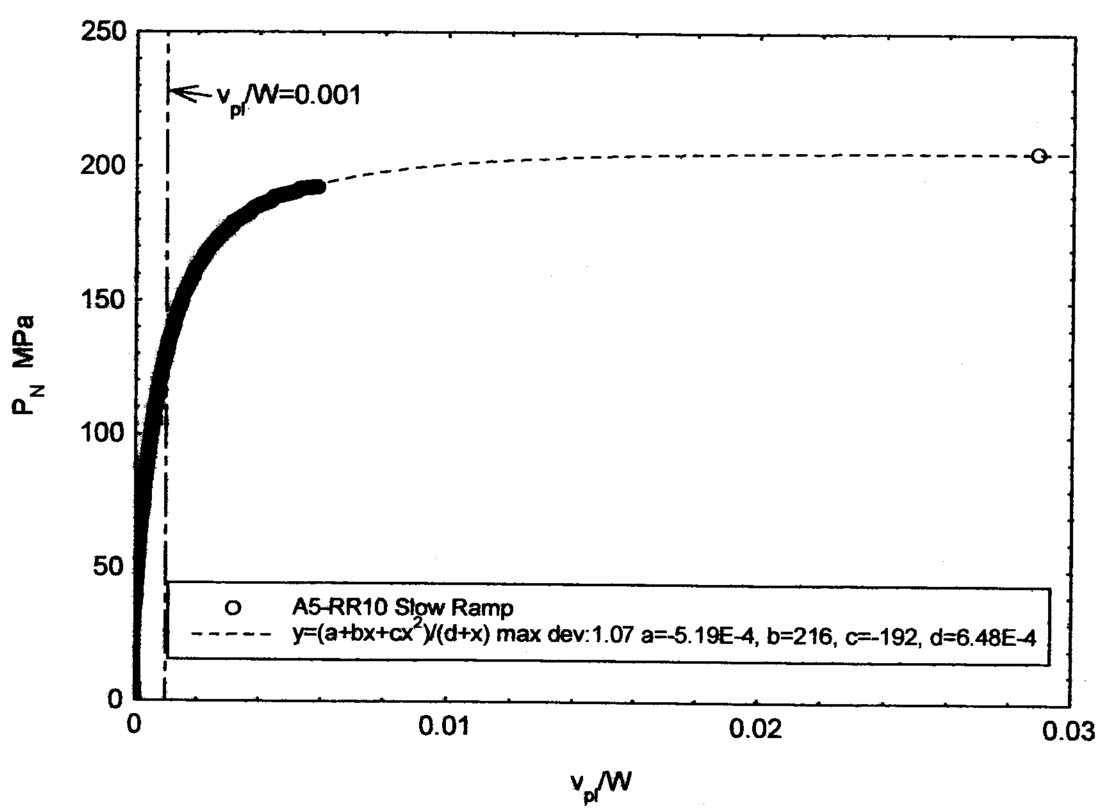


FIG. A15.3 The Normalization Function Shown Fitted to the Normalization Data adjusting the crack size of each data set to get the normalized force and displacement pair defined in A15.2.2 and A15.2.3 to fall on the function defined in Equation A15.5. To do so, start at the first data point with $v_{pl}/W \geq 0.002$, normalize the force and displacement using the initial measured crack size a_o, and compare the normalized force with the result of the normalization function of A15.2.7. Adjust the crack size until the measured P_{Ni} and the functional value of P_N are within ±0.1 %. Each subsequent data set is treated similarly. If each step is started with the crack size resulting from the previous data set, only small, positive adjustments of crack size are necessary, and the process of obtaining the crack sizes corresponding to each data set is relatively rapid.

A15.2.8.1 The data of Fig. A15.1, normalized and adjusted to fit the normalization function of Fig. A15.3 is shown in Fig. A15.4.

A15.2.9 Since force, load line displacement, and crack size estimates are now available at each data point, the standard equations of Annex A1 and Annex A2 are used to evaluate the J integral at each data point, resulting in a J-R curve as shown in Fig. A15.5. A J_{Ic} value can now be evaluated from this J-R curve using the method of Section Annex A9.

A15.3 Additional Requirements

A15.3.1 Requirements presented in 9.1, Annex A8, and Annex A9 shall be met to qualify a J-R curve or a J_{Ic} value obtained by the normalization method. Additional requirements specific to the use of the normalization method are presented below.

A15.3.2 If the normalization method is used to obtain J_{Ic}, at least one additional, confirmatory specimen shall be tested at the same test rate and under the same test conditions. From the normalization method the load line displacement corresponding to a ductile crack extension of 0.5 mm shall be estimated. The additional specimen shall then be loaded to this load line displacement level, marked, broken open and the ductile crack growth measured. The measured crack extension shall be 0.5 ± 0.25 mm in order for these results, and hence the J_{Ic} value, to be qualified according to this method.

A15.4 Report

A15.4.1 Section 10 describes the reporting requirements for this method. If the normalization function method is used the following additional items shall be reported.

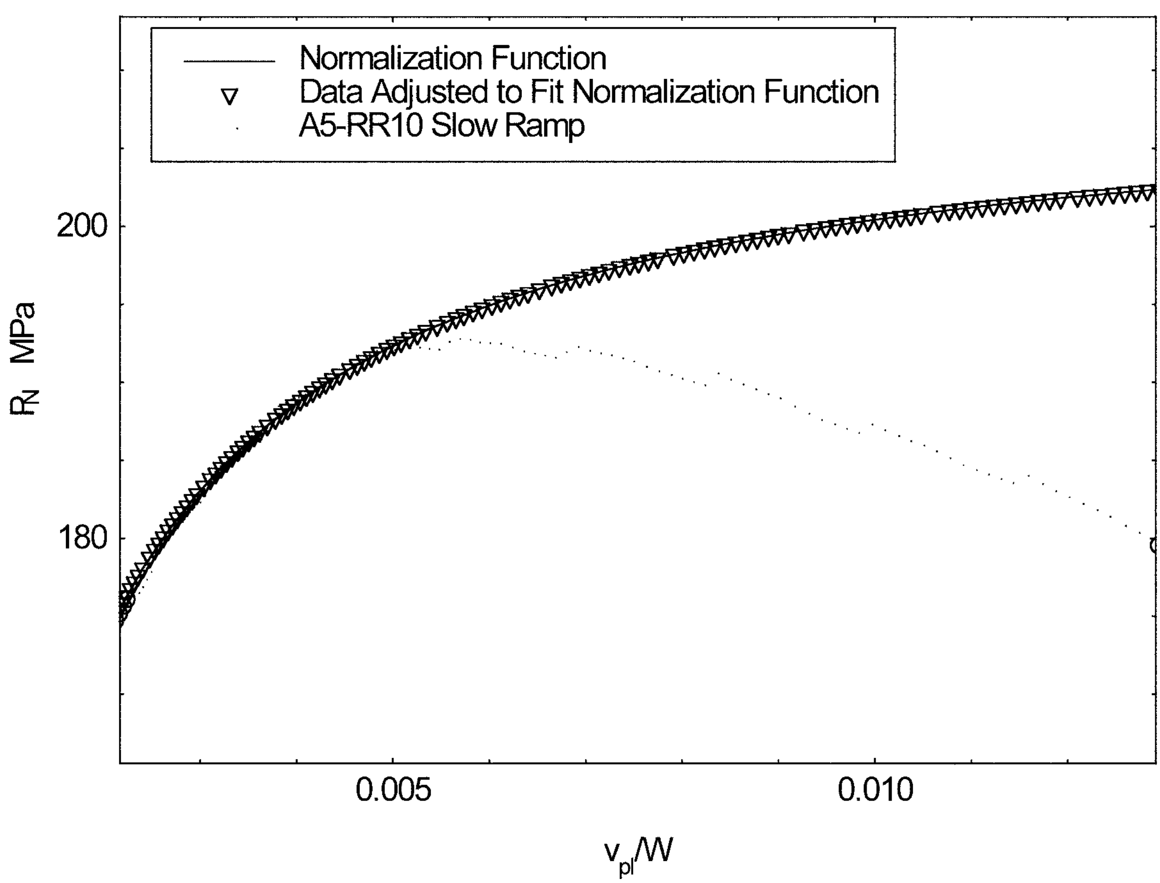


FIG. A15.4 Data is Adjusted, Defining the Crack Size Necessary to Place All Points on the Analytical Normalization Function (Only a portion of the data is shown for clarity)

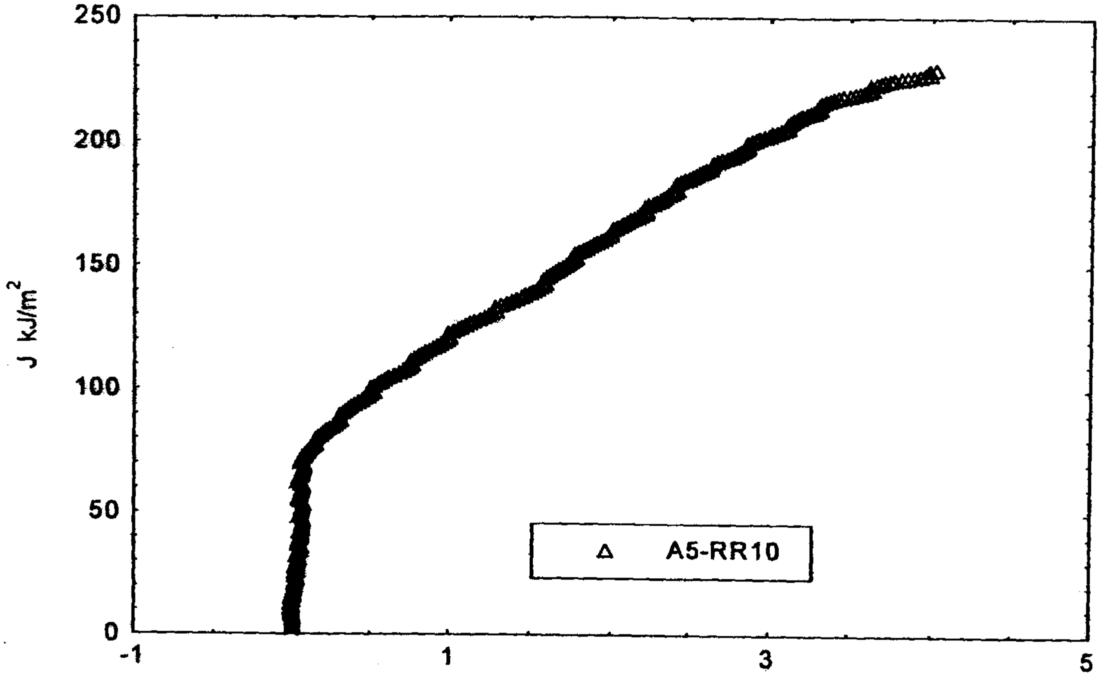


FIG. A15.5 The Resulting *J-R* Curve for this Specimen

A15.4.2 If the normalization function is used the coefficients of the fit shall be reported as well as the maximum deviation of the fit and the number of data used.

A15.4.3 If J_{Ic} is reported, the accuracy of the confirmatory specimen of A15.3.2 shall be reported.

A15.5 Precision and Bias

A15.5.1 *Precision*—The precision of the *J* resistance curve is a function of material variability, the precision of the various measurements of linear dimensions of the specimen and testing fixtures, precision of the displacement measurement, precision of the force measurement, as well as the precision of the recording devices used to produce the force displacement record used to calculate *J* and crack size. For the test rates allowed by this annex, if the procedures outlined in this annex are followed, the crack size throughout the fracture toughness test can be measured with a precision comparable with that of the unloading compliance procedure described in the main body. A round robin describing the use of the normalization procedure on rapidly loaded SE(B) and C(T) specimens is presented in (**21**). A requirement for the testing of a confirmatory specimen tested near the point of stable crack initiation is present to validate the J_{Ic} measurement.

A15.5.2 *Bias*—Crack sizes generally vary through the thickness of fracture toughness specimens. A nine point average procedure based on optical measurements obtained from the post-test fracture surface is generally used to give a reportable crack size. Different measurements would be obtained using more or less measurement points. Alternative crack sizes can be estimated using compliance methods, which obtain different average crack size estimates for irregular crack front shapes. Stringent crack front straightness requirements are present in this standard to minimize differences caused by these effects. The normalization method acts to interpolate between optically measured crack average lengths measured at the start and end of the stable resistance curve fracture toughness test. This method has been demonstrated in (**21**) to give results consistent with those obtained by unloading compliance procedures.

A16. EVALUATION OF CRACK GROWTH CORRECTED J-INTEGRAL VALUES

A16.1 *J Correction Procedure*:

A16.1.1 Evaluate J_{el0} and J_{pl0} values for each specimen using the basic method equations of Annex A1-Annex A3 for the specimen type.

A16.1.2 Obtain initial crack growth correct *J* values using the following relationship (**27**):

$$J = J_{el0} + \frac{J_{pl0}}{1 + \left(\frac{\alpha - 0.5}{\alpha + 0.5}\right)\frac{\Delta a}{b_o}} \quad \text{(A16.1)}$$

with α = 1 for SE(B) specimens and α = 0.9 for C(T) and DC(T) specimens.

A16.1.3 Fit a power law expression $J = J_{1mm}\Delta a^{m}$ to the corrected J (Δa) data for crack growths exceeding $\Delta a/b_o \geq 0.05$.

A16.1.4 Calculate the final crack growth corrected J (Δa) data using:

$$J = J_{el0} + \frac{J_{pl0}}{1 + \left(\frac{\alpha - m}{\alpha + m}\right)\frac{\Delta a}{b_o}} \quad \text{(A16.2)}$$

APPENDIX

(Nonmandatory Information)

X1. EXAMPLE

X1.1 To fit Eq A9.1 to the J_i, a_i data using the method of least squares, the following equation must be set up and solved for a_{oq}, B, and C:

$$\begin{Bmatrix} \Sigma\, a_i - \dfrac{\Sigma\, J_i}{2\sigma_Y} \\ \Sigma\, a_i J_i^2 - \dfrac{\Sigma\, J_i^3}{2\sigma_Y} \\ \Sigma\, a_i J_i^3 - \dfrac{\Sigma\, J_i^4}{2\sigma_Y} \end{Bmatrix} = \begin{bmatrix} n & \Sigma\, J_i^2 & \Sigma\, J_i^3 \\ \Sigma\, J_i^2 & \Sigma\, J_i^4 & \Sigma\, J_i^5 \\ \Sigma\, J_i^3 & \Sigma\, J_i^5 & \Sigma\, J_i^6 \end{bmatrix} \begin{Bmatrix} a_{oq} \\ B \\ C \end{Bmatrix} \quad \text{(X1)}$$

X1.2 This equation can be set up and solved using a standard spreadsheet or using a mathematical analysis program like MathCad, Maple, or Mathematica.

REFERENCES

(1) Joyce, J. A., and Tregoning, R. L., "Development of Consistent Size Criteria for ASTM Combined Fracture Mechanics Standards," *Fatigue and Fracture Mechanics*, Vol 30, ASTM STP 1360, P. C. Paris, et al, eds., ASTM, West Conshohocken, PA, 1999.

(2) Joyce, J. A., "Manual on Elastic-Plastic Fracture: Laboratory Test Procedures," *ASTM Manual Series MNL 27*, 1996.

(3) Dawes, M. G.," Elastic-Plastic Fracture Toughness Based on the COD and J-Integral Concepts," *Elastic-Plastic Fracture, ASTM STP 668*, J. D. Landes, J. A. Begley, and G. A. Clarke, eds., ASTM, 1979, pp. 307–333.

(4) Willoughby, A. A., and Garwood, S. J., "On the Loading Compliance Method of Deriving Single Specimen *R*Curves in Three Point Bending," *Elastic-Plastic Fracture: Second Symposium, Volume II—Fracture Resistance Curves and Engineering Applications, ASTM STP 803*, C. F. Shih and J. P. Gudas, eds., ASTM, 1983, pp. II-372–II-397.

(5) Hackett, E. M., and Joyce, J. A., "Dynamic *J-R* Curve Testing of a High Strength Steel Using Key Curve and Multi-Specimen Techniques," *Fracture Mechanics, Seventeenth Volume, ASTM STP 905*, ASTM, 1986, pp. 741–774.

(6) Hellman, D., Rohwerder, G., and Schwalbe, K. H.," Development of a Test Setup for Measuring Deflections of Single Edge Notched Bend (SENB) Specimens," *Journal of Testing and Evaluation*, Vol 12, No. 1, January 1984, pp. 62–64.

(7) KarisAllen, K. J. and Mathews, J. R., "The Determination of Single Edge-Notched Bend Specimen Load-Line Displacement from Remotely Located Sensors in Elastic-Plastic Fracture Testing," *Journal of Testing and Evaluation*, JTEVA, Vol 22, No. 6, Nov. 1994, pp. 581-583.

(8) McCabe, D. E., "Evaluation of the Compact Specimen for Plane Strain Fracture Toughness of High Strength Materials," *Journal of Materials*, Vol 7, No. 4, December 1972, p. 449.

(9) Begley, J. A., Clarke, G. A., and Landes, J. D., "Results of an ASTM Cooperative Test Program on the J_{Ic} Determination of HY-130 Steel," *Journal of Testing and Evaluation*, Vol 8, No. 5, September 1980.

(10) Gudas, J. P., and Davis, D. A., "Evaluation of the Tentative J_I-R Curve Testing Procedure by Round Robin Tests of HY-130 Steel," *Journal of Testing and Evaluation*, Vol 10, No. 6, November 1982, pp. 252–262.

(11) Zhu, X. K., Leis, B.N., and Joyce, J.A., "Experimental Estimation of J-R Curves for Load-CMOD Records for SE(B) Specimens," *Journal of ASTM International*, Vol. 5 No. 5 March 2008, http://www.astm.org/DIGITAL_LIBRARY/JOURNALS/JAI/PAGES/1135.htm

(12) Srawley, J. E., "Wide Range Stress Intensity Factor Expressions for ASTM E 399 Standard Fracture Toughness Specimens," *International Journal of Fracture*, Vol 12, June 1976, pp. 475–476.

(13) Newman, J. C., Jr., "Stress Analysis of the Compact Specimen Including the Effects of Pin Loading," *ASTM STP 560*, 1974, pp. 105–121.

(14) Newman, J. C., Jr., "Stress Intensity Factors and Crack Opening Displacements for Round Compact Specimens," *International Journal of Fracture*, 17(6), December 1981, pp. 567–578.

(15) Underwood, J. H., Kapp, J. A., and Baratta, F. I., "More on Compliance of the Three-Point Bend Specimen," *International Journal of Fracture*, Vol 28, 1985, pp. R41–R45.

(16) Saxena, A., and Hudak, S. J., "Review and Extension of Compliance Information for Common Crack Growth Specimens," *International Journal of Fracture*, Vol 14, October 1978, pp. 453–468.

(17) Yoon, K. K., Gross, L. B., Wade, C. S., and VanDerSluys, W. A., "Evaluation of Disk-Shaped Specimen for Determining J-R Curves," *Fracture Mechanics: 26th Volume, ASTM STP 1256*, W. G. Reuter, J. H. Underwood, and J. C. Newman, eds., American Society for Testing and Materials, Philadelphia, 1995.

(18) Shoemaker, A. K., and Seeley, R. R., "Summary Report of Round Robin Testing By ASTM Task Group E24.01.06 on Rapid Loading

Plane Strain Fracture Toughness K_{Ic} Testing," *Journal of Testing and Evaluation*, Vol 11, No. 4, July 1983.

(19) Nakamura, T., Shih, C. F., and Freund, L. B., "Analysis of a Dynamically Loaded Three-Point-Bend Ductile Fracture Specimen," *Engineering Fracture Mechanics*, Vol 25, No. 3, 1986, pp. 323–339.

(20) Joyce, J. A., and Hackett, E. M., "An Advanced Procedure for J-R Curve Testing Using a Drop Tower," *Nonlinear Fracture Mechanics: Vol 1–Time Dependent Fracture, ASTM STP 995*, A. Saxena, J. D. Landes, and J. L. Bassani, Eds., ASTM, Philadelphia, 1989, pp. 298–317.

(21) Joyce, J. A., "Analysis of the E08.02 High Rate Round Robin," *Journal of Testing and Evaluation*, JTEVA, Vol 29. No. 4. July 2001, pp. 329–351.

(22) Herrera, R., and Landes, J. D., "Direct J-R Curve Analysis: A Guide to the Methodology," *Fracture Mechanics: Twenty-First Symposium, ASTM STP 1074*, J.P. Gudas, J.A. Joyce, and E.M. Hackett, Eds., ASTM, Conshohocken, PA, 1990, pp 24–43.

(23) Landes, J. D., Zhou, Z., Lee, K., and Herrera, R., "Normalization Method for Developing J-R Curves with the LMN Function," *Journal of Testing and Evaluation*, JTEVA, Vol 19, No. 4, July 1991, pp. 305–311.

(24) Lee, Kang, "Elastic-Plastic Fracture Toughness Determination Under Some Difficult Conditions," Ph.D Dissertation, The University of Tennessee, Knoxville, August, 1995.

(25) Merkle, J. G., Wallin, K., and McCabe, D. E., *Technical Basis for an ASTM Standard for Determining the Reference Temperature, T_o, for Ferritic Steels in the Transition Range*, U.S. Nuclear Regulatory Commission NUREG/CR-5504 (ORNL)/TM-13631), November 1998.

(26) Pisarski, H. G., "Measurement of Heat Affected Zone Fracture Toughness," Paper TS31, Steel in Marine Structures, C. Noordhoek and J. de Back, eds., Proceedings of 3rd International ECSC Conference, Delft, June 15-18, 1987, Elsevier Science Publishers B.V., Amsterdam, 1987, pp. 647–656.

(27) Wallin, K., and Laukkanen, A., "Improved Crack Growth Corrections for J-R Curve Testing," *Engineering Fracture Mechanics*, 71, 2004, pp. 1601–1614.