Designation: E 561 – 05$^{\epsilon 1}$

Standard Test Method for *K-R* Curve Determination[1]

This standard is issued under the fixed designation E 561; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

ϵ^1 NOTE—Equation 6 was editorially corrected in February 2007.

1. Scope*

1.1 This test method covers the determination of the resistance to fracture of metallic materials under Mode I loading at static rates using any of the following notched and precracked specimens: the middle-cracked tension M(T) specimen, the compact tension C(T) specimen, or the crack-line-wedge-loaded C(W) specimen. A *K-R* curve is a continuous record of toughness development (resistance to crack extension) in terms of K_R plotted against crack extension in the specimen as a crack is driven under an increasing stress intensity factor, *K*.

1.2 Materials that can be tested for *K-R* curve development are not limited by strength, thickness, or toughness, so long as specimens are of sufficient size to remain predominantly elastic to the effective crack extension value of interest.

1.3 Specimens of standard proportions are required, but size is variable, to be adjusted for yield strength and toughness of the materials.

1.4 Only three of the many possible specimen types that could be used to develop *K-R* curves are covered in this method.

1.5 The test is applicable to conditions where a material exhibits slow, stable crack extension under increasing crack driving force, which may exist in relatively tough materials under plane stress crack tip conditions.

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

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

2. Referenced Documents

2.1 *ASTM Standards:* [2]

E 4 Practices for Force Verification of Testing Machines

E 399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials

E 1823 Terminology Relating to Fatigue and Fracture Testing

2.2 *Other Documents:*

AISC Steel Construction Manual [3]

3. Terminology

3.1 *Definitions*—Terminology E 1823 is applicable to this method.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *apparent plane-stress fracture toughness,* K_{app}—The value of *K* calculated using the original crack size and the maximum force achieved during the test. K_{app} is an engineering estimate of toughness that can be used to calculate residual strength. K_{app} depends on the material, specimen size, and specimen thickness and as such is not a material property.

3.2.2 *effective modulus,* E_{eff} (FL^{-2})—the value of Young's modulus that produces an accurate correspondence between the experimentally measured compliance at the original crack size and the analytically developed compliance calculated for the same crack size.

3.2.3 *plane-stress fracture toughness,* K_c—The value of K_R at instability in a force-controlled test corresponding to the maximum force point in the test. K_c depends on the material, specimen size, and specimen thickness and as such is not a material property.

3.2.3.1 *Discussion*—See the discussion of plane-strain fracture toughness in Terminology E 1823.

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

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[2] 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] Available from American Institute of Steel Construction (AISC), One E. Wacker Dr., Suite 3100, Chicago, IL 60601-2001.

*A Summary of Changes section appears at the end of this standard.

4. Summary of Test Method

4.1 During slow-stable fracturing, the developing crack extension resistance K_R is equal to the applied stress intensity factor *K*. The crack is driven forward by continuously or incrementally increasing force or displacement. Measurements are made periodically for determination of the effective crack size and for calculation of *K* values, which are individual data points that define the *K-R* curve for the material under those test conditions.

4.2 The crack starter is a low-stress-level fatigue crack.

4.3 The method covers two techniques for determination of effective crack size: *(1)* direct measurement of the physical crack size which is then adjusted for the developing plastic zone size, and *(2)* compliance measurement techniques that yield the effective crack size directly. Methods of measuring crack extension and of making plastic-zone corrections to the physical crack size are prescribed. Expressions for the calculation of crack-extension force K_R are given. Criteria for determining if the specimen is predominantly elastic are provided.

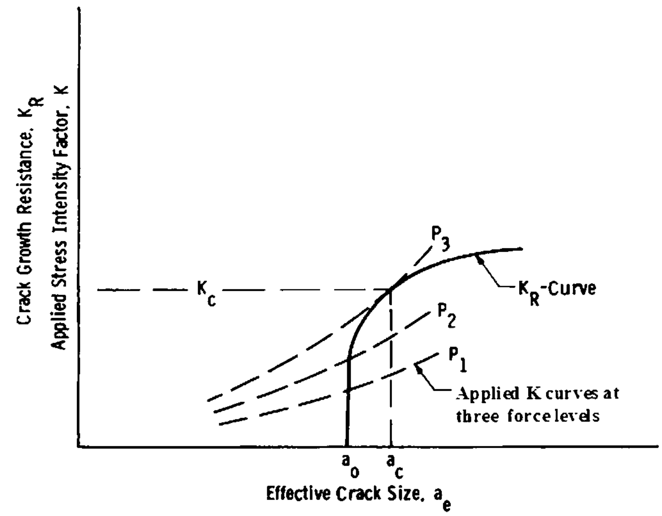


FIG. 1 Schematic Representation of *K-R* curve and Applied *K* Curves to Predict Instability; K_c, P_3, a_c, Corresponding to an Original Crack Size, a_o

5. Significance and Use

5.1 The *K-R* curve characterizes the resistance to fracture of materials during slow, stable crack extension and results from the growth of the plastic zone ahead of the crack as it extends from a fatigue precrack or sharp notch. It provides a record of the toughness development as a crack is driven stably under increasing applied stress intensity factor *K*. For a given material, *K-R* curves are dependent upon specimen thickness, temperature, and strain rate. The amount of valid *K-R* data generated in the test depends on the specimen type, size, method of loading, and, to a lesser extent, testing machine characteristics.

5.2 For an untested geometry, the *K-R* curve can be matched with the crack driving (applied *K*) curves to estimate the degree of stable crack extension and the conditions necessary to cause unstable crack propagation (**1**).[4] In making this estimate, *K-R* curves are regarded as being independent of original crack size a_o and the specimen configuration in which they are developed. For a given material, material thickness, and test temperature, *K-R* curves appear to be a function of only the effective crack extension Δa_e (**2**).

5.2.1 To predict crack behavior and instability in a component, a family of crack driving curves is generated by calculating *K* as a function of crack size for the component using a series of force or displacement loading conditions. The *K-R* curve may be superimposed on the family of crack driving curves as shown in Fig. 1, with the origin of the *K-R* curve coinciding with the assumed original crack size a_o. The intersection of the crack driving curves with the *K-R* curve shows the expected effective stable crack extension for each loading condition. The crack driving curve that develops tangency with the *K-R* curve defines the critical loading condition that will cause the onset of unstable fracture.

5.2.2 Conversely, the *K-R* curve can be shifted left or right in Fig. 1 to bring it into tangency with a crack driving curve to determine the original crack size that would cause crack instability under that loading condition.

5.3 If the *K*-gradient (slope of the crack driving curve) of the specimen chosen to develop the *K-R* curve has negative characteristics (see Note 1), as in a displacement-controlled test condition, it may be possible to drive the crack until a maximum or plateau toughness level is reached (**3, 4, 5**). When a specimen with positive *K*-gradient characteristics (see Note 2) is used, the extent of the *K-R* curve which can be developed is terminated when the crack becomes unstable.

NOTE 1—Fixed displacement in crack-line-loaded specimens results in a decrease of *K* with crack extension.

NOTE 2—With force control, *K* usually increases with crack extension, and instability will occur at maximum force.

6. Apparatus

6.1 *Testing Machine*—Machines used for *K-R* curve testing shall conform to the requirements of Practices E 4. The forces used in determining K_R values shall be within the verified force application range of the testing machine as defined in Practices E 4.

6.2 *Grips and Fixtures for Middle-Cracked Tension (M(T)) Specimens*—In middle-cracked tension specimens, the grip fixtures are designed to develop uniform stress distribution in the central region of the specimen. Single pin grips can be used on specimens less than 305 mm (12 in.) wide if the specimen is long enough to ensure uniform stress distribution in the crack plane (see 8.5.3.) For specimens wider than 305 mm (12 in.), multiple-bolt grips such as those shown in Fig. 2 or wedge grips that apply a uniform displacement along the entire width of the specimen end shall be used if the stress intensity factor and compliance equations in Section 11 are to be used. Other gripping arrangements can be used if the appropriate stress intensity factor and compliance relationships are verified and used. Grips should be carefully aligned to minimize the

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

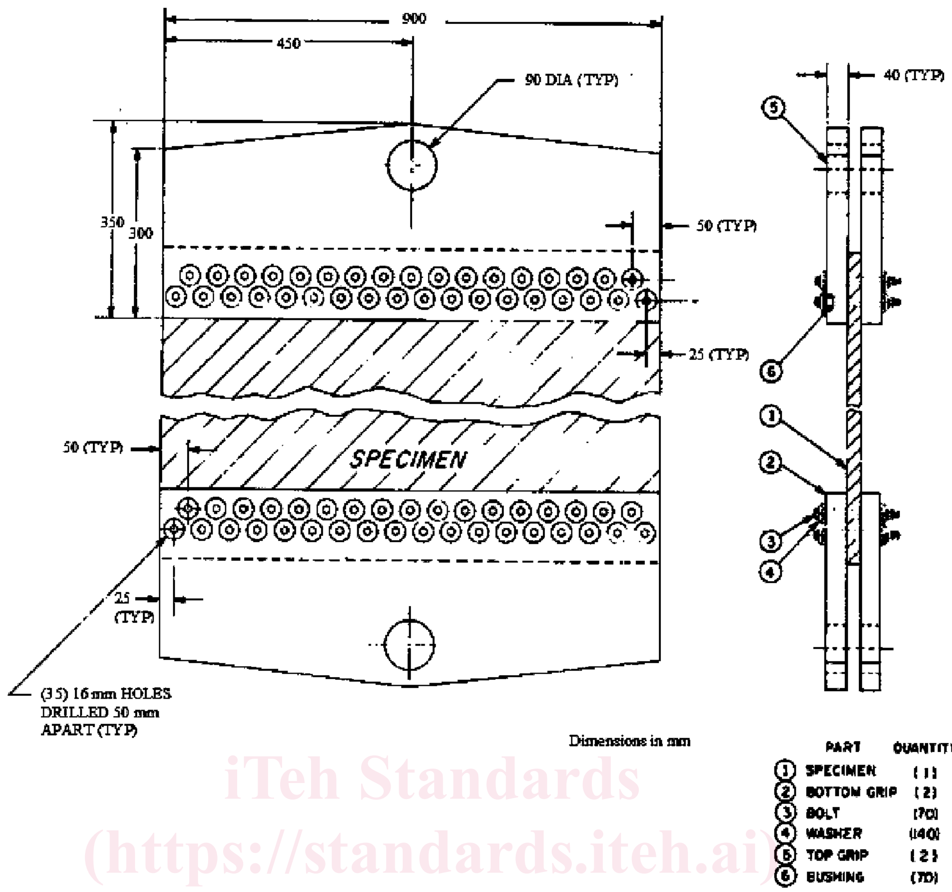


FIG. 2 Middle-Cracked Tension (M(T)) Panel Test Setup

introduction of bending strain into the specimen. Pin or gimbal connections can be located between the grips and testing machine to aid the symmetry of loading. If extra-heavy-gauge, high-toughness materials are to be tested, the suitability of the grip arrangement may be checked using the *AISC Steel Construction Manual*.

6.3 *Grips and Fixtures for Compact Tension (C(T)) Specimens*—The grips and fixtures described in Test Method E 399 are recommended for *K-R* curve testing where C(T)-type specimens are loaded in tension.

6.4 *Fixtures for Crack-Line-Wedge-Loaded (C(W)) Specimens*:

6.4.1 Crack-line-wedge-loaded specimens are loaded using a low-taper-angle wedge with a polished finish and split-pin arrangement as shown in Fig. 3. Sketches of a segmented split-pin system which has proved effective for maintaining the

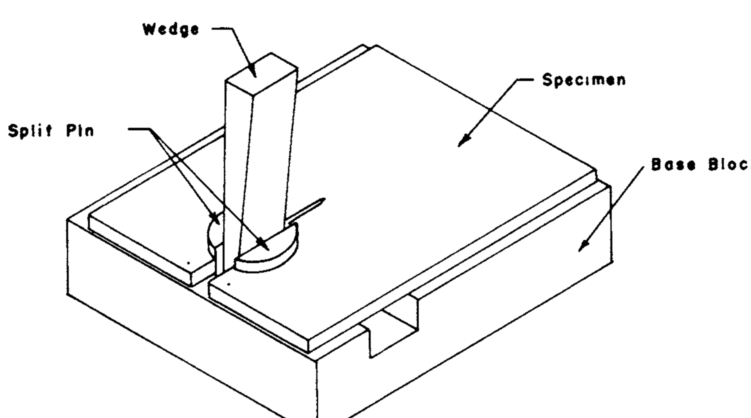


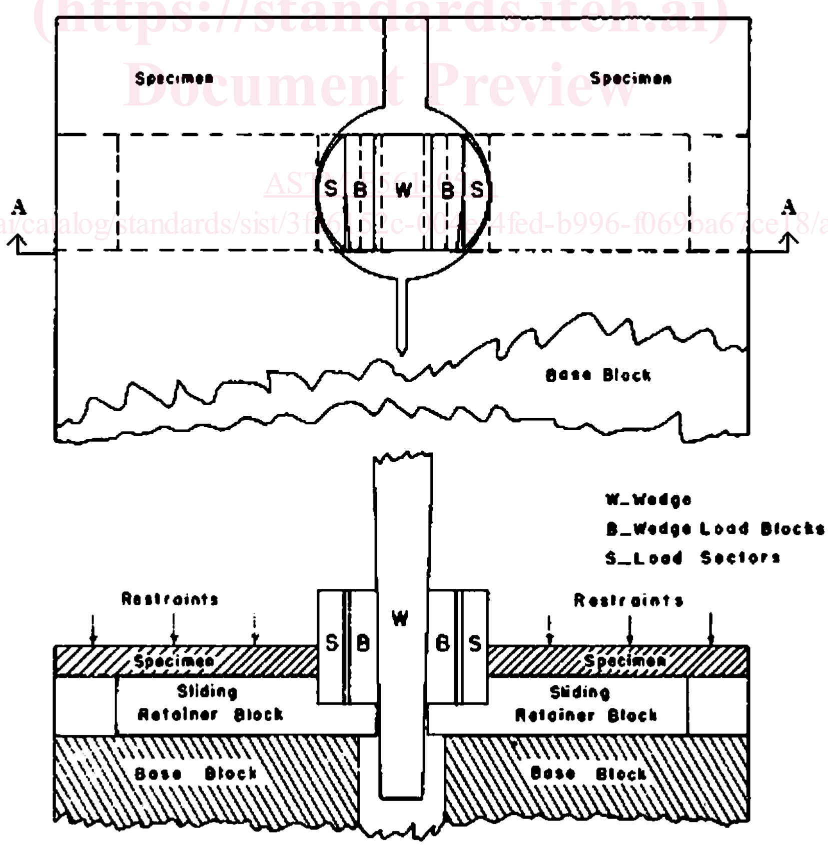
FIG. 3 Crack-Line-Loaded Specimen with Displacement-Controlled Wedge Loading

load line independent of rotation of the specimen arms are provided in Fig. 4. It has been found convenient to use a wedge whose included angle is 3°. With proper lubrication and system alignment, a mechanical advantage of five can be expected. Thus, a loading machine producing ⅕ the maximum expected test force will be adequate. The wedge must be long enough to develop the maximum expected crack-opening displacement. The maximum required stroke can be calculated from the maximum expected displacement v, using the EB ($\Delta v/\Delta P$) values found in Table 1, the maximum expected K level in the test, and the wedge angle.

6.4.2 The wedge-load blocks which drive the load sectors are constrained on top (not shown) and bottom to restrict motion to a plane parallel to the plane of the specimen. This allows the force to be applied or released conveniently without driving the load blocks and sectors out of the hole in the specimen. The wedge-load blocks are designed so that line contact exists between the wedge-load block and the load sector at a point that falls on the load line of the specimen. This enables the load sectors to rotate as the wedge is driven and the original load line is maintained. Any air- or oil hardening tool steel will be suitable for making the wedge and wedge-load blocks. A maraging 300-grade steel should be used for the load sectors. The diameter of the sectors shall be slightly smaller (nominally 0.79 mm (0.03 in.)) than the diameter of the drilled hole in the specimen.

6.5 *Buckling Constraints*—Buckling may develop in unsupported specimens depending upon the sheet thickness, material toughness, crack size, and specimen size (**6**). Buckling seriously affects the validity of a K analysis and is particularly troublesome when using compliance techniques to determine crack size (**7**). It is therefore required that buckling constraints be affixed to the M(T), C(T), and C(W) specimens in critical regions when conditions for buckling are anticipated. A procedure for the detection of buckling is described in 9.8.3.

6.5.1 For an M(T) specimen in tension, the regions above and below the notch are in transverse compression which can cause the specimen to buckle out of plane. The propensity for buckling increases as W/b and $2a/W$ ratios increase and as the force increases. Unless it can be shown by measurement or analysis that buckling will not occur during a test, buckling constraints shall be attached to the central portion of the specimen. The guides shall be so designed to prevent sheet kinking about the crack plane and sheet wrinkling along the specimen width. Buckling constraints should provide a high stiffness constraint against out-of-plane sheet displacements while minimizing friction. Buckling constraints with additional pressure adjustment capability near the center of the specimen are recommended (**6**). Friction between the specimen and the buckling constraints shall not interfere with the in-plane stress distribution in the specimen. Friction can be minimized by using a low-friction coating (such as thin TFE-fluorocarbon



NOTE—Properly dimension section line A-A to show direction.

FIG. 4 Detail of Special Wedge and Split-Pin Setup Designed to Prevent Load-Line Shift

TABLE 1 Dimensionless Stress Intensity Factors and Compliance in Plane Stress for the Recommended C(T) and C(W) Specimens

NOTE—H/W = 0.6.
V_1 at 0.1576W from loading hole centerline; see Fig. 8(a).
V_0 at 0.25W from loading pin centerline; see Fig. 8(a).

a/W^A	C(T) $EB(\Delta\nu/\Delta P)^B$		C(W) $EB(\Delta\nu/\Delta P)^B$	a/W^A	C(T) $EB(\Delta\nu/\Delta P)^B$		C(W) $EB(\Delta\nu/\Delta P)^B$
	at V_0	at V_1	at V_1		at V_0	at V_1	at V_1
0.350	29.89	25.82	22.83	0.480	50.15	44.31	41.52
0.355	30.44	26.33	23.35	0.485	51.24	45.30	42.52
0.360	31.01	26.85	23.88	0.490	52.36	46.33	43.55
0.365	31.59	27.38	24.43	0.495	53.51	47.38	44.61
0.370	32.20	27.94	24.99	0.500	54.71	48.48	45.70
0.375	32.82	28.50	25.57	0.505	55.93	49.60	46.83
0.380	33.45	29.08	26.16	0.510	57.20	50.76	47.99
0.385	34.10	29.68	26.76	0.515	58.51	51.95	49.18
0.390	34.77	30.29	27.38	0.520	59.86	53.19	50.42
0.395	35.46	30.91	28.02	0.525	61.25	54.47	51.70
0.400	36.16	31.55	28.67	0.530	62.70	55.78	53.02
0.405	36.88	32.21	29.33	0.535	64.18	57.15	54.38
0.410	37.62	32.88	30.01	0.540	65.72	58.56	55.79
0.415	38.37	33.57	30.71	0.545	67.32	60.01	57.24
0.420	39.15	34.27	31.42	0.550	68.96	61.52	58.75
0.425	39.94	34.99	32.15	0.555	70.67	63.08	60.31
0.430	40.75	35.73	32.90	0.560	72.43	64.70	61.92
0.435	41.59	36.49	33.67	0.565	74.25	66.37	63.60
0.440	42.44	37.27	34.45	0.570	76.14	68.10	65.32
0.445	43.31	38.07	35.25	0.575	78.10	69.89	67.12
0.450	44.21	38.89	36.08	0.580	80.12	71.74	68.97
0.455	45.14	39.73	36.93	0.585	82.22	73.66	70.89
0.460	46.08	40.60	37.80	0.590	84.40	75.65	72.88
0.465	47.06	41.49	38.69	0.595	86.64	77.72	74.94
0.470	48.06	42.40	39.61	0.600	88.98	79.85	77.07
0.475	49.09	43.34	40.55				

^{A} Inverted form from Ref **(9)**:

$$a/W = C_0 + C_1(U) + C_2(U)^2 + C_3(U)^3 + C_4(U)^4 + C_5(U)^5$$
$$U = 1/[(EB\nu/P)^{1/2} + 1]$$

	C_0	C_1	C_2	C_3	C_4	C_5
C(T) at V_1	+1.0008	−4.4473	+15.400	−180.55	+870.92	−1411.3
C(T) at V_0	+1.0010	−4.6695	+18.460	−236.82	+1214.9	−2143.6

Accuracy is a; ±0.0005W

^{B} From Ref **(10)**:

$$EB\nu/P = A_0 + A_1(a/W) + A_2(a/W)^2 + A_3(a/W)^3 + A_4(a/W)^4$$

	A_0	A_1	A_2	A_3	A_4
C(T) at V_0	+120.7	−1065.3	+4098.0	−6688.0	+4450.5
C(T) at V_1	+103.8	−930.4	+3610.0	−5930.5	+3979.0
C(W) at V_1	+101.9	−948.9	+3691.5	−6064.0	+4054.0

Accuracy ±0.4 %% 0.35 < a/W < 0.60

^{C} From Ref **(11,12)**

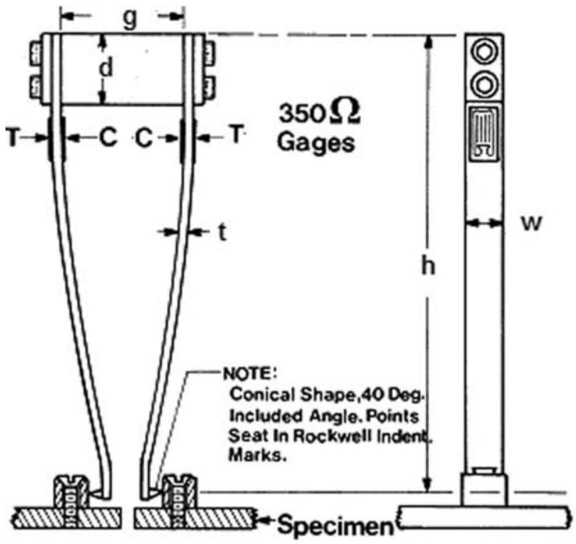
sheet) on the contact surfaces of the constraints and by using just enough clamping force to prevent buckling while allowing free movement of the guides along the length of the specimen. A suspension system to prevent the buckling constraint from sliding down the specimen is recommended. Several buckling constraint configurations for M(T) specimens are shown in **(7)** and **(8)**.

6.5.2 For C(T) and C(W) specimens, the portion of the specimen arms and back edge which are in compression should be restrained from buckling. For sheet specimens, it is convenient to use a base plate and cover plate with ports cut at appropriate locations for attaching clip gages and for crack size observations. Friction between buckling restraints and specimen faces is detrimental and should be minimized as much as possible.

6.5.3 Lubrication shall be provided between the face plates and specimen. Care shall be taken to keep lubricants out of the crack. Sheet TFE-fluorocarbon or heavy oils or both can be used. The initial clamping forces between opposing plates should be high enough to prevent buckling but not high enough to change the stress distribution in the region of the crack tip at any time during the test.

6.6 *Displacement Gages*—Displacement gages are used to accurately measure the crack-mouth opening displacement (CMOD) across the crack at a specified location and span. For small C(W) and C(T) specimens, the gage recommended in Test Method E 399 may have a sufficient linear working range to be used. However, testing specimens with W greater than 127 mm (5 in.) may require gages with a larger working range, such as the gage shown in Fig. 5.

6.6.1 A recommended gage for use in M(T) panels is shown in Fig. 6 **(13)**. This gage is inserted into a machined hole having a circular knife edge. The diameter, d_i, is the gage length $2Y$ and it should be within 3 % of the dimension $2Y$ used



Dimensions				
g mm (in.)	d mm (in.)	t mm (in.)	h mm (in.)	w mm (in.)
23.3 (0.918)	12.7 (0.500)	1.6 (0.062)	86.4 (3.400)	7.6 (0.300)

FIG. 5 Enlarged Clip Gage for Double Compliance Work

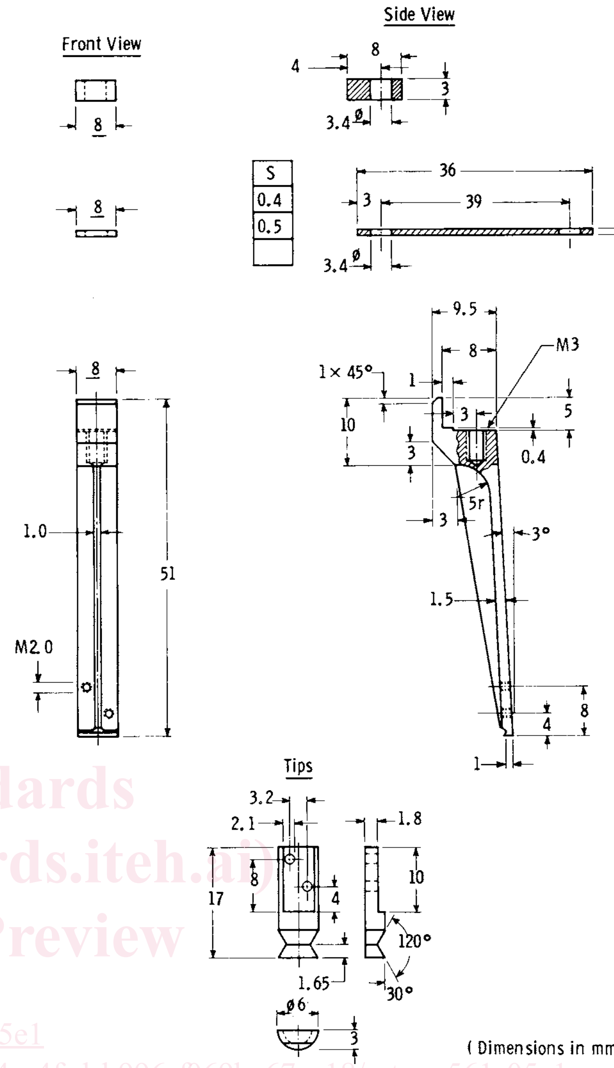


FIG. 7 Detail Drawings of Clip Gage for Use with the M(T) Specimen

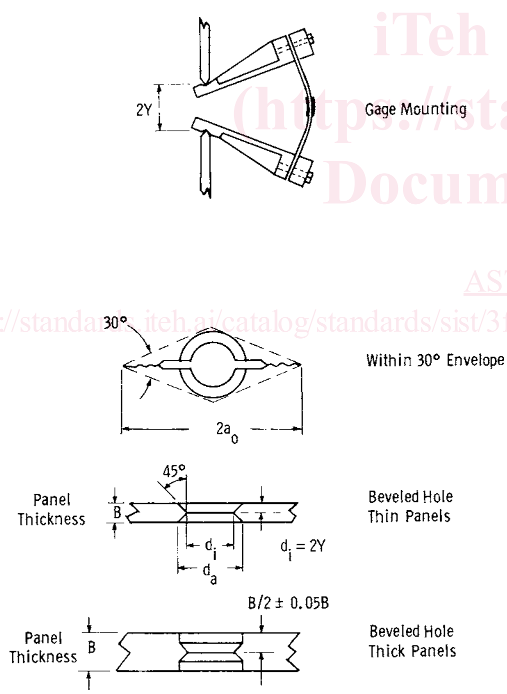


FIG. 6 Recommended Gage for Use in Drilled Hole M(T) Panels

in the calibration. Detail drawings of the gage are given in Fig. 7. Radius of the attachment tip should be less than the radius of the circular knife edge in the specimen.

6.6.2 The gage recommended in 6.6.1 is preferred because of its excellent linearity characteristics and ease of attachment. However, other types of gages used over different span lengths are equally acceptable provided the precision and accuracy requirements are retained. For example, the conventional clip gage of Test Method E 399 may be used with screw attached knife edges spanning the crack at a chosen span $2Y$. In M(T) tests, the proper compliance calibration curve must be used because compliance is a function of Y/W. When using the compliance calibration curve given in Eq 6, the proper $2Y$ value to use with screw-on knife edges is the average distance between attachment points across the notch. This is the actual deformation measurement point, not the gage length of the clip gage itself.

6.6.3 The use of point contacts eliminates error in the readings from the hinge-type rotation of C(T) and C(W) specimens. The precision of all types of gages shall be verified in accordance with the procedure in Test Method E 399. In addition, absolute accuracy within 2 % of reading over the working range of the gage is required for use with compliance measurements. Data for compliance measurements must be taken within the verified range of the gage. The gages shall be verified periodically.

6.7 *Optical Equipment*—If the material being tested is sufficiently thin so that the crack-tip contour does not vary significantly from surface to mid-thickness, crack extension