# Standard Test Method for Plane-Strain (Chevron-Notch) Fracture Toughness of Metallic Materials[1]

This standard is issued under the fixed designation E 1304; 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 the determination of plane-strain (chevron-notch) fracture toughnesses, $K_{Iv}$ or $K_{IvM}$, of metallic materials. Fracture toughness by this method is relative to a slowly advancing steady state crack initiated at a chevron-shaped notch, and propagating in a chevron-shaped ligament (Fig. 1). Some metallic materials, when tested by this method, exhibit a sporadic crack growth in which the crack front remains nearly stationary until a critical load is reached. The crack then becomes unstable and suddenly advances at high speed to the next arrest point. For these materials, this test method covers the determination of the plane-strain fracture toughness, $K_{Ivj}$ or $K_{IvM}$, relative to the crack at the points of instability.

NOTE 1—One difference between this test method and Test Method E 399 (which measures $K_{Ic}$) is that Test Method E 399 centers attention on the start of crack extension from a fatigue precrack. This test method makes use of either a steady state slowly propagating crack, or a crack at the initiation of a crack jump. Although both methods are based on the principles of linear elastic fracture mechanics, this difference, plus other differences in test procedure, may cause the values from this test method to be larger than $K_{Ic}$ values in some materials. Therefore, toughness values determined by this test method cannot be used interchangeably with $K_{Ic}$.

1.2 This test method uses either chevron-notched rod specimens of circular cross section, or chevron-notched bar specimens of square or rectangular cross section (Figs. 1-10). The terms "short rod" and "short bar" are used commonly for these types of chevron-notched specimens.

1.3 *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.*
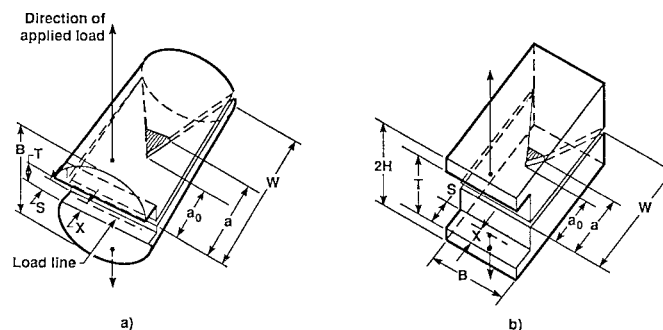
## 2. Referenced Documents

2.1 *ASTM Standards:*
E 4 Practice for Force Verification of Testing Machines[2]

NOTE 1—The crack commences at the tip of the chevron-shaped ligament and propagates (shaded area) along the ligament, and has the length "a" shown. (Not to scale.)

**FIG. 1 Schematic Diagrams of Chevron-Notched Short Rod (a) and Short Bar (b) Specimens**

E 8 Test Methods for Tension Testing of Metallic Materials[2]
E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[2]
E 1823 Terminology Relating to Fatique and Fracture Testing[2]

## 3. Terminology

3.1 *Definitions:*

3.1.1 The terms described in Terminology E 1823 are applicable to this test method.

3.1.2 *stress-intensity factor,* $K_I$ (dimensional units $FL^{-3/2}$)— the magnitude of the ideal crack-tip stress field singularity for mode I in a homogeneous linear-elastic body.

3.1.2.1 *Discussion*—Values of K for mode *I* are given by:

$$K_I = \text{limit } \sigma_y \, [2\pi r_x]^{1/2}$$

$$r_x \rightarrow 0$$

where:
$r_x$ = a distance directly forward from the crack tip to a location where the significant stress is calculated and
$\sigma_y$ = the principal stress $r_x$ normal to the crack plane.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *plane-strain (chevron-notch) fracture toughness,* $K_{Iv}$ or $K_{Ivj}$ ($FL^{-3/2}$)—under conditions of crack-tip plane strain in a chevron-notched specimen: $K_{Iv}$ relates to extension resistance with respect to a slowly advancing steady-state crack. $K_{Ivj}$
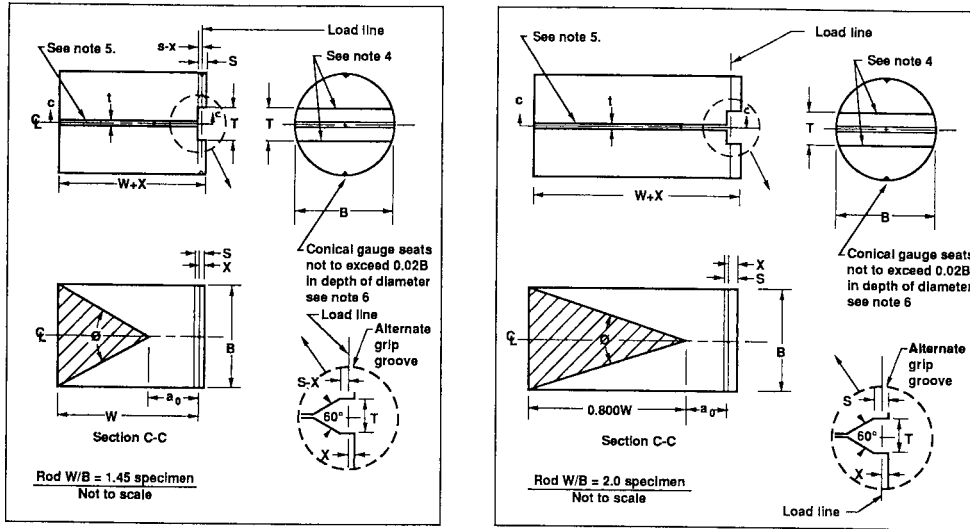
NOTE 1—See Table 1 for tolerances and other details.
**FIG. 2 Rod Specimens Standard Proportions**
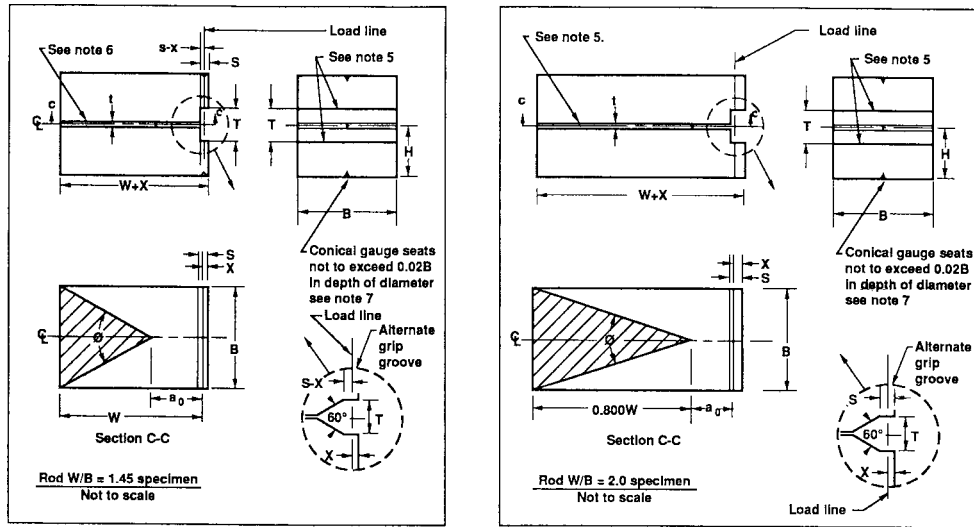


NOTE 1—See Table 2 for tolerances and other details.
**FIG. 3 Bar Specimens Standard Proportions**

relates to crack extension resistance with respect to a crack which advances sporadically.

3.2.1.1 *Discussion*—For slow rates of loading the fracture toughness, $K_{Iv}$ or $K_{Ivj}$, is the value of stress-intensity factor as measured using the operational procedure (and satisfying all of the validity requirements) specified in this test method.

3.2.2 *plane-strain (chevron-notch) fracture toughness,* $K_{IvM}$ (FL$^{-3/2}$)—determined similarly to $K_{Iv}$ or $K_{Ivj}$ (see 3.2.1) using the same specimen, or specimen geometries, but using a simpler analysis based on the maximum test force. The analysis is described in Annex A1. Unloading-reloading cycles as described in 3.2.6 are not required in a test to determine $K_{IvM}$.

3.2.3 *smooth crack growth behavior*—generally, that type of crack extension behavior in chevron-notch specimens that is characterized primarily by slow, continuously advancing crack growth, and a relatively smooth force displacement record

(Fig. 4). However, any test behavior not satisfying the conditions for crack jump behavior is automatically characterized as smooth crack growth behavior.

3.2.4 *crack jump behavior*—in tests of chevron-notch specimens, that type of sporadic crack growth which is characterized primarily by periods during which the crack front is nearly stationary until a critical force is reached, whereupon the crack becomes unstable and suddenly advances at high speed to the next arrest point, where it remains nearly stationary until the force again reaches a critical value, etc. (see Fig. 5).

3.2.4.1 *Discussion*—A chevron-notch specimen is said to have a crack jump behavior when crack jumps account for more than one half of the change in unloading slope ratio (see 3.2.6) as the unloading slope ratio passes through the range from $0.8r_c$ to $1.2r_c$ (see 3.2.6 and 3.2.7, and 8.3.5.2). Only those sudden crack advances that result in more than a 5 % decrease in force during the advance are counted as crack jumps (Fig. 5).
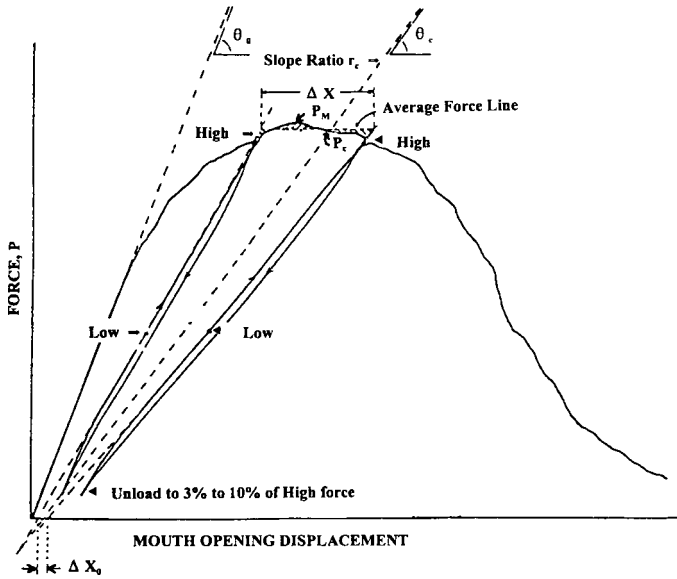
2

**FIG. 4 Schematic of a Load-Displacement Test Record for Smooth Crack Growth Behavior, with Unloading/Reloading Cycles, Data Reduction Constructions, and Definitions of Terms**
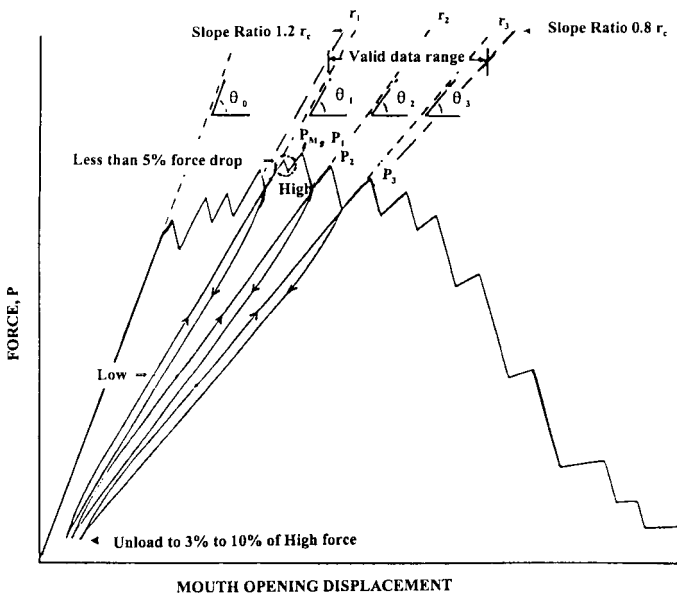


**FIG. 5 Schematic of a Load-Displacement Test Record for Crack Jump Behavior, with Unloading/Reloading Cycles, Data Reduction Constructions, and Definitions of Terms**

3.2.5 *steady-state crack*—a crack that has advanced slowly until the crack-tip plastic zone size and crack-tip sharpness no longer change with further crack extension. Although crack-tip conditions can be a function of crack velocity, the steady-state crack-tip conditions for metals have appeared to be independent of the crack velocity within the range attained by the loading rates specified in this test method.

3.2.6 *effective unloading slope ratio, r*—the ratio of an effective unloading slope to that of the initial elastic loading slope on a test record of force versus specimen mouth opening displacement.

3.2.6.1 *Discussion*—This unloading slope ratio provides a method of determining the crack length at various points on the
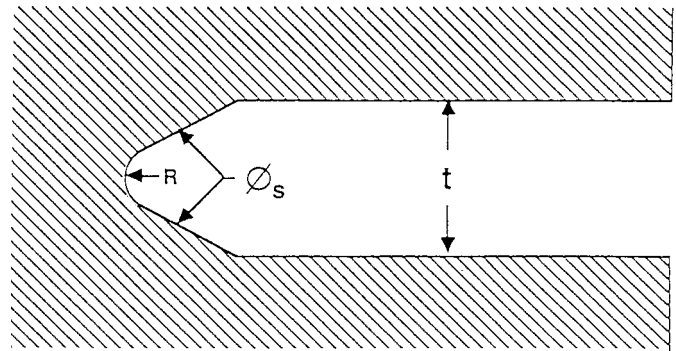


$R \leq 0.010B$
$\phi_s \leq 60°$
$t \leq 0.03B$

Note 1—These requirements are satisfied by slots with a round bottom whenever $t \leq 0.020B$.

**FIG. 6 Slot Bottom Configuration**
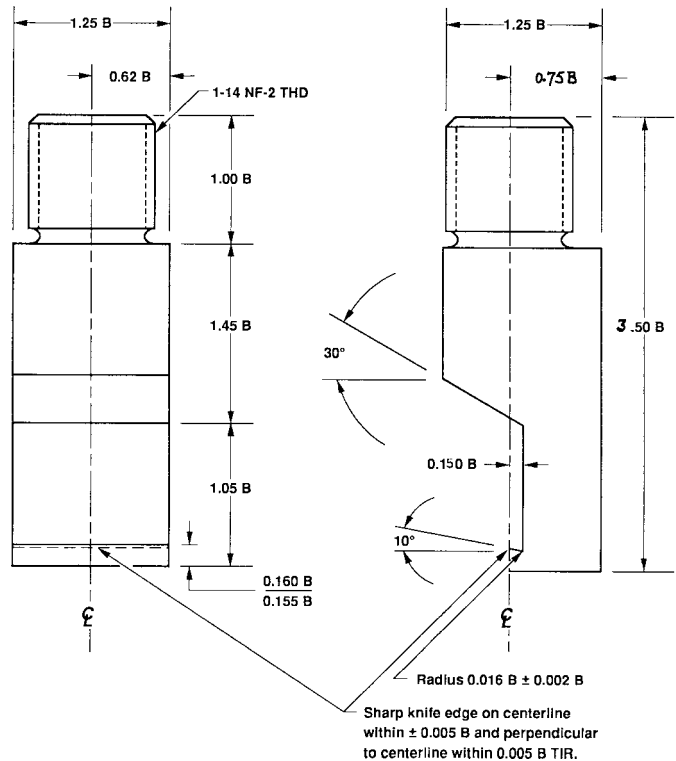


Note 1—Machine finish all over equal to or better than 64 μin.

Note 2—Unless otherwise specified, dimensions ±0.010$B$; angles ±2°.

Note 3—Grip hardness should be RC = 45 or greater.

**FIG. 7 Suggested Loading Grip Design**

test record and therefore allows evaluation of stress intensity coefficient $Y^*$ (see 3.2.11). The effective unloading slope ratio is measured by performing unloading-reloading cycles during the test as indicated schematically in Fig. 4 and Fig. 5. For each unloading-reloading trace, the effective unloading slope ratio, $r$, is defined in terms of the tangents of two angles:

$$r = \tan\theta/\tan\theta_o$$
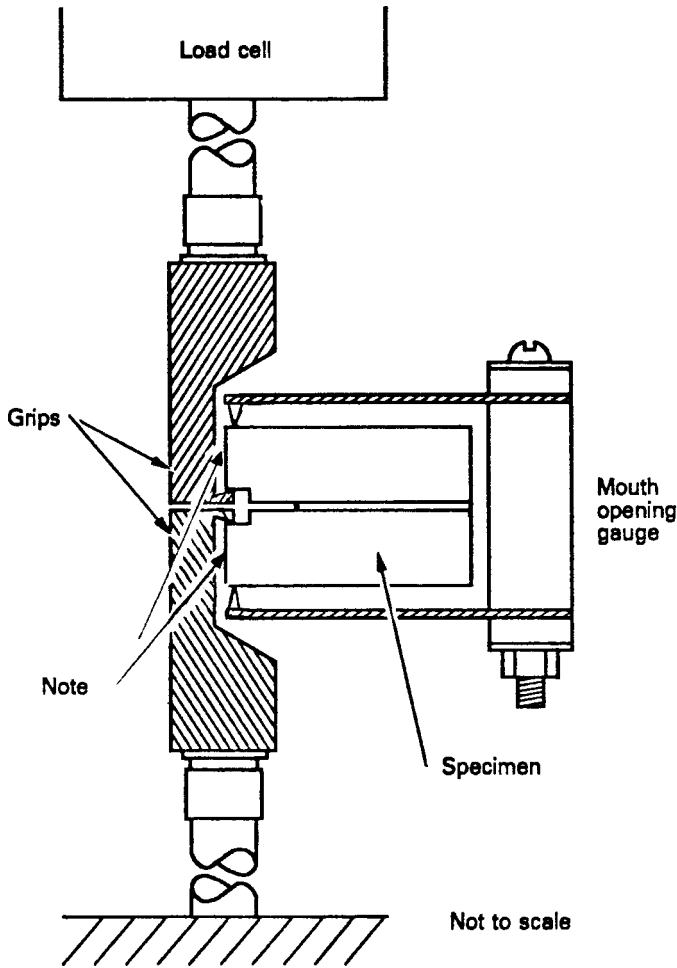
NOTE 1—To assist alignment, shims may be placed at these locations and removed before the load is applied, as described in 8.3.2.

**FIG. 8 Recommended Tensile Test Machine Test Configuration**



**FIG. 9 Suggested Design for the Specimen Mouth Opening Gage**
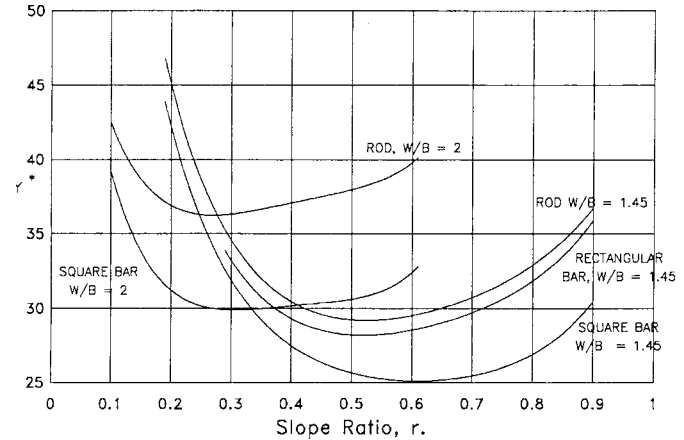


NOTE 1—Compiled from Refs **(8)**, **(10)**, **(11)**, and **(13)**.

**FIG. 10 Normalized Stress-Intensity Factor Coefficients as a Function of Slope Ratio (r) for Chevron-Notch Specimens**

where:

$\tan \theta_o$ = the slope of the initial elastic line, and
$\tan \theta$ = the slope of an effective unloading line.

The effective unloading line is defined as having an origin at the high point where the displacement reverses direction on unloading (slot mouth begins to close) and joining the low point on the reloading line where the force is one half that at the high point.

3.2.6.2 *Discussion*—For a brittle material with linear elastic behavior the unloading-reloading lines of an unloading-reloading cycle would be linear and coincident. For many engineering materials, deviations from linear elastic behavior and hysteresis are commonly observed to a varying degree. These effects require an unambiguous method of obtaining an effective unloading slope from the test record **(1-4)**.[3]

3.2.6.3 *Discussion*—Although *r* is measured only at those crack positions where unloading-reloading cycles are performed, *r* is nevertheless defined at all points during a chevron-notch specimen test. For any particular point it is the value that would be measured for *r* if an unloading-reloading cycle were performed at that point.

3.2.7 *critical slope ratio, $r_c$* —the unloading slope ratio at the critical crack length.

3.2.8 *critical crack length*—the crack length in a chevron-notch specimen at which the specimen's stress-intensity factor coefficient, *Y\** (see 3.2.11 and Table 3), is a minimum, or equivalently, the crack length at which the maximum force would occur in a purely linear elastic fracture mechanics test. At the critical crack length, the width of the crack front is approximately one third the dimension *B* (Figs. 2 and 3).

3.2.9 *high point, High*—the point on a force-displacement plot, at the start of an unloading-reloading cycle, at which the displacement reverses direction, that is, the point at which the specimen mouth begins closing due to unloading (see points labeled High in Figs. 4 and 5).

3.2.10 *low point, Low*—the point on the reloading portion of

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

**TABLE 1 Rod Dimensions**

NOTE 1—All surfaces to be 64-µin. finish or better.

NOTE 2—Side grooves may be made with a plunge cut with a circular blade, such that the sides of the chevron ligament have curved profiles, provided that the blade diameter exceeds 5.0$B$. In this case, φ is the angle between the chords spanning the plunge cut arcs, and it is necessary to use different values of φ and $a_o$ (4), so that the crack front has the same width as with straight cuts, at the critical crack length.

NOTE 3—The dimension $a_o$ must be achieved when forming the side grooves. A separate cut that blunts the apex of the chevron ligament is not permissible.

NOTE 4—Grip groove surfaces are to be flat and parallel to chevron notch within± 2°.

NOTE 5—Notch on centerline within ±0.005$B$ and perpendicular or parallel to surfaces as applicable within 0.005$B$ (TIR).

NOTE 6—The imaginary line joining the conical gage seats must be perpendicular (±2°) to the plane of the specimen slot.

| Sym-bol | Name | Value | | Tolerance |
| --- | --- | --- | --- | --- |
| | | $W/B$ = 1.45 | $W/B$ = 2.0 | |
| $B$ | Diameter | $B$ | $B$ | ... |
| $W$ | Length | 1.450$B$ | 2.000$B$ | ±0.010$B$ |
| $a_o$ | Distance to chevron tip | 0.481$B$ | 0.400$B$ | ±0.005$B$ |
| $S$ | Grip groove depth | 0.150$B$ | 0.150$B$ | ±0.010$B$ |
| | alternate groove | 0.130$B$ | 0.130$B$ | ±0.010$B$ |
| $X$ | Distance to load line | 0.100$B$ | 0.100$B$ | ±0.003$B$ |
| | alternate groove | 0.050$B$ | 0.050$B$ | ±0.003$B$ |
| $T$ | Grip groove width | 0.350$B$ | 0.350$B$ | ±0.005$B$ |
| | alternate groove | 0.313$B$ | 0.313$B$ | ±0.005$B$ |
| $t$ | Slot thickness | ≤0.030$B$[A] | ≤0.030$B$[A] | ... |
| φ | Slot angle | 54.6° | 34.7° | ±0.5° |

[A] See Fig. 6.

**TABLE 2 Bar Dimensions**

NOTE 1—All surfaces to be 64-µin. finish or better.

NOTE 2—Side grooves may be made with a plunge cut with a circular blade, such that the sides of the chevron ligament have curved profiles, provided that the blade diameter exceeds 5.0$B$. In this case, φ is the angle between the chords spanning the plunge cut arcs, and it is necessary to use different values of φ and $a_o$ (4), so that the crack front has the same width as with straight cuts, at the critical crack length.

NOTE 3—The dimension $a_o$ must be achieved when forming the side grooves. A separate cut that blunts the apex of the chevron ligament is not permissible.

NOTE 4—Grip groove surfaces are to be flat and parallel to chevron notch within± 2°.

NOTE 5—Notch on centerline within ±0.005$B$ and perpendicular or parallel to surfaces as applicable within 0.005$B$ (TIR).

NOTE 6—The imaginary line joining the conical gage seats must be perpendicular (±2°) to the plane of the specimen slot.

| Sym-bol | Name | Value | | Tolerance |
| --- | --- | --- | --- | --- |
| | | $W/B$ = 1.45 | $W/B$ = 2.0 | |
| $B$ | Thickness | $B$ | $B$ | ... |
| $W$ | Length | 1.450$B$ | 2.000$B$ | ±0.010$B$ |
| $a_o$ | Distance to chevron tip | 0.481$B$ | 0.400$B$ | ±0.005$B$ |
| $S$ | Grip groove depth | 0.150$B$ | 0.150$B$ | ±0.010$B$ |
| | alternate groove | 0.130$B$ | 0.130$B$ | ±0.010$B$ |
| $X$ | Distance to load line | 0.100$B$ | 0.100$B$ | ±0.003$B$ |
| | alternate groove | 0.050$B$ | 0.050$B$ | ±0.003$B$ |
| $T$ | Grip groove width | 0.350$B$ | 0.350$B$ | ±0.005$B$ |
| | alternate groove | 0.313$B$ | 0.313$B$ | ±0.005$B$ |
| $t$ | Slot thickness | ≤0.030$B$[A] | ≤0.030$B$[A] | ... |
| φ | Slot angle | 54.6° | 34.7° | ±0.5° |
| $H$ | Half-height | | | |
| | (square specimen) | 0.500$B$ | 0.500$B$ | ±0.005$B$ |
| | (rectangular specimen) | 0.435$B$ | $B$ | ±0.005$B$ |

[A] See Fig. 6.
[B] See Note 1.

**TABLE 3 Minimum Stress-Intensity Factor Coefficients and Critical Slope Ratios for Chevron-Notch Specimens**

NOTE 1—The values in this table are derived from the polynomials in Table 5, and are selected from the values in Table 4.

| Specimen | $W/B$ | $a_c/W$ | $H/B$ | $Y^*_m$ | $r_c$ |
| --- | --- | --- | --- | --- | --- |
| Rectangular Bar | 1.45 | 0.332 | 0.435 | 28.22 | 0.52 |
| Square Bar | 1.45 | 0.332 | 0.50 | 25.11 | 0.62 |
| Square Bar | 2 | 0.2 | 0.5 | 29.90 | 0.30 |
| Rod | 1.45 | 0.332 | 0.5 | 29.21 | 0.52 |
| Rod | 2 | 0.2 | 0.5 | 36.25 | 0.28 |

an unloading-reloading cycle where the force is one half the high point force (see points labeled Low in Figs. 4 and 5).

3.2.11 *stress-intensity factor coefficient, Y\**—a dimensionless parameter that relates the applied force and specimen geometry to the resulting crack-tip stress-intensity factor in a chevron-notch specimen test (see 9.6.3).

3.2.11.1 *Discussion*—Values of $Y^*$ can be found from the graphs in Fig. 10, or from the tabulations in Table 4 or from the polynominal expressions in Table 5.

3.2.12 *minimum stress-intensity factor coefficient, $Y^*_m$* —the minimum value of $Y^*$ (Table 3).

## 4. Summary of Test Method

4.1 This test method involves the application of a load to the mouth of a chevron-notched specimen to induce an opening displacement of the specimen mouth. An autographic record is made of the load versus mouth opening displacement and the slopes of periodic unloading-reloading cycles are used to calculate the crack length based on compliance techniques. These crack lengths are expressed indirectly as slope ratios. The characteristics of the force versus mouth opening displacement trace depend on the geometry of the specimen, the specimen plasticity during the test, any residual stresses in the specimen, and the crack growth characteristics of the material being tested. In general, two types of force versus displacement traces are recognized, namely, smooth behavior (see 3.2.3) and crack jump behavior (see 3.2.4).

4.1.1 In metals that exhibit smooth crack behavior (3.2.3), the crack initiates at a low force at the tip of a sufficiently sharp chevron, and each incremental increase in its length corresponds to an increase in crack front width and requires further increase in force. This force increase continues until a point is reached where further increases in force provide energy in excess of that required to advance the crack. This maximum force point corresponds to a width of crack front approximately one third the specimen diameter or thickness. If the loading system is sufficiently stiff, the crack can be made to continue its smooth crack growth under decreasing force. Two unloading-reloading cycles are performed to determine the location of the crack, the force used to calculate $K_{Iv}$, and to provide validity checks on the test. The fracture toughness is calculated from the force required to advance the crack when the crack is at the critical crack length (see 3.2.8). The plane-strain fracture toughness determined by this procedure is termed $K_{Iv}$. An alternative procedure, described in Annex A1, omits the unloading cycles and uses the maximum test force to calculate

**TABLE 4 Stress-Intensity Factor Coefficients as a Function of Slope Ratio (r) for Chevron-Notch Specimen**[A]

| Specimen Type | Rectangular Bar | Square Bar | Square Bar | Rod | Rod |
|---|---|---|---|---|---|
| W/B | 1.45 | 1.45 | 2 | 1.45 | 2 |
| $a_0/W$ | 0.332 | 0.332 | 0.2 | 0.332 | 0.2 |
| r | Y* | Y* | Y* | Y* | Y* |
| 0.16 | ... | ... | 33.14 | ... | 38.20 |
| 0.18 | ... | ... | 32.04 | ... | 37.44 |
| 0.20 | ... | 42.24 | 31.24 | 45.10 | 36.90 |
| 0.22 | ... | 39.39 | 30.68 | 42.16 | 36.55 |
| 0.24 | ... | 37.00 | 30.30 | 39.71 | 36.34 |
| 0.26 | ... | 35.00 | 30.07 | 37.68 | 36.25 |
| 0.28 | ... | 33.32 | 29.95 | 35.98 | 36.25[B] |
| 0.30 | 33.22 | 31.90 | 29.90[B] | 34.57 | 36.32 |
| 0.32 | 32.09 | 30.70 | 29.91 | 33.39 | 36.43 |
| 0.34 | 31.16 | 29.68 | 29.96 | 32.42 | 36.57 |
| 0.36 | 30.40 | 28.82 | 30.02 | 31.62 | 36.74 |
| 0.38 | 29.79 | 28.10 | 30.10 | 30.97 | 36.91 |
| 0.40 | 29.31 | 27.49 | 30.18 | 30.45 | 37.08 |
| 0.42 | 28.93 | 26.97 | 30.25 | 30.04 | 37.25 |
| 0.44 | 28.65 | 26.54 | 30.33 | 29.72 | 37.42 |
| 0.46 | 28.45 | 26.19 | 30.41 | 29.49 | 37.59 |
| 0.48 | 28.31 | 25.89 | 30.50 | 29.33 | 37.77 |
| 0.50 | 28.24 | 25.66 | 30.62 | 29.24 | 37.96 |
| 0.52 | 28.22[B] | 25.47 | 30.78 | 29.21[B] | 38.19 |
| 0.54 | 28.25 | 25.32 | 31.02 | 29.22 | 38.46 |
| 0.56 | 28.31 | 25.22 | 31.34 | 29.28 | 38.81 |
| 0.58 | 28.42 | 25.15 | 31.80 | 29.39 | 39.25 |
| 0.60 | 28.56 | 25.11 | 32.43 | 29.53 | 39.81 |
| 0.62 | 28.73 | 25.11[B] | ... | 29.70 | ... |
| 0.64 | 28.93 | 25.14 | ... | 29.91 | ... |
| 0.66 | 29.16 | 25.21 | ... | 30.16 | ... |
| 0.68 | 29.42 | 25.31 | ... | 30.43 | ... |
| 0.70 | 29.72 | 25.45 | ... | 30.74 | ... |
| 0.72 | 30.05 | 25.63 | ... | 31.09 | ... |
| 0.74 | 30.42 | 25.86 | ... | 31.48 | ... |
| 0.76 | 30.84 | 26.15 | ... | 31.91 | ... |
| 0.78 | 31.32 | 26.49 | ... | 32.38 | ... |
| 0.80 | 31.85 | 26.90 | ... | 32.91 | ... |
| 0.82 | 32.46 | 27.40 | ... | 33.51 | ... |
| 0.84 | 33.15 | 27.98 | ... | 34.17 | ... |

[A] Compiled from Refs (8), (10), (11), and (13), and using the polynomials in Table 5.
[B] Minimum value of Y*.

a plane-strain fracture toughness $K_{IvM}$, where $M$ signifies the use of the maximum force. Values of $K_{Iv}$ versus $K_{IvM}$ are discussed in Annex A1.

4.1.2 A modified procedure is used to determine $K_{Ivj}$ when crack jump behavior is encountered. In this procedure, unloading-reloading cycles are used to determine the crack location at which the next jump will begin. The $K_{Ivj}$ values are calculated from the forces that produce crack jumps when the crack front is in a defined region near the center of the specimen. The $K_{Ivj}$ values so determined have the same significance as $K_{Iv}$.

4.1.3 The equations for calculating the toughness have been established on the basis of elastic stress analyses of the specimen types described in this test method.

4.2 The specimen size required for testing purposes increases as the square of the ratio of fracture toughness to yield strength of the material (see 6.1), therefore proportional specimen configurations are provided.

## 5. Significance and Use

5.1 The fracture toughness determined by this test method characterizes the resistance of a material to fracture by a slowly advancing steady-state crack (see 3.2.5) in a neutral environment under severe tensile constraint. The state of stress near the crack front approaches plane strain, and the crack-tip plastic region is small compared with the crack size and specimen dimensions in the constraint direction. A $K_{Iv}$ or $K_{Ivj}$ value may be used to estimate the relation between failure stress and defect size when the conditions described above would be expected, although the relationship may differ from that obtained from a $K_{Ic}$ value (see Note 1). Background information concerning the basis for development of this test method in terms of linear elastic fracture mechanics may be found in Refs (1-15).

5.1.1 The $K_{Iv}$, $K_{Ivj}$, or $K_{IvM}$ value of a given material can be a function of testing speed (strain rate) and temperature. Furthermore, cyclic forces can cause crack extension at $K_I$ values less than $K_{Iv}$, and crack extension can be increased by the presence of an aggressive environment. Therefore, application of $K_{Iv}$ in the design of service components should be made with an awareness of differences that may exist between the laboratory tests and field conditions.

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

5.2 This test method can serve the following purposes:

5.2.1 To establish 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 For specifications of acceptance and manufacturing quality control, but only when there is a sound basis for specification of minimum $K_{Iv}$, $K_{Ivj}$, or $K_{IvM}$ values, and then only if the dimensions of the product are sufficient to provide specimens of the size required for valid $K_{Iv}$ determination (5). The specification of $K_{Iv}$ 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.

5.2.3 To provide high spatial resolution in measuring plane strain fracture toughness variations in parent pieces of material (14).

NOTE 2—The high spatial resolution is possible because of the small allowable specimen size criterion, $B \geq 1.25 \ (K_{Iv}/\sigma_{YS})^2$ (5), and because the toughness is measured at approximately the midline of the specimen, and only in the material covered by the crack's lateral extent, which is about one third of the specimen's lateral dimension, $B$.

## 6. Specimen, Size, Configuration, Dimensions, and Preparation

6.1 *Specimen Size*—In order for a test result to be considered valid in accordance with this test method, it is required that the specimen's lateral dimension, $B$, equals or exceeds 1.25 $(K_{Iv}/\sigma_{YS})^2$, 1.25 $(K_{Ivj}/\sigma_{YS})^2$, or 1.25 $(K_{IvM}/\sigma_{YS})^2$, where$\sigma_{YS}$ is the 0.2 % offset yield strength of the material in the

**TABLE 5 Closed Form Expressions for Stress Intensity Factor Coefficients for Chevron-Notched Specimens of Several Configurations[A,B]**

| Specimen | W/B | $a_0/W$ | H/B | $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|---|---|---|---|
| Rectangular Bar[C] | 1.45 | 0.332 | 0.435 | 5.112 | −10.36 | 22.46 | −21.88 | 8.46 |
| Square Bar[D] | 1.45 | 0.332 | 0.500 | 5.010 | −9.65 | 20.31 | −20.27 | 8.257 |
| Square Bar[E] | 2.00 | 0.200 | 0.500 | 4.300 | −9.238 | 34.77 | −57.24 | 35.25 |
| Rod[D] | 1.45 | 0.332 | 0.500 | 5.052 | −9.488 | 19.78 | −18.48 | 6.921 |
| Rod[E] | 2.00 | 0.200 | 0.500 | 4.163 | −6.104 | 23.32 | −37.97 | 23.07 |

[A] Compiled from Refs (8), (10), (11), and (13).
[B] $Y^* = \exp[C_0 + C_1\, r + C_2\, r^2 + C_3\, r^3 + C_4\, r^4]$, accuracy ±0.5 %.
[C] Estimated from finite element analysis (11), and extrapolated equation from Ref (11). Accuracy for $0.3 \leq r \leq 0.85$ is ±0.5 %.
[D] Extrapolated from equations in Ref (13). Accuracy estimated to be ±0.5 % for $0.2 \leq r \leq 0.85$.
[E] Equation from Ref (13). Accuracy estimated to be± 0.5 % for $0.15 \leq r \leq 0.6$.

**TABLE 6 Mean Values and Sample Standard Deviations of $K_{IvM}$ and $K_{Iv}$ for Five Materials Tested in an Interlaboratory Test Program**

NOTE 1—Specimens of grade 250 maraging steel were heat-treated by individual participants, and some contribution to the scatter may have been made by heat-treatment variations.

| Material | Specimen Orientation | Yield Strength, ksi (MPa) | $K_{IvM}$ ksi $\sqrt{in.}$ (MPa $\sqrt{m}$) | Sample Standard Deviation of $K_{IvM}$ | Number of Valid Tests | $K_{Iv} K_{Ivj}$ ksi $\sqrt{in.}$ (MPa $\sqrt{m}$) | Sample Standard Deviation of $K_{Iv}$ or $K_{Ivj}$ | Number of Valid Tests |
|---|---|---|---|---|---|---|---|---|
| 2024-T351 | L-T | 52.4 (361) | 50.8 (55.9) | 8.0 (8.8) | 3 | 45.2 (49.7) | 2.1 (2.3) | 4 |
| Aluminum | S-L | 42.7 (294) | 35.3 (38.8) | 2.8 (3.1) | 10 | 36.5 (40.2) | 2.8 (3.1) | 4 |
| 7075-T651 | L-T | 78.7 (543) | 31.3 (34.4) | 1.7 (1.9) | 36 | 29.9 (32.9) | 1.9 (2.1) | 20 |
| Aluminum | S-L | 67.8 (468) | 20.7 (22.8) | 1.0 (1.1) | 26 | 20.1 (22.1) | 1.3 (1.4) | 15 |
| Grade 250 | L-T | 230.8 (1592) | 90.6 (99.7) | 12.0 (13.2) | 29 | 92.5 (101.8) | 6.6 (7.3) | 4 |
| Maraging Steel | S-L | 229.6 (1583) | 79.1 (87.0) | 9.0 (9.9) | 21 | 83.2 (91.5) | 12.0 (13.2) | 11 |
| Grade 300 | L-T | 274.0 (1890) | 49.0 (53.9) | 4.0 (4.4) | 15 | 51.9 (57.1) | 2.1 (2.3) | 5 |
| Maraging Steel | S-L | 288.0 (1986) | 47.3 (52.0) | 4.0 (4.4) | 9 | 48.3 (53.1) | 2.6 (2.9) | 5 |
| 6A1-4V | L-T | 131.5 (907) | 103.9 (114.3) | 4.7 (5.2) | 19 | 104.2 (114.6) | 5.5 (6.1) | 3 |
| Titanium | S-L | 122.8 (847) | 95.2 (104.7) | 2.7 (3.0) | 14 | 92.2 (101.4) | 1.1 (1.2) | 3 |

direction of loading in the test, and for the temperature of the test as determined by Test Methods E 8.

6.2 *Specimen Configuration and Dimensions*—Both the rod specimen of the circular cross section and the rectangular bar specimen are equally acceptable. The rod dimensions for which compliance calibrations are provided are given in Fig. 2, and for the bar in Fig. 3. Fig. 6 shows an enlarged cross section of the slot that forms the chevron-shaped ligament.

6.3 *Specimen Preparation*—The dimensional tolerances and surface finishes shown on the specimen drawings shall be followed in specimen preparation.

## 7. Apparatus

7.1 Specimens should be tested in a machine that can record applied force versus specimen mouth opening displacement either digitally for processing by computer or autographically with an x-y plotter.

7.2 *Grips and Fixtures for Tensile Test Machine Loading*— Fig. 7 shows the suggested grip design. Grips should have a hardness of 45 Rockwell C or greater, and the loading system should be capable of maintaining the specimen to the grip alignment specified in 8.3.2. The grip knife edges are inserted into the grip slot in the specimen, and the specimen is loaded as the test machine arms apply an opening displacement to the grips as shown in Fig. 8. A transducer for measuring the specimen mouth opening displacement during the test and a means for automatically recording the force-displacement test record, such as a $X - Y$ recorder, are also required. A suggested design for the specimen mouth opening displacement gage appears in Fig. 9. The transducer output must be linearly

related to the opening displacement within 0.5 % of full scale displacement. Since only displacement ratios are used in the data analysis, it is not necessary to calibrate the displacement axis of the test record. However, calibration can assist in detecting equipment malfunctions and specimen abnormalities.

7.3 Commercial test equipment especially designed for testing chevron-notched short rod and bar specimens, (4), (12), (15), is also suitable for $K_{Iv}$, $K_{Ivj}$, and $K_{IvM}$ measurements, providing it meets the requirements of this test method.

7.4 *Compliance of Machine and Loading Arrangement*—It has been observed that some metals show a behavior in which the force required to initiate the crack at the point of the chevron notch is larger than the force required to advance the crack just after initiation, such that there is an abrupt crack extension following initiation. For some materials, the force at crack initiation can even be the maximum force in the test. When this occurs, a stiff machine and load train with controlled displacement loading is necessary in order to allow the crack to arrest well before passing beyond the valid region for toughness measurements. The large crack initiation force is then ignored, and the subsequent force as the crack passes through the critical crack length (see 3.2.8), or the forces at subsequent crack jumps, are used to determine the fracture toughness. A stiff machine and load train are also required in order to maintain crack growth stability to well beyond the peak load in the test, where the second unloading-reloading cycle is initiated in tests of smooth crack growth materials. For crack jump materials, stiff machine and loading behavior is required to promote crack arrest following each crack jump.

## 8. Procedure

8.1 *Number of Tests*—Complete three valid replicate tests for each material condition.

8.2 *Specimen Measurement*—Measure all specimen dimensions and record the measurements. For a valid test, the dimensions must fall within the tolerances specified in Fig. 2, Fig. 3, and Fig. 6.

8.3 *Specimen Testing Procedure*:

8.3.1 *Force Transducer*—The force indicating system shall meet the requirements of Practice E 4. Accuracy of the indicated force shall be within 1 % in the working range.

8.3.2 Install the specimen in the test machine. If using a tensile test machine, operate the test machine in the "displacement control" mode. Bring the grips sufficiently close together such that they simultaneously fit into the grip slot in the specimen face. Then very carefully increase the spacing between the grips until an opening force just sufficient to hold the specimen in place is applied to the specimen. Check the alignment of the specimen with respect to the grips, and the alignment of the grips with respect to each other. Center the specimen in the grips within $0.05B$. The grip centerlines shall remain coincident within $0.01B$ during the course of the test. The grip knife edges shall contact the specimen at the load line $\pm0.003B$. To achieve this positioning, place a shim $0.050B \pm 0.003B$ (or for the alternate grip groove geometry, $0.100B \pm 0.003B$) temporarily between the specimen face and the grips as shown in Fig. 8. If a commercial test machine is used, follow the installation instructions provided, and maintain the tolerances specified in this section. If the commercial machine is based on the constant point of load application fracture specimen loading machine (**15**), the grips shall contact the specimen at the load line $\pm0.02B$.

8.3.3 Install the specimen mouth opening displacement gage on the specimen ensuring that the cones are seated in the seats provided. The gage must sense the mouth opening on the load line of the specimen $\pm0.1B$. High accuracy is not required, as the use of slope ratios in the test method minimizes the effect of errors in this dimension. If the gage design of Fig. 9, which measures the displacement of the outside faces of the specimen, is used, the spring force between the gage arms and the specimen should be such that the gage will support itself, as indicated in Fig. 8. However, this force must not be more than $\frac{1}{2}$ % of the maximum force in the test, as it adds to the fracture force of the specimen.

8.3.4 Adjust the force (*y*-axis) and displacement (*x*-axis) sensitivities of the force-displacement recorder to produce a convenient-size data trace. Allow for an approximately 70° angle between the *x*-axis and the initial elastic loading trace of the test. The force axis must be accurately calibrated, but a quantitative calibration of the displacement axis is not necessary.

8.3.5 Test the specimen. With the force-displacement recorder operating, open the mouth of the specimen at a rate such that the peak force of the test is reached within 15 to 60 s, exclusive of the time required for unloading-reloading cycles. In determining $K_{Iv}$ or $K_{Ivj}$ continue each unloading until the force on the specimen has decreased to between 3 and 10 % of the force at the initiation of the unloading. Immediately reload the specimen and continue the test after each unloading.

8.3.5.1 If the specimen has a smooth crack growth behavior (see 3.2.3), it must be unloaded twice during the test to determine $K_{Iv}$, by reversing the motion of the grips. Begin the first unloading when the unloading slope ratio (see 3.2.6) is approximately $1.2r_c$, and the second when it is approximately $0.8r_c$ (see Note 3). The force-displacement record should be similar to that shown in Fig. 4, and the unloading slopes should bracket the maximum load.

8.3.5.2 If the specimen has a crack jump behavior (see 3.2.4), it should be unloaded after each crack jump that decreases the applied force by 5 % or more. Unloadings that will produce slope ratios outside the range from $0.8r_c$ to $1.2r_c$ need not be done. At least two unloadings within this slope ratio range should be done if possible. If no crack arrest occurs that allows an unloading with a slope ratio in the range from 0.8 to $1.2r_c$, then a valid $K_{Ivj}$ cannot be determined. A representative force-displacement record for a crack jump material is shown in Fig. 5.

NOTE 3—In testing the specimen in accordance with the instructions in 8.3, one needs to know approximately where the slope ratios $0.8r_c$ and $1.2r_c$ occur on the test record. The following estimation method is suggested:

Before the test, draw three lines upward and to the right from the origin of the graph paper at angles of 70°, $\theta_1$ °, and $\theta_2$ ° from the horizontal, where $\theta_1 = \tan^{-1}(1.2r_c \tan 70°)$, and $\theta_2 = \tan^{-1}(0.8r_c \tan 70°)$. (The value of $r_c$ is given in Table 1.) Then adjust the displacement axis sensitivity of the recorder to cause the initial elastic loading to be along the 70° line. During the test, when the force-displacement trace first reaches the $\theta_1$ ° line, the unloading slope ratio should be approximately $1.2r_c$, and when it reaches the $\theta_2$ ° line, the slope ratio should be approximately $0.8r_c$. The actual slope ratio obtained from an unloading-reloading cycle may differ from the estimate because of plasticity or residual stress effects, or both.

## 9. Calculation and Interpretation of Results

9.1 On completion of the test, break the specimen apart if necessary, and examine the fracture surfaces for any imperfections that may have influenced the force-displacement record. Data should be considered suspect whenever the test record may have been affected by an imperfection in the fracture plane.

9.2 Examine the fracture surface to determine how well the crack followed the chevron slots in splitting the specimen apart. If the′ crack follow′ was imperfect, the crack will have cut substantially farther into one half of the specimen than the other (see Note 4). If the actual crack surface deviates from the intended crack plane, as defined by the chevron slots, by more than $0.04B$ when the width of the crack front is one third $B$, then the test is invalid.

NOTE 4—Deviation of the crack from the intended fracture plane can result from one or more of the following:
(*a*) Inexact centering of the chevron slots (the intended crack plane) in the specimen,
(*b*) Strong residual stresses in the test specimen,
(*c*) Strong anisotropy in toughness, in which the toughness in the intended crack plane is substantially larger than the toughness in another crack orientation, or
(*d*) Coarse grained or heterogeneous material.

9.3 If the value to be measured is $K_{IvM}$ (3.2.2), follow the method in Annex A1.

9.4 If the value to be measured is $K_{Iv}$ or $K_{Ivj}$ (3.2.1), proceed as follows:

9.4.1 Locate the high and low points, (see 3.2.9 and 3.2.10), on each unloading-reloading cycle. The high and low points are labeled High and Low, respectively, in Figs. 4 and 5.

9.4.2 Draw the effective unloading line (3.2.6) through the high and low points of each unloading-reloading cycle (Figs. 4 and 5).

9.4.3 If the test record shows crack jump behavior (3.2.4), proceed as described in 9.6. For smooth crack growth behavior (3.2.3), continue as in 9.5 below.

9.5 *Smooth Crack Growth Data Reduction*:

9.5.1 Draw the horizontal average force line between the two effective unloading lines (Fig. 4). The average force line is drawn at the level of the average load on the data trace between the two unloading-reloading cycles. The average force line is drawn making the shaded areas above and below the line in Fig. 4 approximately equal. It must be drawn horizontally, but the choice of the average force can vary by± 5 % from the correct value without materially affecting the results.

9.5.2 Measure $\Delta X$ (the distance between the effective unloading lines along the average force line) and $\Delta X_o$ (the distance between the effective unloading lines along the zero force line, (see Fig. 4). Calculate $p = \Delta X_o/\Delta X$. If the unloading lines cross before reaching the zero load axis, then $\Delta X_o$, and therefore, $p$, are considered to be negative. The test is valid only if $-0.05 \leq p \leq +0.10$ **(5)**.

9.5.3 The critical slope ratio, $r_c$ (see 3.2.7), is given in Table 1. Measure the initial elastic loading angle, $\theta_o$ (Fig. 4). Calculate the angle, $\theta_c$, of the critical slope ratio from the following equation:

$$\theta_c = \tan^{-1}(r_c \tan \theta_o)$$

9.5.3.1 Next, extend (if necessary) the two effective unloading lines until they intersect. Then draw a critical slope ratio line through the point of intersection at the angle $\theta_c$ from the horizontal. Extend this line until it intersects the force-displacement test record somewhere near the crest of the test curve. The force at the intersection point is called $P_c$. It is the force required to advance the crack when the crack was at the critical crack length (see 3.2.8). Note also the maximum force $P_M$. If $P_M$ is greater than 1.10 $P_c$, the test is invalid.

NOTE 5—The intersection that locates the force $P_c$ will usually fall approximately midway between the two unloading-reloading cycles. If one of the unloading-reloading cycles produces an unloading slope ratio that is close to $r_c$, then the value obtained for $P_c$ may be determined at some part of the unloading-reloading cycle, and therefore be erroneous. If it is judged that $P_c$ was so influenced, then the value of $P$ at the point of unloading is used for $P_c$.

9.5.4 Calculate a conditional value, $K_{Qv}$, of the plane-strain toughness as follows:

$$K_{Qv} = Y^*_m P_c/(B \sqrt{W})$$

where:
$Y^*_m$ = the minimum stress intensity factor coefficient (see Table 3).

If $B \geq 1.25(K_{Qv}/\sigma_{YS})^2$, and if $P_M$ is less than 1.10 $P_c$, and if $-0.05 \leq p \leq 0.10$, and if all other validity criteria are met, then the test is valid, and $K_{Qv} = K_{Iv}$. These other criteria are described in 8.2, 8.3.5.1, 9.1, and 9.2.

9.6 *Crack Jump Data Reduction*:

9.6.1 Measure the angle $\theta_o$ between the horizontal axis and the initial elastic loading path, and the angles $\theta_1$, $\theta_2$, ...$\theta_n$, between the horizontal axis and each of the effective unloading paths drawn through the high and low points. Calculate the slope ratios of the unloading paths from the following equations:

$$r_1 = \tan \theta_1/\tan \theta o,$$
$$r_2 = \tan \theta_2/\tan \theta o,$$

$$.$$
$$.$$
$$.$$

$$r_n = \tan \theta_n/\tan \theta o.$$

9.6.2 Using the slope ratios of the effective unloading paths, interpolate or extrapolate on the force-displacement record to obtain the slope ratio at the initiation of each substantial crack jump. A substantial crack jump is one in which the accompanying force drop is at least 5 % (see Fig. 5). Discard any data for crack jumps that start at slope ratios outside the range from 0.8 to $1.2r_c$.

9.6.3 For each remaining crack jump slope ratio, $r$, find the corresponding value of the specimen stress-intensity factor coefficient, $Y^*$, from the graphs in Fig. 10, or from the tabulations in Table 4, or from the wide-range expressions in Table 5.

9.6.4 Find the load, $P$, at the initiation of each crack jump for which the stress-intensity factor coefficient, $Y^*$, has been found. For each crack jump, use the ($P$, $Y^*$) pair to calculate the toughness as follows:

$$K_{Qv} = Y^*P/(B \sqrt{W})$$

Wherever several values for $K_{Qv}$ are obtained from a given specimen, the $K_{Qv}$ for the specimen is taken as the average of the several values. If $B$ is $\geq 1.25(K_{Qv}/\sigma_{YS})^2$, and if all other validity criteria are satisfied, the test is valid, and $K_{Qv} = K_{Ivj}$. These other criteria are described in 8.2, 8.3.5.2, 9.1, 9.2, and 9.6.2. Note that the $K_{Ivj}$ analysis does not include a validity check in 9.5.2, because the parameter, $p$, in 9.5.2 is a strong function of the plastic zone size of the arrested crack, which will in general differ from the plastic zone size of the crack at the start of the jump. As it is not possible to predict the onset of the next crack jump, it is not possible to perform an unloading cycle at that point, and thus determine $p$ accurately in crack jump materials.

## 10. Report

10.1 Report the following information:

10.1.1 Specimen identification,

10.1.2 Form of product tested, environment of test, test temperature, and crack-plane orientation,

10.1.3 Specimen dimensions, including the transverse dimension, $B$; length, $W$; half-height, $H$ (square or rectangular geometry only); chevron angle, $\phi$; slot thickness, $t$; and slot bottom geometry (Fig. 6),

10.1.4 Provide a description of the fracture surface, especially any unusual appearance,

10.1.5 Measured deviation of the crack surface from the

intended crack plane when the width of the crack front was $B/3$,

10.1.6 Specimen test characteristic, that is, smooth crack growth or crack jump behavior,

10.1.7 For $K_{Iv}$ determinations, the value of $P_c$ (smooth crack growth specimens only), and $P_M$,

10.1.8 Yield strength of the material (0.2 % offset) as determined by Test Methods E 8 in the direction of the applied loading in the chevron-notched specimen, and at the test temperature in 10.1.2.

10.1.9 $1.25(K_{Qv}/\sigma_{YS})^2$ or $1.25(K_{QvM}/\sigma_{YS})^2$

10.1.10 $K_{Iv}$, $K_{Ivj}$, or $K_{IvM}$ (Annex A1), or $K_{Qv}$ or $K_{QvM}$, and

10.1.11 Statement of the test validity, or a summary of failures to meet validity criteria.

## 11. Precision and Bias [4]

11.1 *Precision*—The precision of a $K_{Iv}$ determination is a function of the precision and bias of the various measurements

[4] Supporting data are available from ASTM Headquarters. Request RR: E 24 – 1012.

of the specimen and testing fixtures, the precision of the force measurement as well as the bias of the recording devices used to produce the record, and the precision of the constructions made on the record. The method is unique however, in that the form of the compliance relationship minimizes the effect of inaccuracies in displacement measurement and specimen dimensions when using data gathered close to the minimum value of $Y^*$.

11.2 The results of an interlaboratory test program that used the specimen geometries, test procedures, and data analysis specified in this test method are shown in Table 6. The data are all valid by the test procedure and indicate the reproducibility that can be expected.

11.3 *Bias*—There is no accepted standard value for the fracture toughness of any material. As discussed in 1.1 and 3.2.1, $K_{Iv}$, $K_{Ivj}$, or $K_{IvM}$ values may differ from $K_{Ic}$, the planestrain fracture toughness measured by Test Method E 399. Generally $K_{Iv}$ will be equal to or greater than $K_{Ic}$, but it is necessary to generate correlative data for the material of interest to substantiate the relationship between the two values.

## ANNEXES

### (Mandatory Information)

### A1. CALCULATIONS OF PLANE STRAIN FRACTURE TOUGHNESS USING ONLY THE MAXIMUM LOAD

A1.1 This annex describes a test method for calculating a value of plane-strain fracture toughness designated as $K_{IvM}$ (3.2.2). The toughness value is based on the maximum force, and does not require the use of unloading-reloading cycles. $K_{IvM}$ can be determined from a $K_{Iv}$ or $K_{Ivj}$ test record, both of which contain unloading cycles, but $K_{Iv}$ cannot be determined from a test record which does not contain unloading cycles.

A1.2 In smooth crack growth materials, $K_{IvM}$ will usually be close in value to the corresponding value of $K_{Iv}$ for the specimen configurations used in this test method. The calculation of $K_{IvM}$ from the maximum force inherently assumes that the maximum force occurs at the critical crack length, but no such assumption is involved in the $K_{Iv}$ method. $K_{IvM}$ values lack the $K_{Iv}$ validity check for smooth crack growth materials that $P_M \leq 1.1 P_c$ because $P_c$ requires unloading slopes for its determination (see 9.5.3.1). $K_{IvM}$ also lacks a validity check for excess plasticity or residual stresses (see 9.5.2) that would invalidate the use of the underlying elastic crack stress analysis. This should be kept in mind when testing ductile metals, or any specimens that may contain macroscopic residual stresses.

A1.3 In crack jump materials, the maximum force $P_M$ often does not occur at the critical crack length corresponding to the slope ratio, $r_c$ (see Figs. 4 and 5). As the calculation of $K_{IvM}$ uses $Y^*_m$, the values of $K_{IvM}$ may be conservative. It can differ significantly from the true critical crack tip stress intensity factor, or $K_{Ivj}$.

A1.4 In some specimen sizes, geometry, and material combinations, the maximum force can occur during the initiation of the crack at the tip of the chevron shaped ligament. Such forces must not be used in the $K_{IvM}$ calculation since they are not related to the plane-strain toughness. In these cases, the force $P_m$, used to determine $K_{IvM}$ is not the maximum force in the test, but is the maximum force in a specific region of the tests as follows.

A1.4.1 To eliminate values of $K_{IvM}$ that are influenced by crack initiation at the chevron tip, an additional validity requirement has been placed on $K_{IvM}$. Values of $P_M$ occurring early in the test, before a point corresponding to the slope ratio $1.2r_c$, are considered invalid. This limit of validity is determined from the test record by the following construction.

A1.4.2 From the origin of the force displacement test record, draw a line of slope $1.2r_c \tan \theta_o$, where $\theta_o$ is the angle between the initial elastic loading slope and the horizontal axis. Select the maximum force, $P_M$, on the remainder of the test record following the point of intersection of this line with the record. Maxima occurring at displacements less than that at this point of intersection are invalid because the crack was not sufficiently far from the apex of the chevron at the time of the maximum force.

## A2. CALCULATING CONDITIONAL VALUE FOR $K_{QvM}$

A2.1  Calculate a conditional value for $K_{QvM}$ as follows:

$$K_{QvM} = Y^*_m P_M /(B \sqrt{W})$$

where:
$Y^*_m$ = minimum stress intensity factor coefficient (see Table 3),
$P_M$ = maximum test force,
$B$ = specimen diameter or thickness, and

$W$ = specimen length.

A2.1.1  If $B$ is greater than $1.25(K_{QvM} /\sigma_{YS})^2$, and if the validity criteria in A1.4.1, 9.1, and 9.2 are met, then $K_{QvM} = K_{IvM}$.

A2.2  Report the test as described in Section 10.

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