Designation: E 399 – 90 (Reapproved 1997)

Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials[1]

This standard is issued under the fixed designation E 399; 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.

This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This test method covers the determination of the plane-strain fracture toughness (K_{Ic}) of metallic materials by tests using a variety of fatigue-cracked specimens having a thickness of 0.063 in. (1.6 mm) or greater.[2] The details of the various specimen and test configurations are shown in Annex A1-Annex A7 and Annex A9.

NOTE 1—Plane-strain fracture toughness tests of thinner materials that are sufficiently brittle (see 7.1) can be made with other types of specimens (**1**).[3] There is no standard test method for testing such thin materials.

1.2 This test method also covers the determination of the specimen strength ratio R_{sx} where x refers to the specific specimen configuration being tested. This strength ratio is a function of the maximum load the specimen can sustain, its initial dimensions and the yield strength of the material.

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

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

[1] This test method is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.07 on Linear–Elastic Fracture.

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[2] For additional information relating to the fracture toughness testing of aluminium alloys, see Method B 645.

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

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

Bend Specimen *SE(B)*	Annex A3
Compact Specimen *C(T)*	Annex A4
Arc-Shaped Tension Specimen *A(T)*	Annex A5
Disk-Shaped Compact Specimen *DC(T)*	Annex A6
Arc-Shaped Bend Specimen *A(B)*	Annex A9

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

2. Referenced Documents

2.1 *ASTM Standards:*

E 8 Test Methods for Tension Testing of Metallic Materials[4]

E 337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)[5]

E 338 Test Method of Sharp-Notch Tension Testing of High-Strength Sheet Materials[4]

E 616 Terminology Relating to Fracture Testing[4]

3. Terminology

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

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

3.1.1.1 *Discussion*—Values of *K* for modes 1, 2, and 3 are given by:

$$K_1 = \lim_{r \to o} [\sigma_y (2\pi r)^{1/2}], \quad (1)$$

$$K_2 = \lim_{r \to o} [\tau_{xy} (2\pi r)^{1/2}], \text{ and}$$

$$K_3 = \lim_{r \to o} [\tau_{yz} [\pi_{yz} (2\pi r)^{1/2}],$$

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

3.1.1.2 *Discussion*—In this test method, mode 1 is assumed.

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

3.1.2.1 *Discussion*—For example, in mode 1 for slow rates of loading and negligible plastic-zone adjustment, plane-strain fracture toughness is the value of stress-intensity factor designated $K_{Ic}[FL^{-3/2}]$ as measured using the operational procedure (and satisfying all of the validity requirements) specified in this test method, which provides for the measurement of crack-extension resistance at the start of crack extension and provides operational definitions of crack-tip sharpness, start of crack extension, and crack-tip plane strain.

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

3.1.2.3 *Discussion*—In this test method, mode 1 is assumed.

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

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

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

L = direction of principal deformation (maximum grain flow),
T = direction of least deformation, and
S = third orthogonal direction.

3.1.3.3 *Discussion*—Using a two letter code, the first letter designates the *direction normal* to the crack plane, and the second letter the *expected direction of crack propagation*. For example, in Fig. 1 the *T–L* specimen has a fracture plane whose normal is in the width direction of a plate and an expected direction of crack propagation coincident with the direction of maximum grain flow or longitudinal direction of the plate.

3.1.3.4 *Discussion*—For specimens that are tilted in respect to two of the reference axes, Fig. 2, the orientation is identified by a three-letter code. The code *L–TS*, for example, means that the crack plane is perpendicular to the direction of principal deformation (*L* direction), and the expected fracture direction is intermediate between *T* and *S*. The code *TS–L* means the crack plane is perpendicular to a direction intermediate between *T* and *S*, and the expected fracture direction is in the *L* direction.

3.1.3.5 *Discussion*—For certain cylindrical sections where the direction of principal deformation is parallel to the longitudinal axis of the cylinder, the reference directions are identified as in Fig. 3, which gives examples for a drawn bar. The same system would be useful for extrusions or forged parts having circular cross section.

L = direction of maximum grain flow,
R = radial direction, and
C = circumferential or tangential direction.

4. Summary of Test Method

4.1 This test method involves testing of notched specimens that have been precracked in fatigue by loading either in

[4] *Annual Book of ASTM Standards*, Vol 03.01.

[5] *Annual Book of ASTM Standards*, Vol 11.03.

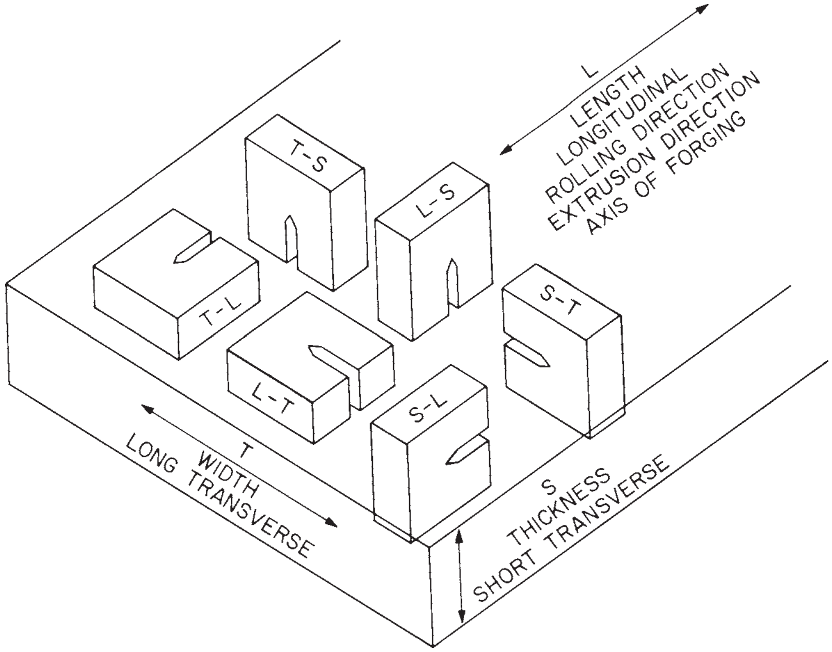


FIG. 1 Crack Plane Orientation Code for Rectangular Sections

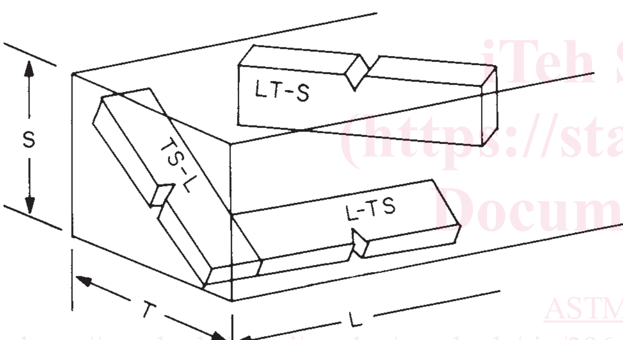


FIG. 2 Crack Plane Orientation Code for Rectangular Sections Where Specimens are Tilted with Respect to the Reference Directions

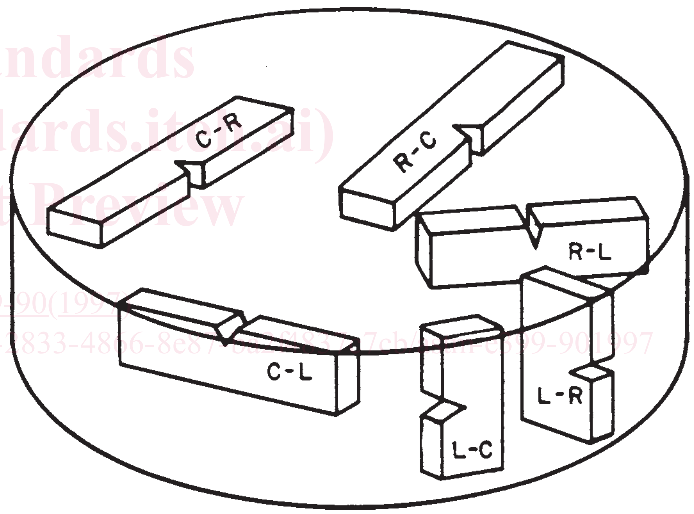


FIG. 3 Crack Plane Orientation Code for Bar and Hollow Cylinder

tension or three-point bending. Load versus displacement across the notch at the specimen edge is recorded autographically. The load corresponding to a 2 % apparent increment of crack extension is established by a specified deviation from the linear portion of the record. The K_{Ic} value is calculated from this load by equations that have been established on the basis of elastic stress analysis of specimens of the types described in this method. The validity of the determination of the K_{Ic} value by this test method depends upon the establishment of a *sharp-crack* condition at the tip of the fatigue crack, in a specimen of adequate size. To establish a suitable crack-tip condition, the stress intensity level at which the fatigue precracking of the specimen is conducted is limited to a relatively low value.

4.2 The specimen size required for testing purposes increases as the square of the ratio of toughness to yield strength of the material; therefore a range of proportional specimens is provided.

5. Significance and Use

5.1 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 tritensile plane strain, and the crack-tip plastic region is small compared with the crack size and specimen dimensions in the constraint direction. A K_{Ic} value is believed to represent a lower limiting value of fracture toughness. This value may be used to estimate the relation between failure stress and defect size for a material in service wherein the conditions of high constraint described above would be expected. Background information concerning the basis for development of this test method in terms of linear elastic fracture mechanics may be found in Refs (**1**) and (**2**).

5.1.1 The K_{Ic} value of a given material is a function of testing speed and temperature. Furthermore, cyclic loads can cause crack extension at K_I values less than the K_{Ic} value. Crack extension under cyclic or sustained load will be increased by the presence of an aggressive environment. Therefore, application of K_{Ic} in the design of service components should be made with awareness to the difference that may exist between the laboratory tests and field conditions.

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

5.1.3 Clearly it will not be possible to determine K_{Ic} if any dimension of the available stock of a material is insufficient to provide a specimen of the required size. In such a case the specimen strength ratio determined by this method will often have useful significance. However, this ratio, unlike K_{Ic}, is not a concept of linear elastic fracture mechanics, but can be a useful comparative measure of the toughness of materials when the specimens are of the same form and size, and that size is insufficient to provide a valid K_{Ic} determination, but sufficient that the maximum load results from pronounced crack propagation rather than plastic instability.

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

5.2 This test method can serve the following purposes:

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

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

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

6. Apparatus

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

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

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

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

6.3.2 Each gage shall be checked for linearity using an extensometer calibrator or other suitable device; the resettability of the calibrator at each displacement interval should be within + 0.000020 in. (0.00050 mm). Readings shall be taken at ten equally spaced intervals over the working range of the gage (see Annex A1). This calibration procedure should be performed three times, removing and reinstalling the gage in the calibration fixture between each run. The required linearity shall correspond to a maximum deviation of + 0.0001 in. (0.0025 mm) of the individual displacement readings from a least-squares-best-fit straight line through the data. The absolute accuracy, as such, is not important in this application, since the method is concerned with relative changes in displacement rather than absolute values (see 9.1).

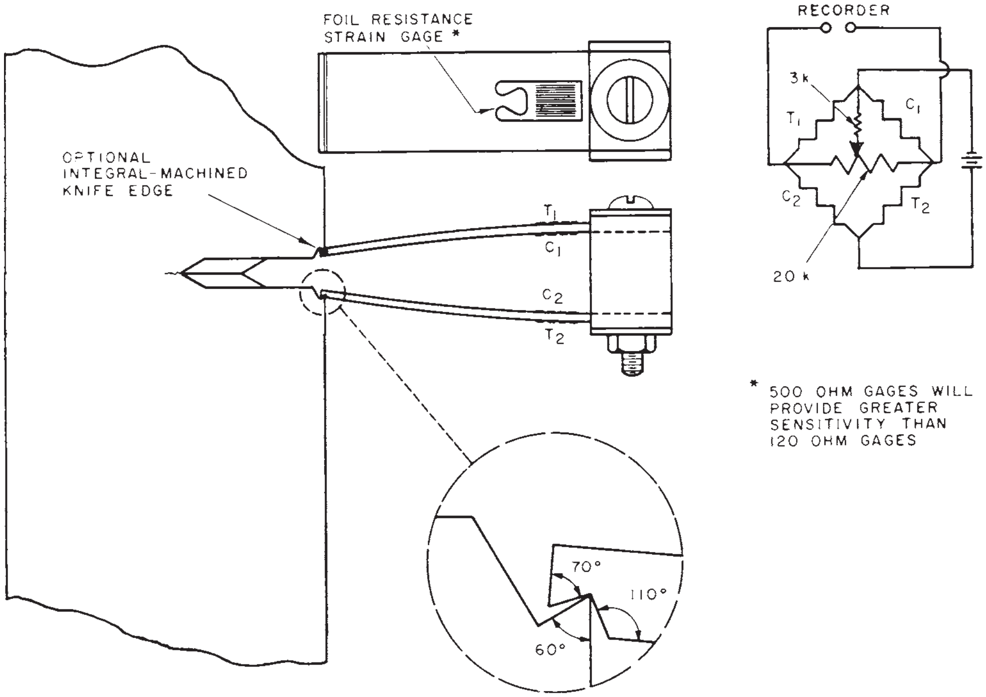
6.3.3 It is not the intent of this method to exclude the use of other types of gages or gage-fixing devices provided the gage used meets the requirements listed below and provided the gage length does not exceed those limits given in the annex appropriate to the specimen being tested.

7. Specimen Size, Configurations, and Preparation

7.1 *Specimen Size*:

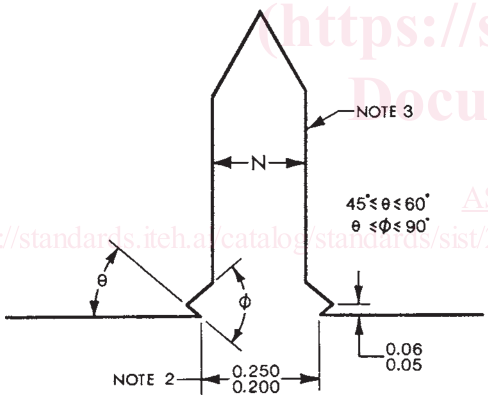
7.1.1 In order for a result to be considered valid according to this method it is required that both the specimen thickness, B, and the crack length, a, exceed $2.5\ (K_{Ic}/\sigma_{YS})^2$, where σ_{YS} is the 0.2 % offset yield strength of the material for the temperature and loading rate of the test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

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



NOTE—Gage details are given in the Annex.

FIG. 4 Double–Cantilever Clip-In Displacement Gage Showing Mounting by Means of Integral Knife Edges (Gage Design Details are Given in Annex A1)



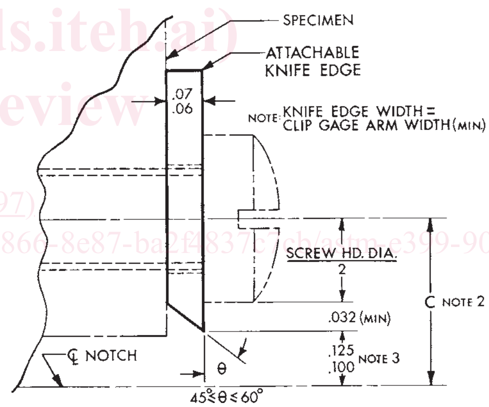
NOTE 1—Dimensions in inches.

NOTE 2— Gage length shown corresponds to clip gage spacer block dimensions shown in Annex A1, but other gage lengths may be used provided they are appropriate to the specimen (see 6.3.3).

NOTE 3—For starter notch configurations see Fig. 7.

in.	0.050	0.060	0.200	0.250
mm	1.3	1.5	5.1	6.4

FIG. 5 Example of Integral Knife Edge Design



NOTE 1—Dimensions are in inches.

NOTE 2—Effective gage length = 2*C* + Screw Thread Diameter ≤ *W/2*. (This will always be greater than the gage length specified in A1.1.)

NOTE 3—Dimension shown corresponds to clip gage spacer block dimension in Annex A1.

Metric Equivalents

in.	0.032	0.06	0.07	0.100	0.125
mm	0.81	1.5	1.8	2.54	3.18

FIG. 6 Example of Attachable Knife Edge Design

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

σ_{YS}/E	Minimum Recommended Thickness and Crack Length, in.	Minimum Recommended Thickness and Crack Length, mm
0.0050 to 0.0057	3	75
0.0057 to 0.0062	2½	63
0.0062 to 0.0065	2	50
0.0065 to 0.0068	1¾	44
0.0068 to 0.0071	1½	38
0.0071 to 0.0075	1¼	32
0.0075 to 0.0080	1	25
0.0080 to 0.0085	¾	20
0.0085 to 0.0100	½	12½
0.0100 or greater	¼	6½

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

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

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

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

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

7.3.1 *Fatigue Crack Starter Notch*—Three forms of fatigue crack starter notches are shown in Fig. 7. To facilitate fatigue cracking at low stress intensity levels, the root radius for a straight-through slot terminating in a V-notch should be 0.003 in. (0.08 mm) or less. If a chevron form of notch is used, the root radius may be 0.010 in. (0.25 mm) or less. In the case of a slot tipped with a hole it will be necessary to provide a sharp stress raiser at the end of the hole. Care should be taken to ensure that this stress raiser is so located that the crack plane orientation requirements (8.2.4) can be met.

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

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

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

8. General Procedure

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

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

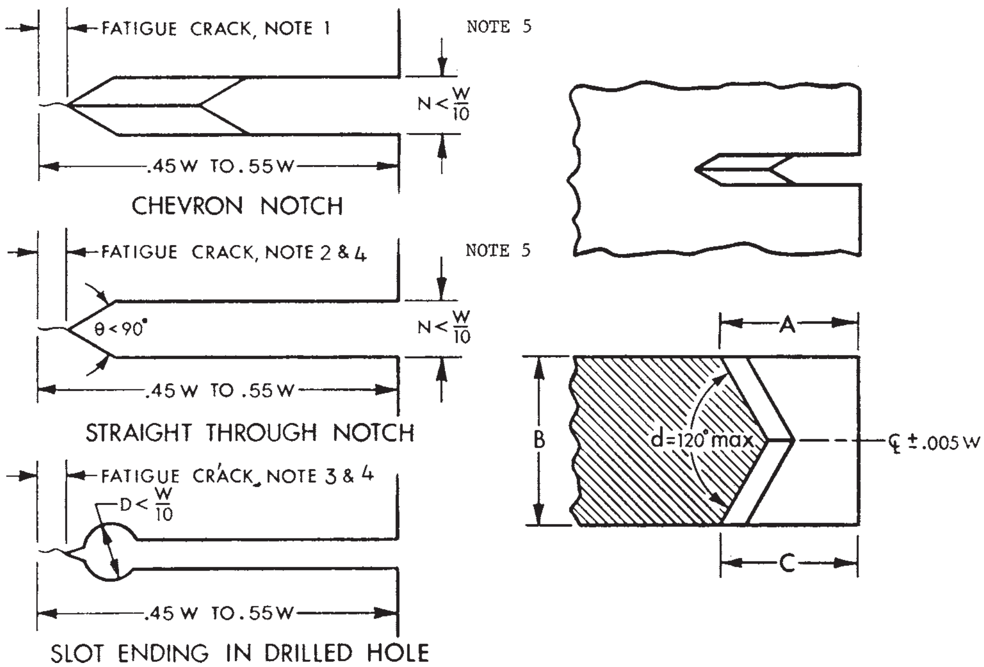
8.2.1 Measure the thickness, *B*, to the nearest 0.001 in. (0.025 mm) or to 0.1 %, whichever is larger, at not less than three equally spaced positions along the line of intended crack extension from the fatigue crack tip to the unnotched side of the specimen. The average of these three measurements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

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

8.2.3 Measure the width, *W*, as described in the annex appropriate to the specimen type being tested.

8.2.4 The plane of the crack shall be parallel to both the specimen width and thickness direction within ±10° (**7**).

8.3 *Loading Rate*—For conventional (static) testing load the specimen at a rate such that the rate of increase of stress intensity is within the range from 30 000 to 150 000 psi ·



(*a*) Starter Notches and Fatigue Cracks

(*b*) Detail of Chevron Notch

NOTE 1—For a chevron crack starter notch the fatigue crack shall emerge on both surfaces of the specimen.

NOTE 2—Fatigue crack extension on each surface of the specimen containing a straight-through notch shall be at least 0.025 *W* or 0.050 in. (1.3 mm), whichever is larger.

NOTE 3—Fatigue crack extension on each surface of the specimen from the stress raiser tipping the hole shall be at least 0.5 *D* or 0.050 in. (1.3 mm), whichever is larger.

NOTE 4—Crack starter notch shall be perpendicular to the specimen surfaces and to the intended direction of crack propagation within ±2°.

NOTE 5—Notch width *N* need not be less than 1⁄16 in. (1.6 mm).

NOTE 1—A = C within 0.010 W

NOTE 2—Cutter tip angle 90° max

NOTE 3—Radius at chevron notch bottom 0.010 in. (0.25 mm) max

FIG. 7 Crack Starter Notch and Fatigue Crack Configurations

in.$^{1/2}$/min (0.55 to 2.75 MPa·m$^{1/2}$/s). The loading rates corresponding to these stress intensity rates are given in the appropriate annex for the specimen being tested. For rapid-load testing the loading rates are given in Annex A7.

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

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

9. Calculation and Interpretation of Results

9.1 *Interpretation of Test Record and Calculation of* K_{Ic}—In order to establish that a valid K_{Ic} has been determined, 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 the size and yield strength of the specimen according to 7.1. The procedure is as follows:

9.1.1 Draw the secant line OP_5, shown in Fig. 7 through the origin of the test record with slope $(P/v)_5 = 0.95\ (P/v)_o$, where $(P/v)_o$ is the slope of the tangent OA to the initial linear part of the record (Note 2). The load P_Q is then defined as follows: if the load at every point on the record which precedes P_5 is lower than P_5, then P_5 is P_Q (Fig. 8 Type I); if, however, there is a maximum load preceding P_5 which exceeds it, then this maximum load is P_Q(Fig. 8 Types II and III).

NOTE 2—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 load not producing a stress intensity level exceeding that used in the final stage of fatigue cracking.

9.1.2 Calculate the ratio P_{max}/P_Q, where P_{max} is the maximum load the specimen was able to sustain (see 8.4). If this ratio does not exceed 1.10, proceed to calculate K_Q as described in the annex appropriate to the specimen being tested. If P_{max}/P_Q does exceed 1.10, then the test is not a valid

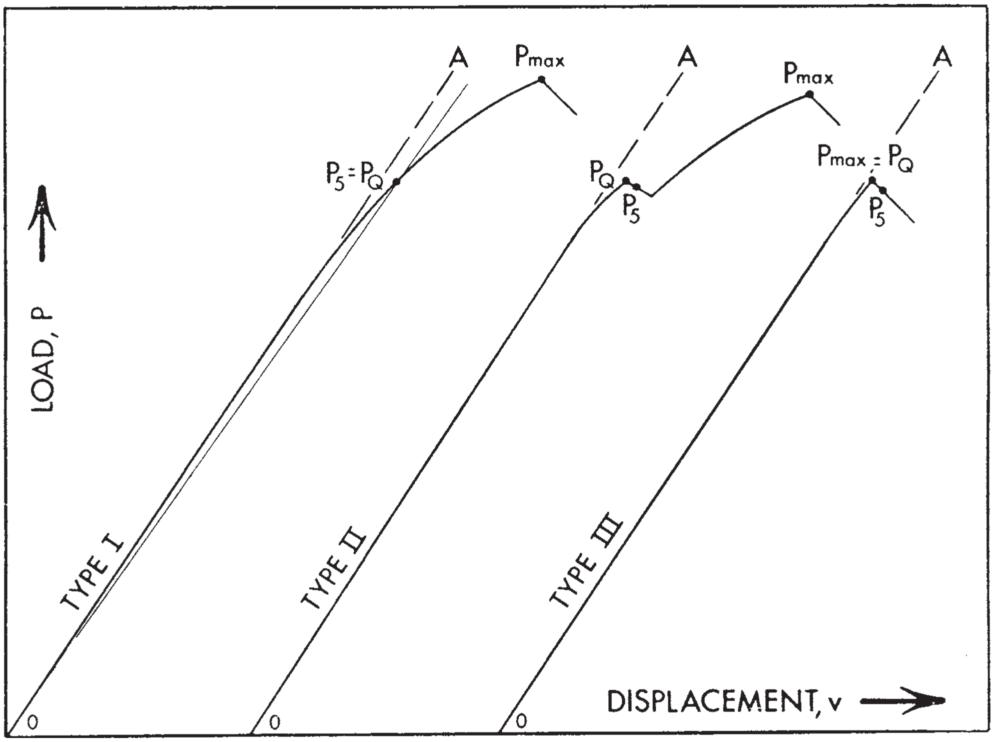


FIG. 8 Principal Types of Load-Displacement Records

K_{Ic} test because it is then possible that K_Q bears no relation to K_{Ic}. In this case proceed to calculate the specimen strength ratio.

9.1.3 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). If this quantity is less than both the specimen thickness and the crack length, then K_Q is equal to K_{Ic}. Otherwise, the test is not a valid K_{Ic} test. Expressions for calculations of K_Q are given in the annex appropriate to the specimen being tested.

9.1.4 If the test result fails to meet the requirements in 9.1.2 or in 9.1.3, or both, it 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 valid K_{Ic} value.

9.1.5 Calculate the specimen-strength ratio R_{sx} *according to the annex appropriate to the specimen being tested.*

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

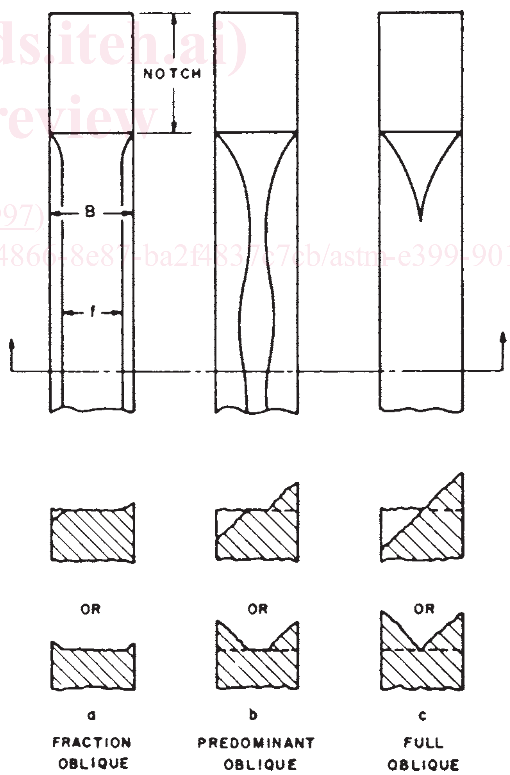


FIG. 9 Common Types of Fracture Appearance

10. Report

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

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

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

10.2.2 Thickness, B.

10.2.3 Width (depth), W.

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

10.2.3.2 Outer and inner radii, r_2 and r_1, for arc-shaped specimens.

10.2.4 Fatigue precracking conditions in terms of:

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

10.2.4.2 The stress intensity range for terminal crack extension.

10.2.5 Crack length measurements:

10.2.5.1 At center of crack front;

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

10.2.6 Test temperature.

10.2.7 Relative humidity as determined by Test Method E 337.

10.2.8 Loading rate in terms of $\dot{K}_I$ (change in stress intensity factor per unit time) (**2**).

10.2.9 Load-displacement record and associated calculations.

10.2.10 Fracture appearance.

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

10.2.12 K_{Ic}; or, K_Q followed by the parenthetical statement "invalid according to section(s) ..... of ASTM Test Method E 399."

10.2.13 R_{sx} where x refers to the specimen configuration as given in the appropriate annex.

10.2.14 P_{max}/P_Q.

10.3 It is desirable to list the information required in 10.1 and 10.2 in the form of a table. A suggested form for such a table is given in Fig. 10.

11. Precision and Bias

11.1 Information on the precision of K_{Ic} measurements may be obtained from the results of several interlaboratory programs. Such programs, incorporating selected high strength alloys, have been reported for the bend specimen (**8, 9**), the compact specimen (**9**), and arc-shaped specimen (**18**). The results of these programs are summarized in this section. Interlaboratory programs of a more restrictive nature were also completed for beryllium and for dynamic plane strain fracture measurements on a strain rate sensitive steel. Summaries of the results from these two interlaboratory programs are presented in Annex A7 and Annex A8 because certain special procedures are involved. No interlaboratory program was conducted for the disk-shaped specimen, but some data comparing results

TABLE 1 Estimates of Precision for K_{Ic} Measurements for Three Specimen Types

	2219-T851 σ_{YS} = 353 MPa (51.0 ksi)	4340 σ_{YS} = 1640 MPa (238 ksi)	18Ni Mar σ_{YS} = 1902 MPa (276 ksi)	4340 σ_{YS} = 1419 MPa (206 ksi)
	Bend Specimens			
Grand mean, $\bar{X}^{A,B}$	35.9 (32.7)	48.2 (43.9)	56.9 (51.8)	86.7 (78.9)
Standard deviation, $S^{A,B}$	2.06 (1.87)	2.08 (1.89)	2.24 (2.04)	3.67 (3.34)
	Compact Specimens			
Grand Mean, $\bar{X}^{A,B}$	35.6 (32.4)	50.0 (45.5)	58.2 (53.0)	87.3 (79.4)
Standard deviation, $S^{A,B}$	1.24 (1.13)	1.40 (1.27)	1.80 (1.64)	1.96 (1.78)
	Arc-tension specimens 4335V σ_{YS} = 1320 MPa (192 ksi)			
	X/W = 0		X/W = 0.5	
Grand mean, $\bar{X}^{A,B}$	112.4 (102.3)		111.8 (101.7)	
Standard deviation, $S^{A,B}$	3.85 (3.50)		2.59 (2.36)	

[A] Units of grand mean and standard deviation are MPa m$^{1/2}$ (ksi in.$^{1/2}$).

[B] The standard deviation has been pooled for all laboratories testing a given alloy. For data on which this Table was based, see Refs **(8, 9)** for the bend specimen, Ref **(9)** for the compact specimen, and Ref **(18)** for the arc-tension specimen.

from that specimen design with those from other specimen designs are given in Annex A6. It should be mentioned that not all of the results reported for the bend, compact and arc-shaped specimens met all the validity requirements. Statistical analysis (**17, 18**) was used to exclude data that were judged to be influenced by deviations from the validity requirements.

11.2 *Precision*—The precision of a K_{Ic} determination depends in part on errors in the load and in the various required measurements of specimen dimensions including crack length. The method specifies a precision for each of these quantities and, based on this information coupled with the K determination, a theoretical precision has been developed (**33**). This analysis shows that precision decreases with increasing relative crack length and is somewhat higher for the compact than for the bend specimen. In actual practice, the precision of a K_{Ic} measurement will depend to an unknown extent on the characteristics and analysis of the test record. It is possible to derive useful information concerning the precision of a K_{Ic} measurement from the interlaboratory test programs. The results of these interlaboratory programs for the bend, compact and arc-shaped specimen are given in Table 1 for tests on several high strength alloys. These particular alloys were chosen because they are known to be producible with very uniform composition and microstructure. Thus the contribution of material variability to the measurements of K_{Ic} *was* minimized. It should be understood that the measures of precision listed in Table 1 apply to alloys which do not exhibit strong transitional fracture behavior with changes in temperature or strain rate. When temperature and strain rate variations induce large changes in toughness, increased scatter in K_{Ic} measurements may be noted. For example, within or below the transition range of a structural steel, the initial advance from the fatigue crack will be controlled by the abrupt fracture of

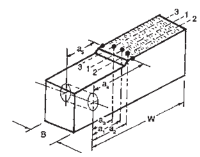
K_{Ic} DATA SHEET

(SAMPLE)

MATERIAL/FORM ____________________ HEAT TREAT ____________________

SPECIMEN I.D. ____________________ SPECIMEN TYPE ____________________

DATE ____/____/____ DATE REPORT



PARTICULARS	DATA	REF. PARAGRAPH
● Crack Plane Orientation		9.2
● Material 0.2% Offset Yield Strength, σ_{ys}, per E8		7.1.1
● Thickness, B		8.2.1
● Depth (Width), W	———	8.2.2
for - SE(B)		3.4.1 (Annex 3)
for - C(T)		4.4.1 (Annex 4)
for - DC(T)		6.4.1.2(Annex 6)
○ *Arc Shaped Specimen* -		
— Width, W		5.4.1 (Annex 5)
— Loading Hole Offset, X		5.4.1 (Annex 5)
— Outer and Inner Radii, r_1 & r_2		5.4.1 (Annex 5)

FATIGUE PRECRACKING	DATA	REF. PARAGRAPH
● $\frac{K_{max}}{E} < 0.002 in^{1/2}$ $(0.00032 m^{1/2})$		A2.3.3
● $K_{max} < 0.6\ K_Q$		A2.3.3
● $K_{max} \leq 0.8\ K_{Ic}$		A2.4.1 and A2.4.2
○ *at Temperature*		
— $K_{maxT1} \left[\frac{\sigma_{ys(T1)}}{\sigma_{ys(T2)}}\right] .6\ K_Q\ (T2)$		A2.4.4
○ *Crack Length - Starter Slot plus Fatigue*		
— a = 0.50W		A2.3.2 and Figure 4
— K_{max}, ΔK		
— Cycles for last 2.5% of "a"		

FRACTURE TEST	DATA	REF. PARAGRAPH
● *Crack Lengths* -		
— At Center of Crack Front (a_1)		8.2.2
— At Right of Center (a_2)		8.2.2
— At Left of Center (a_3)		8.2.2
— At Right of Surface (a_4)		8.2.2
— At Left Surface (a_5)		8.2.2
— Crack Plane Symmetry		8.2.4
— Loading Rate (ksi $\sqrt{in.}$/min.)		8.3
— Test Temperature		10.2.6
— Relative Humidity		10.2.7
— Load-Displacement Record		8.4 & 9.1

CALCULATION OF K & R_{sx}	DATA	REF. PARAGRAPH
● $P_{max}/P_Q < 1.1$		9.1.2
— K_Q SE(B)		3.5.3 (Annex 3)
— K_Q C(T)		4.5.3 (Annex 4)
— K_Q A(T)		5.5.3 (Annex 5)
— K_Q DC(T)		6.5.3 (Annex 6)
● Valid K_{Ic}		9.1.3
— R_{sx}		9.1.5

FIG. 10 Suggested Form of Table for Reporting Information Listed in 10.1 and 10.2

local elements at the crack tip, accompanied by rapid transfer of load to adjacent regions which may then exhibit cleavage fracture. Under these circumstances, a specimen size effect may be observed in which both the mean and the standard deviation of K_{Ic} values tend to increase with decreasing specimen size.

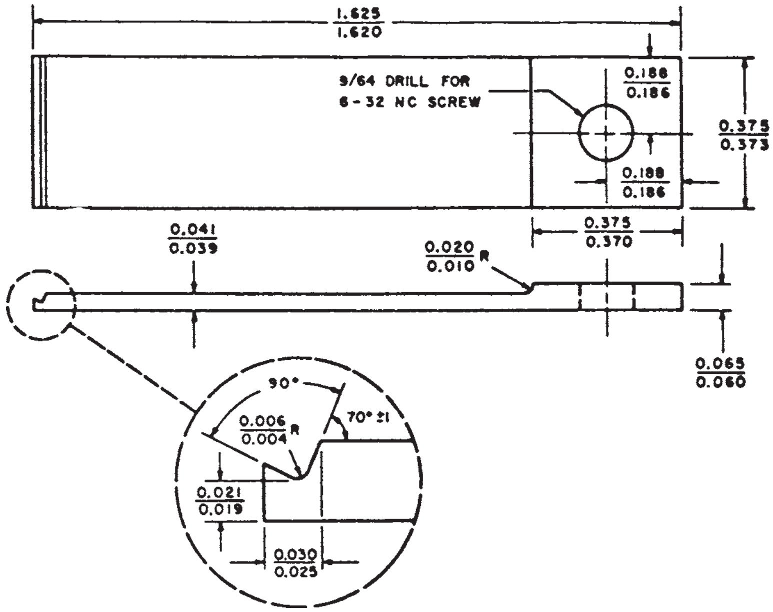
11.3 *Bias*—There is no accepted "standard" value for the plane strain fracture toughness of any material. In the absence of such a true value, any statement concerning bias is not meaningful.

ANNEXES

(Mandatory Information)

A1. DESIGN FOR DOUBLE-CANTILEVER DISPLACEMENT GAGE

A1.1 The gage consists of two cantilever beams and a spacer block which are clamped together with a single nut and bolt, as shown in Fig. 4. Electrical-resistance strain gages are cemented to the tension and compression surfaces of each beam, and are connected as a Wheatstone bridge incorporating a suitable balancing resistor. The material for the gage beams should have a high ratio of yield strength to elastic modulus, and titanium alloy 13V-11Cr-3Al in the solution treated condition has been found very satisfactory for this purpose. If a material of different modulus is substituted, the spring constant of the assembly will change correspondingly, but the other characteristics will not be affected. Detailed dimensions for the beams and spacer block are given in Fig. A1.1 and Fig. A1.2. For these particular dimensions the linear range (working range) is from 0.15 to 0.30 in. (3.8 to 7.6 mm) and the recommended gage length is from 0.20 to 0.25 in. (5.1 to 6.3 mm). The clip gage can be altered to adapt it to a different gage length by substituting a spacer block of appropriate height. As discussed in 6.3.2 the required precision of the gage corresponds to a maximum deviation of ±0.0001 in. (0.0025 mm) of the displacement readings from a least-squares-best-fit straight line through the data. Further details concerning design, construction and use of these gages are given in Ref (**10**).



NOTE 1—Dimensions are in inches.

Metric Equivalents

in.	mm	in.	mm
0.004	0.10	0.060	1.52
0.006	0.15	0.065	1.65
0.010	0.25	9⁄64	3.6
0.019	0.48	0.186	4.72
0.020	0.51	0.188	4.78
0.021	0.53	0.370	9.40
0.025	0.64	0.373	9.47
0.030	0.76	0.375	9.52
0.039	0.99	1.620	41.15
0.041	1.04	1.625	41.28

FIG. A1.1 Beams for Double-Cantilever Displacement Gage