Designation: E399 – 17

Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials[1]

This standard is issued under the fixed designation E399; 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 U.S. Department of Defense.

1. Scope

1.1 This test method covers the determination of fracture toughness (K_{Ic}) of metallic materials under predominantly linear-elastic, plane-strain conditions using fatigue precracked specimens having a thickness of 1.6 mm (0.063 in.) or greater[2] subjected to slowly, or in special (elective) cases rapidly, increasing crack-displacement force. Details of test apparatus, specimen configuration, and experimental procedure are given in the Annexes.

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

1.2 This test method is divided into two parts. The first part gives general recommendations and requirements for K_{Ic} testing. The second part consists of Annexes that give specific information on displacement gage and loading fixture design, special requirements for individual specimen configurations, and detailed procedures for fatigue precracking. Additional annexes are provided that give specific procedures for beryllium and rapid-force testing.

1.3 General information and requirements common to all specimen configurations:

1.4 Specific requirements related to test apparatus:

1.5 Specific requirements related to individual specimen configurations:

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

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[2] For additional information relating to the fracture toughness testing of alumi–inum alloys, see Practice B645.

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

1.6 Specific requirements related to special test procedures:

Fatigue Precracking KIc Specimens	Annex A8
Hot-Pressed Beryllium Testing	Annex A9
Rapid-Force Testing	Annex A10

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

1.8 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[4]

B909 Guide for Plane Strain Fracture Toughness Testing of Non-Stress Relieved Aluminum Products
B645 Practice for Linear-Elastic Plane–Strain Fracture Toughness Testing of Aluminum Alloys
E4 Practices for Force Verification of Testing Machines
E8/E8M Test Methods for Tension Testing of Metallic Materials
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E456 Terminology Relating to Quality and Statistics
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1820 Test Method for Measurement of Fracture Toughness
E1823 Terminology Relating to Fatigue and Fracture Testing
E1921 Test Method for Determination of Reference Temperature, $\boldsymbol{T_o}$, for Ferritic Steels in the Transition Range

3. Terminology

3.1 *Definitions:*Terminology E1823 is applicable to this test method*:*

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

3.1.1.1 *K* is a function of applied force and test specimen size, geometry, and crack size, and has the dimensions of force times length$^{-3/2}$.

3.1.1.2 Values of *K* for modes I, II, and III are given as:

$$K_I = \lim_{r\to 0} \left[\sigma_{yy}(2\pi r)^{1/2}\right] \tag{1}$$

$$K_{II} = \lim_{r\to 0} \left[\tau_{xy}(2\pi r)^{1/2}\right] \tag{2}$$

$$K_{III} = \lim_{r\to 0} \left[\tau_{yz}(2\pi r)^{1/2}\right] \tag{3}$$

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

3.1.2 *plane-strain fracture toughness, K_{Ic} [$FL^{-3/2}$]*—the crack-extension resistance under conditions of crack-tip plane strain in Mode I for slow rates of loading under predominantly linear-elastic conditions and negligible plastic-zone adjustment. The stress intensity factor, K_{Ic}, is measured using the operational procedure (and satisfying all of the validity requirements) specified in Test Method E399, that provides for the measurement of crack-extension resistance at the onset (2% or less) of crack extension and provides operational definitions of crack-tip sharpness, onset of crack extension, and crack-tip plane strain.

3.1.2.1 See also definitions of crack-extension resistance, crack-tip plane strain, and mode in Terminology E1823.

3.1.3 *crack mouth opening displacement (CMOD), V_m* [L]—crack opening displacement resulting from the total deformation (elastic plus plastic), measured under force at the location on a crack surface that has the largest displacement per unit force.

3.1.4 *crack plane orientation*—identification of the plane and direction of crack extension in relation to the characteristic directions of the product. A hyphenated code defined in Terminology E1823 is used wherein the letter(s) preceding the hyphen represents the direction normal to the crack plane and the letter(s) following the hyphen represents the anticipated direction of crack extension (see Fig. 1).

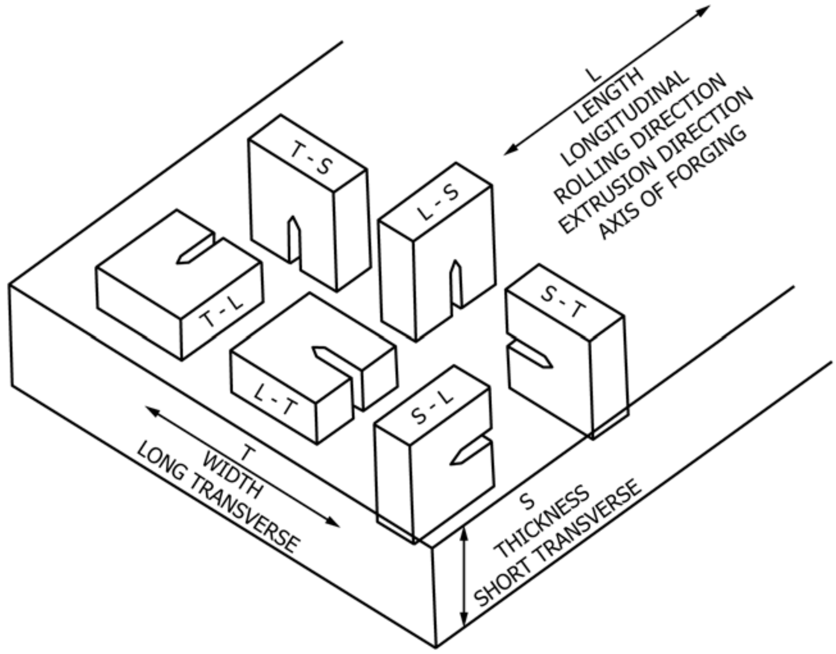
3.1.4.1 *Wrought Products*—the fracture toughness of wrought material depends on, among other factors, the orientation and propagation direction of the crack in relation to the material's anisotropy, which depends, in turn, on the principal directions of mechanical working and grain flow. Orientation of the crack plane shall be identified wherever possible. In addition, product form shall be identified (for example, straight-rolled plate, cross-rolled plate, pancake forging, and so forth) along with material condition (for example, annealed, solution treated plus aged, and so forth). The user shall be referred to product specifications for detailed processing information.

3.1.4.2 For rectangular sections, the reference directions are identified as in Fig. 1(a) and Fig. 1(b), which give examples for rolled plate. The same system is used for sheet, extrusions, and forgings with nonsymmetrical grain flow.

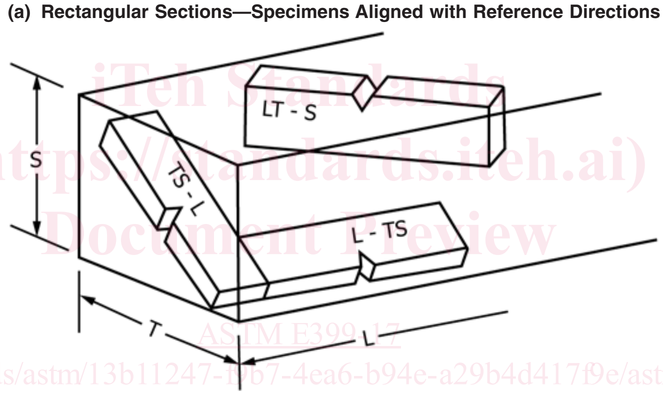
L = direction of principal deformation (maximum grain flow)
T = direction of least deformation
S = third orthogonal direction

3.1.4.3 Using the two-letter code, the first letter designates the direction normal to the crack plane, and the second letter

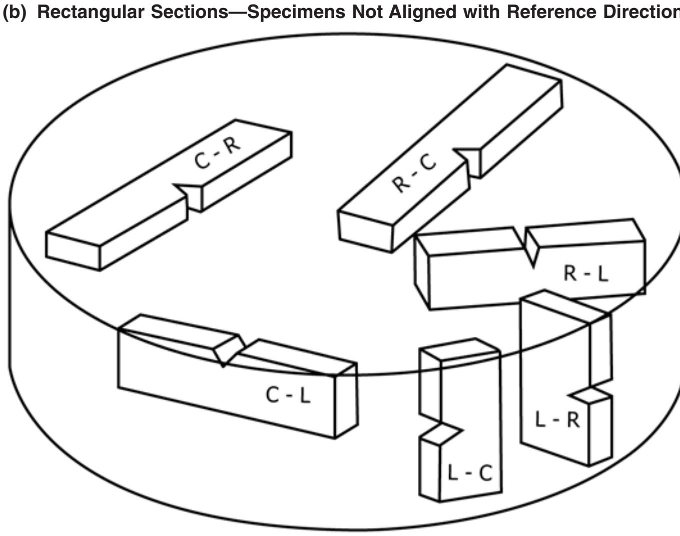
[4] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.



(a) Rectangular Sections—Specimens Aligned with Reference Directions



(b) Rectangular Sections—Specimens Not Aligned with Reference Directions



(c) Cylindrical Bars and Tubes

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

FIG. 1 Crack Plane Identification

the expected direction of crack propagation. For example, in Fig. 1(a), the T-L specimen fracture plane normal is in the width direction of a plate and the expected direction of crack propagation is coincident with the direction of maximum grain flow (or longitudinal) direction of the plate.

3.1.4.4 For specimens tilted in respect to two of the reference axes as in Fig. 1(b), crack plane orientation is identified by a three-letter code. The designation L-TS, for example, indicates the crack plane to be perpendicular to the principal deformation (L) direction, and the expected fracture direction to be intermediate between T and S. The designation TS-L means that the crack plane is perpendicular to a direction intermediate between T and S, and the expected fracture direction is in the L direction.

3.1.4.5 For cylindrical sections, where grain flow can be in the longitudinal, radial or circumferential direction, specimen location and crack plane orientation shall reference original cylindrical section geometry such that the L direction is always the axial direction for the L-R-C system, as indicated in Fig. 1(c), regardless of the maximum grain flow. Note that this is a geometry based system. As such, the direction of maximum grain flow shall be reported when the direction is known.

NOTE 2—The same system is useful for extruded or forged parts having circular cross section. In most cases the L direction corresponds to the direction of maximum grain flow, but some products such as pancake, disk, or ring forgings can have the R or C directions correspond to the direction of maximum grain flow, depending on the manufacturing method.

L = axial direction
R = radial direction
C = circumferential or tangential direction

3.1.4.6 In the case of complex structural shapes, where the grain flow is not uniform, specimen location and crack plane orientation shall reference host product form geometry and be noted on component drawings.

3.1.4.7 *Non-Wrought Products*—for non-wrought products, specimen location and crack plane orientation shall be defined on the part drawing. The result of a fracture toughness test from a non-wrought product shall not carry an orientation designation.

3.1.4.8 *Discussion*—when products are to be compared on the basis of fracture toughness, it is essential that specimen location and orientation with respect to product characteristic directions be comparable and that the results not be generalized beyond these limits.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *stress-intensity factor rate,* $\dot{K}$ (FL$^{-3/2}$ t^{-1})—change in stress-intensity factor, K, per unit time.

4. Summary of Test Method

4.1 This test method covers the determination of the plane-strain fracture toughness (K_{Ic}) of metallic materials by increasing-force tests of fatigue precracked specimens. Force is applied either in tension or three-point bending. Details of the test specimens and experimental procedures are given in the Annexes. Force versus crack-mouth opening displacement (CMOD) is recorded either autographically or digitally. The force at a 5 % secant offset from the initial slope (corresponding to about 2.0 % apparent crack extension) is established by a specified deviation from the linear portion of the record (**1**). The value of K_{Ic} is calculated from this force using equations that have been established by elastic stress analysis of the specimen configurations specified in this test method. The validity of the K_{Ic} value determined by this test method depends upon the establishment of a sharp-crack condition at the tip of the fatigue crack in a specimen having a size adequate to ensure predominantly linear-elastic, plane-strain conditions. To establish the suitable crack-tip condition, the stress-intensity factor level at which specimen fatigue precracking is conducted is limited to a relatively low value.

4.2 The specimen size required for test validity increases as the square of the material's toughness-to-yield strength ratio. 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 essentially linear-elastic stress and severe tensile constraint, such that *(1)* the state of stress near the crack front approaches tritensile plane strain, and *(2)* the crack-tip plastic zone is small compared to the crack size, specimen thickness, and ligament ahead of the crack.

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

5.1.2 Lower values of K_{Ic} can be obtained for materials that fail by cleavage fracture; for example, ferritic steels in the ductile-to-brittle transition region or below, where the crack front length affects the measurement in a stochastic manner independent of crack front constraint. The present test method does not apply to such materials and the user is referred to Test Method E1921 and E1820. Likewise this test method does not apply to high toughness or high tearing-resistance materials whose failure is accompanied by appreciable amounts of plasticity. Guidance on testing elastic-plastic materials is given in Test Method E1820.

5.1.3 The value of K_{Ic} obtained by this test method may be used to estimate the relation between failure stress and crack 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**).

5.1.4 Cyclic forces can cause crack extension at K_I values less than K_{Ic}. Crack extension under cyclic or sustained forces (as by stress corrosion cracking or creep crack growth) can be influenced by temperature and environment. Therefore, when K_{Ic} is applied to the design of service components, differences between laboratory test and field conditions shall be considered.

5.1.5 Plane-strain fracture toughness testing is unusual in that there can be no advance assurance that a valid K_{Ic} will be