Designation: E 1921 – 97$^{\epsilon 1}$

Standard Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range[1]

This standard is issued under the fixed designation E 1921; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ϵ^1 NOTE—Editorial changes were made through-out the standard in December 2001.

1. Scope

1.1 This test method covers the determination of a reference temperature, T_o, which characterizes the fracture toughness of ferritic steels that experience onset of cleavage cracking at elastic, or elastic-plastic K_{Jc} instabilities, or both. The specific types of ferritic steels (3.2.1) covered are those with yield strengths ranging from 275 to 825 MPa (40 to 120 ksi) and weld metals, after stress-relief annealing, that have 10 % or less strength mismatch relative to that of the base metal.

1.2 The specimens covered are fatigue precracked single-edge notched bend bars, SE(B), and standard or disk-shaped compact tension specimens, C(T) or DC(T). A range of specimen sizes with proportional dimensions is recommended. The dimension on which the proportionality is based is specimen thickness.

1.3 Requirements are set on specimen size and the number of replicate tests that are needed to establish acceptable characterization of K_{Jc} data populations.

1.4 The statistical effects of specimen size on K_{Jc} in the transition range are treated using weakest-link theory **(1)**[2] applied to a three-parameter Weibull distribution of fracture toughness values. A limit on K_{Jc} values, relative to the specimen size, is specified to ensure high constraint conditions along the crack front at fracture. For some materials, particularly those with low strain hardening, this limit may not be sufficient to ensure that a single-parameter (K_{Jc}) adequately describes the crack-front deformation state **(2)**.

1.5 Statistical methods are employed to predict the transition toughness curve and specified tolerance bounds for 1T specimens of the material tested. The standard deviation of the data distribution is a function of Weibull slope and median K_{Jc}. The procedure for applying this information to the establishment of transition temperature shift determinations and the establishment of tolerance limits is prescribed.

1.6 The fracture toughness evaluation of local brittle zones that are located in heat-affected zones of multipass weldments is not amenable to the statistical methods employed in the present test method.

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

2. Referenced Documents

2.1 *ASTM Standards:*

E 4 Practices for Force Verification of Testing Machines[3]
E 8M Test Methods for Tension Testing of Metallic Materials (Metric)[3]
E 74 Practice for Calibration of Force Measuring Instruments for Verifying the Force Indication of Testing Machines[3]
E 208 Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels[3]
E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[3]
E 436 Test Method for Drop-Weight Tear Tests of Ferritic Steels[3]
E 561 Practice for R-Curve Determination[3]
E 812 Test Method for Crack Strength of Slow-Bend, Precracked Charpy Specimens of High-Strength Metallic Materials[3]
E 813 Test Method for J_{Ic}, A Measure of Fracture Toughness[3]
E 1152 Test Method for Determining J-R Curves[3]
E 1823 Terminology Relating to Fatigue and Fracture Testing[3]

3. Terminology

3.1 Terminology given in Terminology E 1823 is applicable to this test method.

3.2 *Definitions*:

3.2.1 *ferritic steel*— carbon and low-alloy steels, and higher

[1] This test method is under the jurisdiction of ASTM Committee E-8 on Fatigue and Fracture and is the direct responsibility of E08.08 on Elastic-Plastic Fracture Mechanics Technology.

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

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

alloy steels, with the exception of austenitic stainless, martensitic, and precipitation hardening steels. All ferritic steels have body centered cubic crystal structures that display a ductile-to-cleavage transition temperature (see also Test Methods E 208 and E 436).

NOTE 1—This definition is not intended to imply that all of the many possible types of ferritic steels have been verified as being amenable to analysis by this test method.

3.2.2 *stress-intensity factor,* $K[FL^{-3/2}]$—the magnitude of the mathematically ideal crack-tip stress field coefficient (stress field singularity) for a particular mode of crack-tip region deformation in a homogeneous body.

3.2.3 *Discussion*—In this test method, Mode I is assumed. See Terminology E 1823 for further discussion.

3.2.4 *J-integral,* $J[FL^{-1}]$—a mathematical expression; a line or surface integral that encloses the crack front from one crack surface to the other; used to characterize the local stress-strain field around the crack front **(3)**. See Terminology E 1823 for further discussion.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *control load,* P_M[F]—a calculated value of maximum load used in Test Method E 1152-87 (7.6.1) to stipulate allowable precracking limits.

3.3.1.1 *Discussion*—In this method, P_M is not used for precracking, but is used as a minimum load above which partial unloading is started for crack growth measurement.

3.3.2 *crack initiation*—describes the onset of crack propagation from a preexisting macroscopic crack created in the specimen by a stipulated procedure.

3.3.3 *effective modulus,* $E_e[FL^{-2}]$—an elastic modulus that can be used with experimentally determined elastic compliance to effect an exact match to theoretical (modulus-normalized) compliance for the actual initial crack size, a_o.

3.3.4 *elastic modulus,* $E'[FL^{-2}]$—a linear-elastic factor relating stress to strain, the value of which is dependent on the degree of constraint. For plane strain, $E' = E/(1 - v^2)$ is used, and for plane stress $E' = E$.

3.3.4.1 *Discussion*—In this test method, plane stress elastic modulus is used.

3.3.5 *elastic-plastic* $K_J[FL^{-3/2}]$—An elastic-plastic equivalent stress intensity factor derived from *J*-integral.

3.3.5.1 *Discussion*—In this test method, K_J also implies a stress intensity factor determined at the test termination point under conditions determined to be invalid by 8.9.2.

3.3.6 *elastic-plastic* $K_{Jc}[FL^{-3/2}]$—an elastic-plastic equivalent stress intensity factor derived from the *J*-integral at the point of onset of cleavage fracture, J_c.

3.3.7 *Eta* (η)—a dimensionless parameter that relates plastic work done on a specimen to crack growth resistance defined in terms of deformation theory *J*-integral **(4)**.

3.3.8 *failure probability,* p_f—the probability that a single selected specimen chosen at random from a population of specimens will fail at or before reaching the K_{Jc} value of interest.

3.3.9 *initial ligament length,* b_o[L]— the distance from the initial crack tip, a_o, to the back face of a specimen.

3.3.10 *pop-in*—a discontinuity in a load versus displacement test record **(5)**.

3.3.10.1 *Discussion*—A pop-in event is usually audible, and is a sudden cleavage crack initiation event followed by crack arrest. A test record will show increased displacement and drop in applied load if the test frame is stiff. Subsequently, the test record may continue on to higher loads and increased displacement.

3.3.11 *reference temperature,* T_o [°C]—The test temperature at which the median of the K_{Jc} distribution from 1T size specimens will equal 100 MPa$\sqrt{m}$ (90.9 ksi$\sqrt{in.}$).

3.3.12 *SE(B) specimen span, S[L]*—the distance between specimen supports (see Test Method E 1152, Fig. 2).

3.3.13 *specimen thickness, B[L]*—the distance between the sides of specimens.

3.3.13.1 *Discussion*—In the case of side-grooved specimens, thickness, B_N, is the distance between the roots of the side-groove notches.

3.3.14 *specimen size, nT*—a code used to define specimen dimensions, where *n* is expressed in multiples of 1 in.

3.3.14.1 *Discussion*—In this method, specimen proportionality is required. For compact specimens and bend bars, specimen thickness $B = n$ in.

3.3.15 *temperature,* T_Q [°C]—For K_{Jc} values that are developed using specimens or test practices, or both, that do not conform to the requirements of this test method, a temperature of 100 MPa$\sqrt{m}$ fracture toughness is defined as T_Q. T_Q is not a provisional value of T_o.

3.3.16 *Weibull fitting parameter,* K_0— a scale parameter located at the 63.2 % cumulative failure probability level **(6)**. $K_o = K_{Jc}$ when $p_f = 0.632$.

3.3.17 *Weibull slope, b*—with p_f and K_{Jc} data pairs plotted in linearized Weibull coordinates (see Fig. X1.1), *b* is the slope of a line that defines the characteristics of the typical scatter of K_{Jc} data.

3.3.17.1 *Discussion*—A Weibull slope of 4 is used exclusively in this method.

3.3.18 *yield strength,* $\sigma_{ys}[FL^{-2}]$—a value of material strength at 0.2 % plastic strain as determined by tensile testing.

4. Summary of Test Method

4.1 This test method involves the testing of notched and fatigue precracked bend or compact specimens in a temperature range where either cleavage cracking or crack pop-in develop during the loading of specimens. Crack aspect ratio, *a/W*, is nominally 0.5. Specimen width in compact specimens is two times the thickness. In bend bars, specimen width can be either one or two times the thickness.

4.2 Load versus displacement across the notch at a specified location is recorded by autographic recorder or computer data acquisition, or both. Fracture toughness is calculated at a defined condition of crack instability. The *J*-integral value at instability, J_c, is calculated and converted into its equivalent in units of stress intensity factor, K_{Jc}. Validity limits are set on the suitability of data for statistical analyses.

4.3 Tests that are replicated at least six times can be used to estimate the median K_{Jc} of the Weibull distribution for the data population **(7)**. Extensive data scatter among replicate tests is expected. Statistical methods are used to characterize these data populations and to predict changes in data distributions with changed specimen size.

4.4 The statistical relationship between specimen size and K_{Jc} fracture toughness can be assessed using weakest-link theory, thereby providing a relationship between the specimen size and K_{Jc} **(1)**. Limits are placed on the fracture toughness range over which this model can be used.

4.5 For definition of the toughness transition curve, a master curve concept is used **(8, 9)**. The position of the curve on the temperature coordinate is established from the experimental determination of the temperature, designated T_o, at which the median K_{Jc} for 1T size specimens is 100 MPa$\sqrt{m}$ (90.9 ksi$\sqrt{in.}$). Selection of a test temperature close to that at which the median K_{Jc} value will be 100 MPa$\sqrt{m}$ is encouraged and a means of estimating this temperature is suggested. Small specimens such as precracked Charpy may have to be tested at temperatures below T_o where $K_{Jc(med)}$ is well below 100 MPa$\sqrt{m}$. In such cases, additional specimens may be required as stipulated in 8.5.

4.6 Tolerance bounds can be determined that define the range of scatter in fracture toughness throughout the transition range. The standard deviation of the fitted distribution is a function of Weibull slope and median K_{Jc} value, $K_{Jc(med)}$.

5. Significance and Use

5.1 Fracture toughness is expressed in terms of an elastic-plastic stress intensity factor, K_{Jc}, that is derived from the *J*-integral calculated at fracture.

5.2 Ferritic steels are inhomogeneous with respect to the orientation of individual grains. Also, grain boundaries have properties distinct from those of the grains. Both contain carbides or nonmetallic inclusions on the size scale of individual grains that can act as nucleation sites for cleavage microcracks. The random location of such nucleation sites with respect to the position of the crack front manifests itself as variability of the associated fracture toughness **(10)**. This results in a distribution of fracture toughness values that is amenable to characterization using statistical methods.

5.3 Distributions of K_{Jc} data from replicate tests can be used to predict distributions of K_{Jc} for different specimen sizes. Theoretical reasoning **(6)**, confirmed by experimental data, suggests that a fixed Weibull slope of 4 applies to all data distributions and, as a consequence, standard deviation on data scatter can be calculated. Data distribution and specimen size effects are characterized using a Weibull function that is coupled with weakest-link statistics **(11)**. An upper limit on constraint loss and a lower limit on test temperature are defined between which weakest-link statistics can be used.

5.4 The experimental results can be used to define a master curve that describes the shape and location of median K_{Jc} transition temperature fracture toughness for 1T specimens **(12)**. The curve is positioned on the abscissa (temperature coordinate) by an experimentally determined reference temperature, T_o. Shifts in reference temperature are a measure of transition temperature change caused, for example, by metallurgical damage mechanisms.

5.5 Tolerance bounds on K_{Jc} can be calculated based on theory and generic data. For added conservatism, an offset can be added to tolerance bounds to cover the uncertainty associated with estimating the reference temperature, T_o, from a relatively small data set. From this it is possible to apply a margin adjustment to T_o in the form of a reference temperature shift.

5.6 For some materials, particularly those with low strain hardening, the value of T_o may be influenced by specimen size due to a partial loss of crack-tip constraint **(2)**. When this occurs, the value of T_o may be lower than the value that would be obtained from a data set of K_{Jc} values derived using larger specimens.

6. Apparatus

6.1 *Precision of Instrumentation*—Measurements of applied loads and load-line displacements are needed to obtain work done on the specimen. Load versus load-line displacements may be recorded digitally on computers or autographically on *x-y* plotters. For computers, digital signal resolution should be 1/32,000 of the displacement transducer signal range and 1/4000 of the load transducer signal range.

6.2 *Grips for C(T) Specimens*—A clevis with flat-bottom holes is recommended. See Test Method E 399-90, Fig. A6.2, for a recommended design. Clevises and pins should be fabricated from steels of sufficient strength to elastically resist indentation loads (greater than 40 Rockwell hardness C scale (HRC)).

6.3 *Bend Test Fixture*—A suitable bend test fixture scheme is shown in Fig. A3.2 of Test Method E 399-90. It allows for roller pin rotation and minimizes friction effects during the test. Fixturing and rolls should be made of high-hardness steel (HRC greater than 40).

6.4 *Displacement Gage for Compact Specimens*:

6.4.1 Displacement measurements are made so that *J* values can be determined from area under load versus displacement test records (a measure of work done). If the test temperature selection recommendations of this practice are followed, crack growth measurement will probably prove to be unimportant. Results that fall within the limits of uncertainty of the recommended test temperature estimation scheme will probably not have significant slow-stable crack growth prior to instability. Nevertheless, crack growth measurements are recommended to provide supplementary information, and these results may be reported.

6.4.2 Unloading compliance is the primary recommendation for measuring slow-stable crack growth. See Test Method E 1152-87. When multiple tests are performed sequentially at low test temperatures, there will be condensation and ice buildup on the grips between the loading pins and flats of the clevis holes. Ice will interfere with the accuracy of the unloading compliance method. Alternatively, crack growth can be measured by other methods such as electric potential, but care must be taken to avoid specimen heating when low test temperatures are used.

6.4.3 In compact C(T) specimens, displacement measurements on the load line are recommended for *J* determinations. However, the front face position at 0.25 W in front of the load line can be used with interpolation to load-line displacement, as suggested in 7.1.

6.4.4 The extensometer calibrator shall be resettable at each displacement interval within 0.0051 mm (0.0002 in.). Accuracy of the clip gage at test temperature must be demonstrated to be within 1 % of the working range of the gage.

6.4.5 All clip gages used shall have temperature compensation.

6.5 *Displacement Gages for Bend Bars, SE(B)*:

6.5.1 The SE(B) specimen has two displacement gage locations. A load-line displacement transducer is primarily intended for *J* computation, but may also be used for calculations of crack size based on elastic compliance, if provision is made to subtract the extra displacement due to the elastic compliance of the fixturing. The load-line gage shall display accuracy of 1 % over the working range of the gage. The gages used shall not be temperature sensitive.

6.5.2 Alternatively, a crack-mouth opening displacement (CMOD) gage can also be used to determine the plastic part of *J*. However, it is necessary to employ a plastic eta (η_p) value developed specifically for that position **(13)** or to infer load-point displacement from mouth opening using an expression that relates the two displacements **(14)**. In either case, the procedure described in 9.1.4 is used to calculate the plastic part of *J*. The CMOD position is the most accurate for the compliance method of slow-stable crack growth measurement.

6.5.3 Crack growth can be measured by alternative methods such as electric potential, but care must be taken to minimize specimen heating effects in low-temperature tests (see also 6.4.2)**15**.

6.6 *Force Measurement*:

6.6.1 Testing shall be performed in a machine conforming to Practices of E 4-93 and E 8M-95. Applied force may be measured by any transducer with a noise-to-signal ratio less than 1/2000 of the transducer signal range.

6.6.2 Calibrate force measurement instruments by way of Practice E 74-91, 10.2. Annual calibration using calibration equipment traceable to the National Institute of Standards and Technology is a mandatory requirement.

6.7 *Temperature Control*—Temperature shall be measured with calibrated thermocouples and potentiometers. Accuracy of temperature measurement shall be within 3°C of true temperature and repeatability shall be within 2°C. Precision of measurement shall be ±1°C or better. The temperature measuring apparatus shall be checked every six months using instruments traceable to the National Institute of Standards and Technology in order to ensure the required accuracy.

7. Specimen Configuration, Dimensions, and Preparation

7.1 *Compact Specimens*—Three recommended C(T) specimen designs are shown in Fig. 1. One C(T) specimen configuration is taken from Test Method E 399-90; the two with cutout sections are taken from E 1152-87. The latter two designs are modified to permit load-line displacement measurement. Room is provided for attachment of razor blade tips on the load line. Care should be taken to maintain parallel alignment of the blade edges. When front face (at 0.25*W* in front of the load line) displacement measurements are made with the Test Method E 399 design, the load-line displacement can be inferred by multiplying the measured values by the constant 0.73 **(16)**. The ratio of specimen height to width, 2H/W is 1.2, and this ratio is to be the same for all types and sizes of C(T) specimens. The initial crack size, a_o, shall be 0.5W ± 0.05W. Specimen width, W, shall be 2B.

7.2 *Disk-shaped compact Specimens*—A recommended DC(T) specimen design is shown in Fig. 2. Initial crack size, a_o, shall be 0.5W± 0.05W. Specimen width shall be 2B.

7.3 *Single-edge Notched Bend*—The recommended SE(B) specimen designs, shown in Fig. 3, are made for use with a span-to-width ratio, S/W = 4. The width, W, can be either 1B or 2B. The initial crack size, a_o, shall be 0.5*W* ± 0.05W.

7.4 *Machined Notch Design*—The machined notch plus fatigue crack for all specimens shall lie within the envelope shown in Fig. 4.

7.5 *Specimen Dimension Requirements*—The crack front straightness criterion defined in 8.9.1 must be satisfied. The specimen remaining ligament, b_o, must have sufficient size to maintain a condition of high crack-front constraint at fracture. The maximum K_{Jc} capacity of a specimen is given by:

$$K_{Jc\,(\mathrm{limit})} = (Eb_o\sigma_{ys}/30)^{1/2} \quad (1)$$

where:

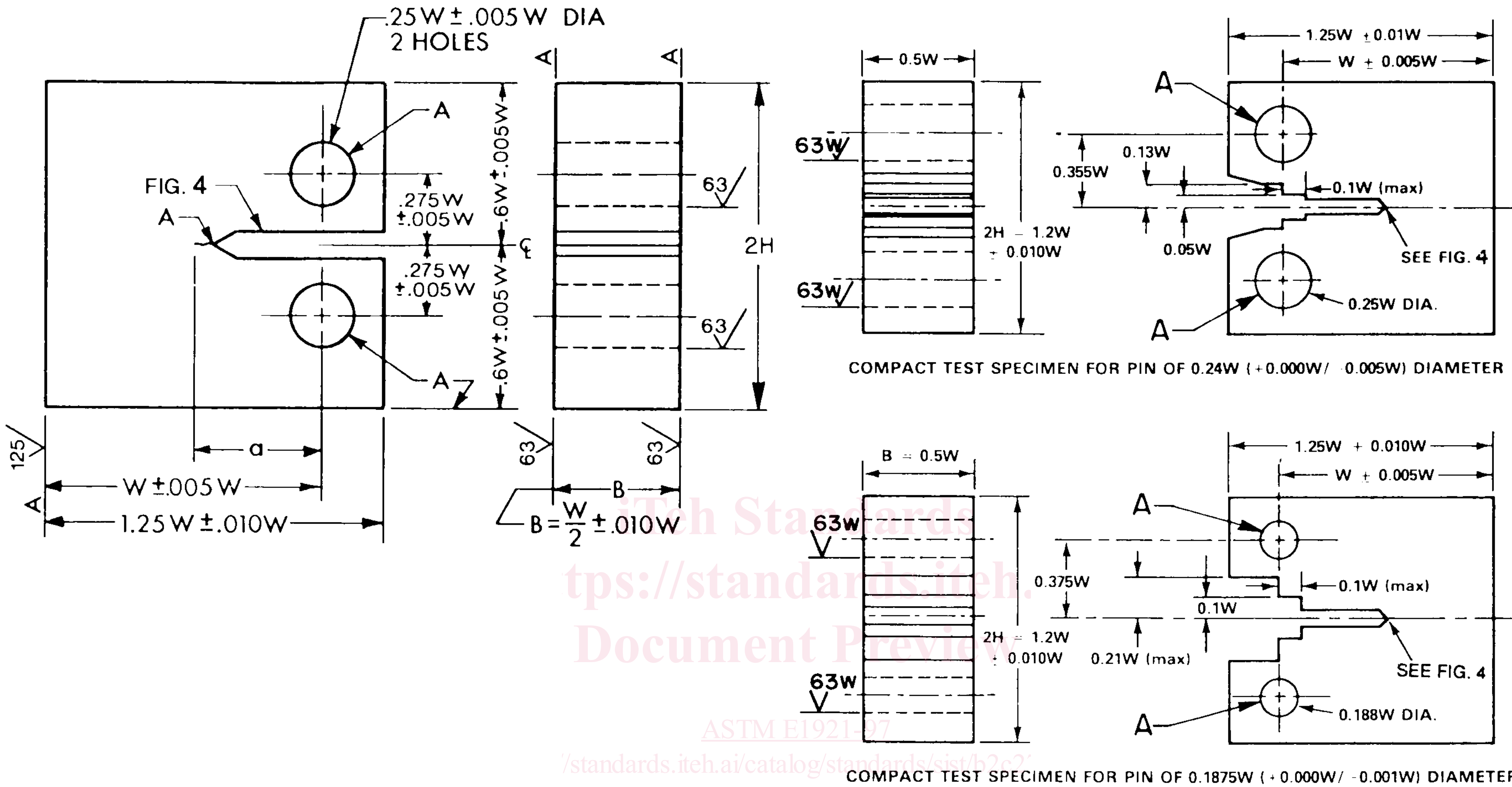
σ_{ys} = material yield strength at the test temperature.

K_{Jc} data that exceed this requirement may be used in a data censoring procedure described in Section 10, subject to the additional restrictions imposed there.

7.6 *Side Grooves*— Side grooves are optional. Precracking prior to side-grooving is recommended, despite the fact that crack growth on the surfaces might be slightly behind. Specimens may be side-grooved after precracking to decrease the curvature of the initial crack front. In fact, side-grooving may be indispensable as a means for controlling crack front straightness in bend bars of square cross section. The total side-grooved depth shall not exceed 0.25B. Side grooves with an included angle of 45° and a root radius of 0.5 ± 0.2 mm (0.02 ± 0.01 in.) usually produce the desired results.

7.7 *Precracking*— All specimens shall be precracked in the final heat treated condition. The length of the fatigue precrack extension shall not be less than 5 % of the total crack size. Precracking may include two stages–crack initiation and finish sharpening of the crack tip. To avoid growth retardation from a single unloading step, intermediate levels of load shedding can be added, if desired. One intermediate level usually suffices. To initiate fatigue crack growth from a machined notch, use K_{max}/E = 0.00013 $m^{1/2}$ (0.00083 $in.^{1/2}$)± 5 %.[4] Stress ratio, R, shall be controlled within the following range: 0.01 < R < 0.1. Finish sharpening is to be started at least 0.6 mm (0.025 in.) before the end of precracking. K_{max}/E for finish sharpening is to be 0.000096 $m^{1/2}$ (0.0006 $in.^{1/2}$) ± 5 % and stress ratio shall be maintained in the range 0.01 < *R* < 0.1. If the precracking temperature, T1, is different than the test temperature, T2, then the finish sharpening K_{max}/E shall be equal to or less than $[\sigma_{ys(T1)}/\sigma_{ys(T2)}]$ 0.000096 $m^{1/2}$ ± 5 %. The lowest practical stress ratio is suggested in all cases. Finish sharpening can be expected to require between 5×10^3 to 5×10^5 cycles for most metallic test materials when using the above recommended *K* levels. If the material in preparation does not precrack using the above recommended K_{max} requirements, variance is allowed only if it is shown that the finishing K_{max} does not exceed 60 % of the K_{Jc} value obtained in the

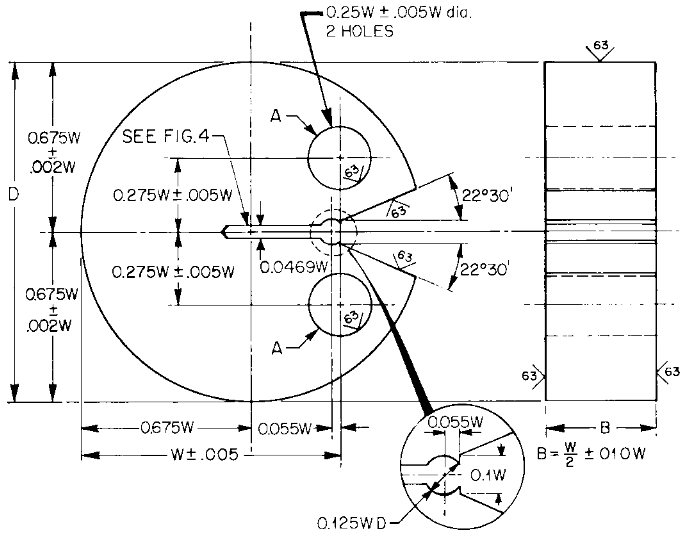
[4] Elastic (Young's) modulus, E, in units of MPa will result in K_{max} in units of MPa$\sqrt{m}$. Elastic (Young's) modulus, E, in units of ksi will result in K_{max} in units of ksi$\sqrt{in}$.



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

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

FIG. 1 Recommended Compact Specimen Designs

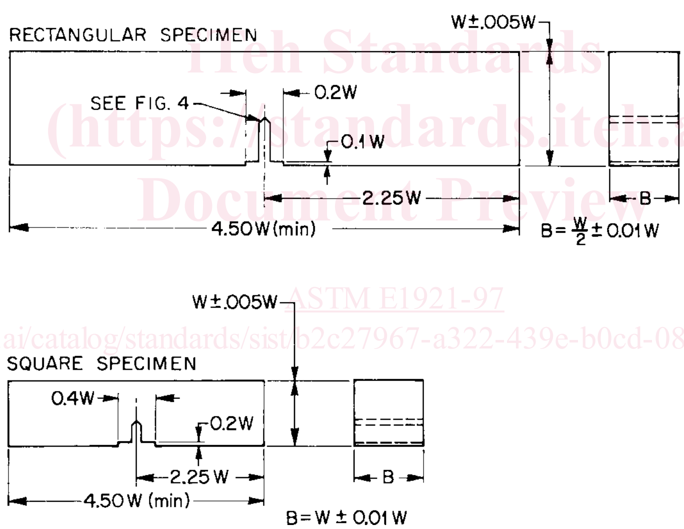


NOTE 1—A surfaces shall be perpendicular and parallel as applicable to within 0.002W TIR.

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

NOTE 3—Integral or attached knife edges for clip gage attachment may be used. See also Fig. 6, Test Method E 399.

FIG. 2 Disk-shaped Compact Specimen DC(T) Standard Proportions



NOTE 1—All surfaces shall be perpendicular and parallel within 0.001W TIR; surface finish 64v.

NOTE 2—Crack starter notch shall be perpendicular to specimen surfaces to within ± 2°.

FIG. 3 Recommended Bend Bar Specimen Design

subsequent test. Finish sharpening shall not take less than 10^3 cycles to produce the last 0.6 mm of growth.

8. Procedure

8.1 *Testing Procedure*—The objective of the procedure described here is to determine the *J*-integral at the point of crack instability, J_c. Crack growth can be measured by partial unloading compliance, or by any other method that has precision and accuracy, as defined below. However, the *J*-integral is not corrected for slow-stable crack growth in this test method.

8.2 *Test Preparation*— Prior to each test, certain specimen dimensions should be measured, the clip gage checked, and the starting crack size estimated from the average of the optical side face measurements.[5]

8.2.1 The dimensions B, B_N, and W shall be measured to within 0.05 mm (0.002 in.) accuracy or 0.5 %, whichever is larger.

8.2.2 Because most tests conducted under this method will terminate in specimen instability, clip gages tend to be abused, thus they shall be examined for damage after each test and checked electronically before each test. Clip gages shall be calibrated at the beginning of each day of use, using an extensometer calibrator as specified in 6.4.4.

[5] When side-grooving is to be used, first precrack without side grooves and optically measure the fatigue crack growth on both surfaces.