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

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[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,* σ_{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:

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

where:

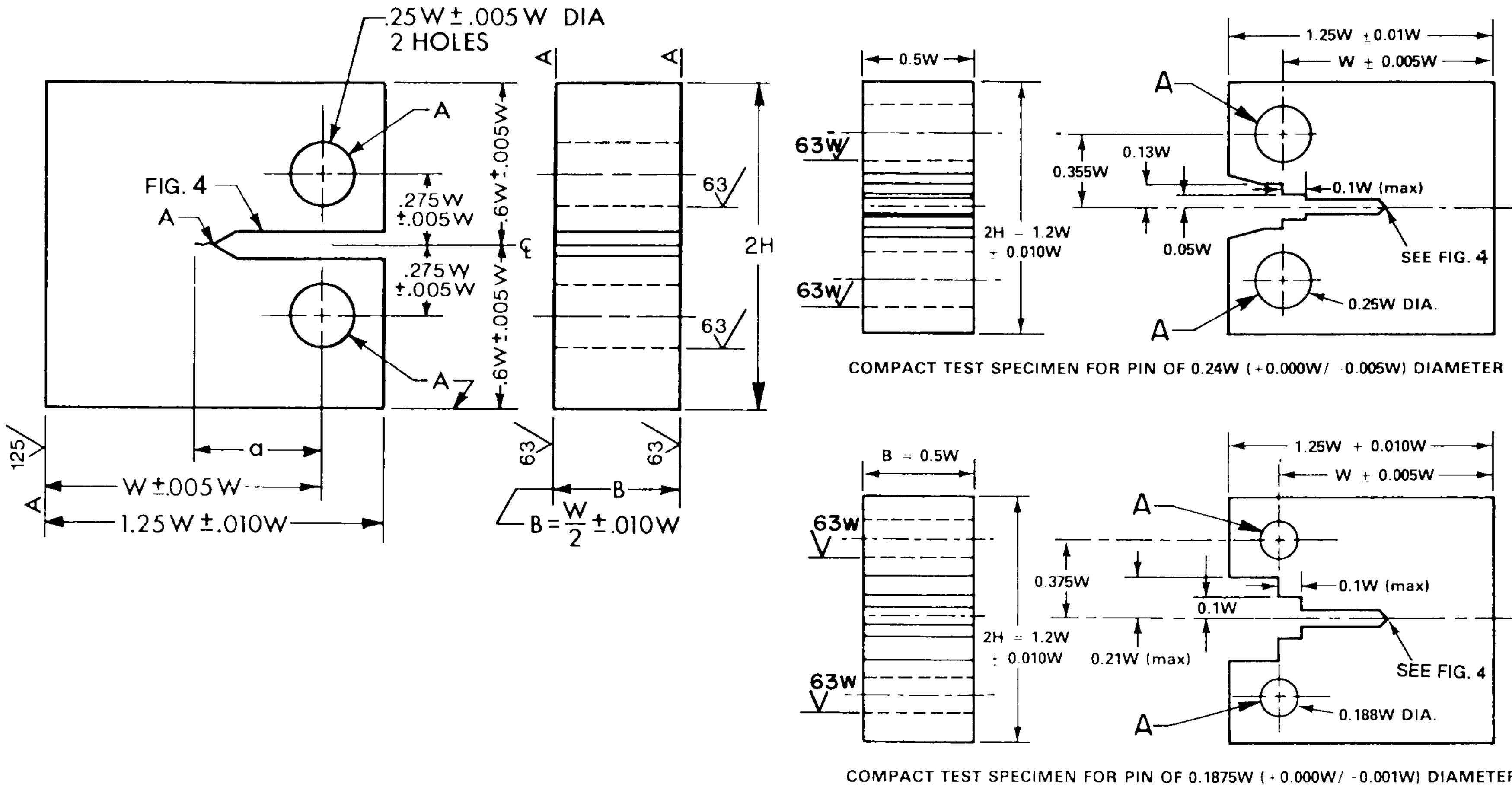
σ_{ys} = material yield strength at the test temperature.

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

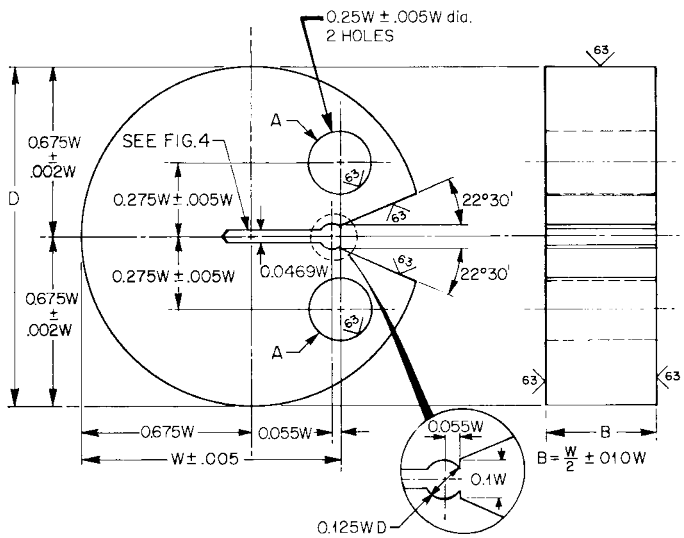
[4] Elastic (Young's) modulus, E, in units of MPa will result in K_{max} in units of MPa$\sqrt{m}$. Elastic (Young's) modulus, E, in units of ksi will result in K_{max} in units of ksi$\sqrt{in}$.



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

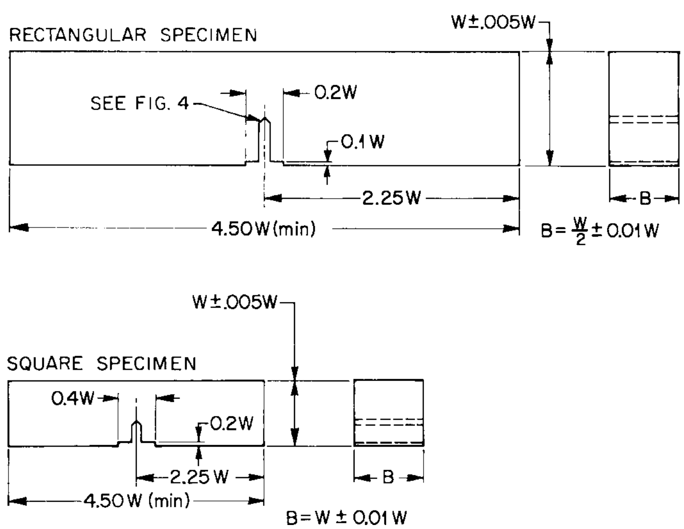


NOTE 1—A surfaces shall be perpendicular and parallel as applicable to within 0.002W TIR.

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

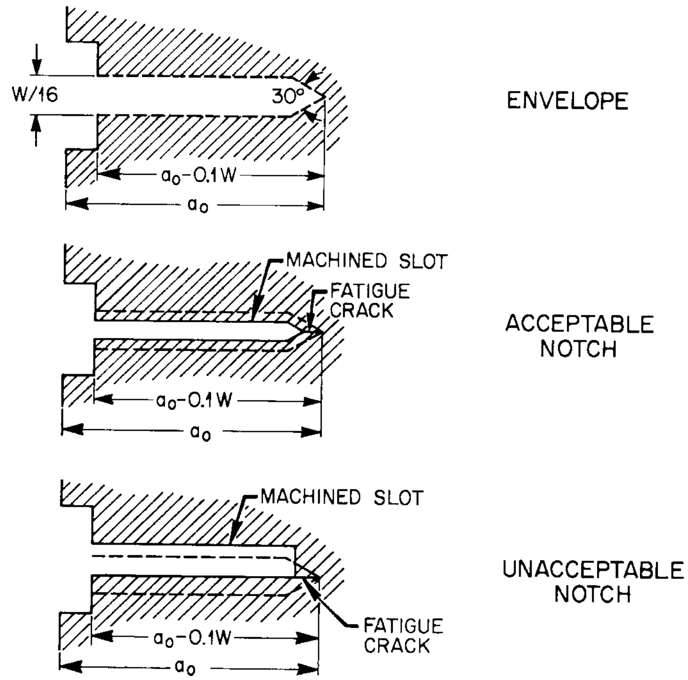
8.1 *Testing Procedure*—The objective of the procedure described here is to determine the *J*-integral at the point of crack instability, J_c. Crack growth can be measured by partial unloading compliance, or by any other method that has precision and accuracy, as defined below. However, the *J*-integral 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.



NOTE 1—N need not be less than 1.6mm (1⁄16 in.) but not exceed W/16.

NOTE 2—The intersection of the crack starter surfaces with the two specimen faces shall be equidistant from the top and bottom edges of the specimen within 0.005W.

FIG. 4 Envelope Crack Starter Notches

8.2.3 Follow Test Method E 1152-87, 8.7 for crack size measurement, 8.2.3 for testing compact specimens and 8.2.4 for testing bend specimens.

8.3 The required minimum number of valid K_{Jc} tests is specified according to the value of $K_{Jc(med)}$, see 8.5.

8.4 *Test Temperature Selection*—It is recommended that the selected temperature be close to that at which the $K_{Jc(med)}$ values will be about 100 MPa$\sqrt{m}$ for the specimen size tested. Charpy V-notch data, preferably in the T-L orientation, can be used as an aid for predicting a viable test temperature. Determine the temperature for a Charpy V-notch energy of 28 J, T_{28J}. Estimate test temperature, T, using the following **(9)**.

$$T = T_{28J} + C. \quad (2)$$

Units of the constant C are in °C, and C is a function of specimen size, nT (defined in 3.3.14) as follows:[6]

Specimen Size (nT)	Constant, C (°C)
0.4T[A]	–32
0.5T	–28
1T	–18
2T	–8
3T	–1
4T	2

[A]For precracked Charpy specimens, use C = –50°C.

8.4.1 Despite the large scatter in the estimate of T (Eq 2), the likelihood of slow-stable crack growth prior to onset of cleavage fracture will be low. Also, all specimens of the material sample are likely to provide valid K_{Jc} data.[7]

8.5 *Testing Below Temperature,* T_o—When the equivalent value of $K_{Jc(med)}$ for 1T specimens is greater than 83 MPa$\sqrt{m}$, the required number of valid K_{Jc} values to perform the analyses covered in Section 10 is six. However, small specimens such as precracked Charpy specimens (Test Method E 812) can develop excessive numbers of invalid K_{Jc} values by Eq 1 when testing close to the T_o temperature. In such cases it is advisable to test at temperatures below T_o, where most, if not all, K_{Jc} data developed can be valid. The disadvantage here is that the uncertainty in T_o determination increases as the lower-shelf toughness is approached. This increase in uncertainty can be countered by increasing the accuracy of the $K_{Jc(med)}$ determination by testing more specimens. Table 1 establishes the

TABLE 1 Number of Valid K_{Jc} Tests Required to Evaluate T_o

$K_{Jc(med)}$ range 1T equivalent[A,B] (MPa$\sqrt{m}$)	Number of valid K_{Jc} required	Possible number of invalid tests[C] by Eq. 1
100 to 84	6	3
83 to 66	7	1
65 to 58	8	0
57 to 53	9	0
52 to 50	10	0

[A]Convert $K_{Jc(med)}$ to 1T equivalence using Eq 23. Round off to nearest whole digit.

[B]Values of (T – T_o) corresponding to the values of $K_{Jc(med)}$ given here could be calculated using Eq 28. However, it is required that sample size via $K_{Jc(med)}$ always be used as the control parameter.

[C]Established specifically for precracked Charpy specimens. Use this column for total specimen needs.

[6] Standard deviation on this estimate has been determined to be 15°C.

[7] Data validation is covered in 8.9.2 and Section 10.

number of valid K_{Jc} tests required to evaluate T_o according to this test method.

8.6 *Specimen Test Temperature Control and Measurement*—For tests at temperatures other than ambient, any suitable means (liquid, gas vapor, or radiant heat) may be used to cool or heat the specimens, provided the region near the crack tip can be maintained at the desired temperature within ±2°C (± 4°F) during the soak period and during the conduct of the test.

8.6.1 Temperature shall be measured throughout testing by a thermocouple attached to the specimen near the crack tip but not directly on the plane of crack propagation. The attachment method can be by spot weld, drilled hole, or by a firm mechanical holding device so long as these practices do not disturb the crack tip stress field of the specimen during loading. After the specimen surface reaches test temperature and soaks at the test temperature for 2 min per centimeter of test specimen thickness, the testing may proceed. Temperature shall be maintained within ±2°C (±4°F) during the test.

8.6.2 To verify that the specimen is properly seated into the loading device and that the clip gage is properly seated, repeated preloading and unloading in the linear elastic range shall be applied. Load and unload the specimen between loads of 0.2 P_{max} and P_{max} (where P_{max} is the top precracking load of the finishing cycles) at least three times. Check the calculated crack size from each unloading slope against the average precrack size defined in 8.2. Refer also to Test Method E 1152, Eq 16 for C(T) specimens and to Eq 19 for SE(B) specimens. Be aware that ice buildup at the loading clevis hole between tests can affect accuracy. Therefore, the loading pins and devices should be dried before each test. For working-in fixtures, the elastic modulus to be used should be the nominally known value, E, for the material, and for side-grooved specimens, the effective thickness for compliance calculations is defined as:

$$B_e = B_N(2 - B_N/B) \quad (3)$$

8.6.3 For J calculations in Section 9, B_N is used as the thickness dimension. All calculated crack sizes should be within 10 % of the visual average and replicate determinations within 1 % of each other. If the repeatability of determination is outside this limit, the test setup is suspect and should be thoroughly rechecked. After working-in the test fixtures, the load shall be returned to the lowest practical value at which the fixture alignment can be maintained.

8.7 *Testing for* K_{Jc}—All tests shall be conducted using displacement control with either stroke or clip gage devices. Load versus load-point displacement measurements shall be recorded. Periodic partial unloading can be used to determine the extent of slow-stable crack growth if it occurs. Alternative methods of measuring crack extension, for example the potential drop method, can be used **(15)**. If displacement measurements are made at a location other than at the load point, the ability to infer load point displacement within 2 % of the absolute values shall be demonstrated. In the case of the front face for compact specimens (7.1), this requirement has been sufficiently proven so that no demonstration is required. For bend bars, see 6.5.2. Crack size prediction from partial unloading slopes at a different location will require different compliance calibration equations than those recommended in 8.6.2. Table 2 in Practice E 561-92a contains equations that define compliance for other locations on the compact specimen.

8.7.1 Load specimens at a rate such that the time of loading taken to reach load P_M lies between 0.1 and 10 min. P_M is nominally 40 % of limit load; see Test Method E 1152-87, 7.6.1, Eqs. 1 and 2. The crosshead speed during periodic partial unloadings may be as slow as needed to accurately estimate crack growth, but shall not be faster than the rate specified for loading.

8.7.2 Partial unloadings that are initiated between load levels P_M and 1.5P_M can be used to establish an "effective" elastic modulus, E_e, such that the modulus-normalized elastic compliance predicts an initial crack size within 0.001W of the actual initial crack size. The resulting E_e should not differ from an expected or theoretical E of the material by more than 10 % (see also Practice E 561-92a, Section 10). A minimum of two such unloadings should be made and the slopes should be repeatable within 1 % of the mean value. Slow-stable crack growth usually develops at loads well above 1.5P_M and the spacing of partial unloadings depends on judgement. As an aim, every 0.01a_o increment of crack growth is suitable. Use E_e in place of E and B_e for thickness to calculate crack growth.

8.8 *Test Termination*— After completion of the test, optically measure initial crack size and the extent of slow-stable crack growth or crack extension due to crack pop-in, or both, when applicable.

8.8.1 When the failure event is full cleavage fracture, determine the initial fatigue precrack size, a_o, as follows: measure the crack length at nine equally spaced points centered about the specimen centerline and extending to 0.01B from the free surfaces of plane sided specimens or near the side groove roots on side grooved specimens. Average the two near-surface measurements and combine the average of these two readings with the remaining seven crack measurements. Determine the average of those eight values. Measure the extent of slow-stable crack growth if it develops applying the same procedure. The measuring instruments shall have an accuracy of 0.025 mm (0.001 in.).

8.9 *Qualification of Data*:

8.9.1 The K_{Jc} datum shall be discarded if any of the nine physical measurements of the starting crack size differ by more than 7 % or 0.5 mm, whichever is larger, from the average defined in 8.8.1.

8.9.2 The K_{Jc} datum is not valid if the specimen cannot satisfy the size requirement of 7.5 or if the test is terminated at a final K_J that exceeds the K_{Jc} (limit) without cleavage crack intervention. For tests that terminate in cleavage but that have prior crack growth greater than 5 % of the initial remaining ligament, 0.05 (W – a_o), the values are also considered invalid, K_J. When K_J or K_{Jc} values are invalid, these data contain statistically useable information that can be applied as censored data in 10.1.4.

8.9.3 For any test terminated with no cleavage fracture, and for which the final K_J does not exceed the constraint limit, $K_{Jc(limit)}$, of 7.5, the record is to be considered a nontest, the results of which are of no use. Such data shall be discarded.

8.9.4 Data sets that contain all valid K_{Jc} values can be used without modification in Section 10. Data sets that contain some invalid data but that meet the requirements of 8.5 can be used with data censoring (10.1.4). Remedies for excessive invalid data include (*1*) testing at a lower test temperature, (*2*) testing with larger specimens, or (*3*) testing more specimens to satisfy data censoring requirements.

8.9.5 A discontinuity in a load-displacement record, that may be accompanied by a distinct sound like a click emanating from the test specimen, is probably a pop-in event. All pop-in crack initiation K values for cracks that advance by a cleavage-driven mechanism are to be regarded as eligible K_{Jc} data. It is recognized that test equipment can at times introduce false pop-in indications in test records. If a questionable discontinuity develops, stop the loading as soon as possible and assess the compliance ratio by 9.2. If the compliance change leads to a ratio calculated by 9.2 that is greater than the calculated ratio corresponding to more than a 1 % increase in crack size, the recommended practice is to assume that a pop-in event has occurred and to terminate the test, followed by heat tinting and breaking the specimen open at liquid nitrogen temperature. Measure the initial crack size and calculate K_{Jc}, for the pop-in load, based on that crack size. Measure the post pop-in crack size visually and record it. If there is no evidence of crack extension by cleavage, then the K_{Jc} value at the discontinuity point is not a part of the K_{Jc} data distribution.

9. Calculations

9.1 Determine the *J*-integral at onset of cleavage fracture as the sum of elastic and plastic components:

$$J_c = J_e + J_p \tag{4}$$

9.1.1 For compact specimens, *C(T)*, the elastic component of *J* is calculated as follows:

$$J_e = (K_e)^2/E, \tag{5}$$

where:

K_e = $[P/(BB_N W)^{1/2}]\ f(a_o/W)$,

$$f(a_o/W) = \frac{(2 + a_o/W)}{(1 - a_o/W)^{3/2}}[0.886 + 4.64\,(a_o/W) - 13.32(a_o/W)^2 + 14.72(a_o/W)^3 - 5.6(a_o/W)^4], \tag{6}$$

and a_o = initial crack size.

9.1.2 For disk-shaped compact specimens, *DC(T)*, the elastic component of *J* is calculated as follows:

$$J_e = (K_e)^2/E, \tag{7}$$

where:

K_e = $[P/(BB_N W)^{1/2}]\ f(a_o/W)$,

$$f(a_o/W) = \frac{(2 + a_o/W)}{(1 - a_o/W)^{3/2}}[0.76 + 4.8(a_o/W) - 11.58(a_o/W)^2 + 11.43(a_o/W)^3 - 4.08(a_o/W)^4], \tag{8}$$

and a_o = initial crack size.

9.1.3 For SE(B) specimens of both B × B and B × 2B cross sections and span-to-width ratios of 4, the elastic component of *J* is calculated as follows:

$$J_e = (K_e)^2/E \tag{9}$$

,

where:

K_e = $\{PS/[(BB_N)^{1/2}\ W^{3/2}]\}\ f(a_o/W)$,

$$f(a_o/W) = \frac{3(a_o/W)^{1/2}}{2[1 + 2(a_o/W)]} \frac{1.99 - (a_o/W)(1 - a_o/W)[2.15 - 3.93(a_o/W) + 2.7(a_o/W)^2]}{(1 - a_o/W)^{3/2}}, \tag{10}$$

and a_o = the initial crack size.

9.1.4 When slow-stable crack growth does not exceed 0.05 $(W - a_o)$, the plastic component of J is calculated as follows:

$$J_p = \frac{\eta A_p}{B_N b_o}, \tag{11}$$

where:

A_p = $A - 1/2 C_o P^2$,
A = $A_e + A_p$ (see Fig. 5),
C_o = reciprocal of the initial elastic slope, V/P (Fig. 5), and
b_o = initial remaining ligament.

9.1.4.1 For standard and disk-shaped compact specimens, A_p is based on load-line displacement (LLD) and $\eta = 2 + 0.522\ b_o/W$. For bend bar specimens of both $B \times B$ and $B \times 2\ B$

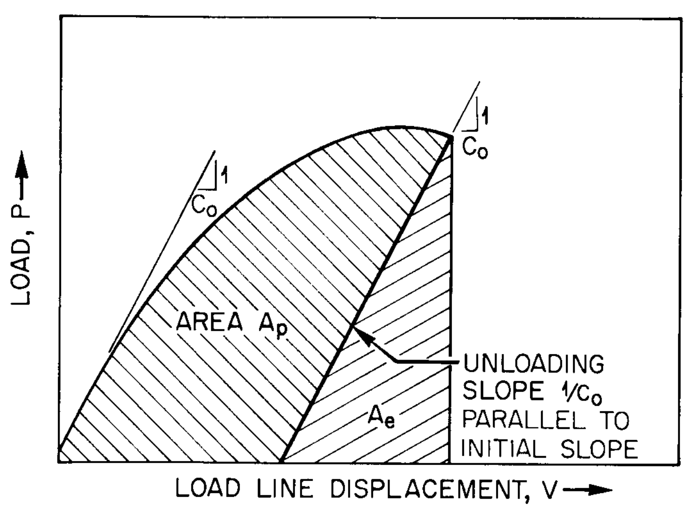


FIG. 5 Definition of the Plastic Area for J_p Calculations

cross sections and span-to-width ratios of 4, A_p may be based on either LLD or crack-mouth opening displacement (CMOD). Using LLD, η = 1.9. Values of η for bend bars based on CMOD are discussed in 6.5.2.

9.1.5 K_{Jc} is determined for each datum from J at onset of cleavage fracture, J_c. Assume plane stress for elastic modulus, *E:*

$$K_{Jc} = \sqrt{J_c E} \tag{12}$$

9.1.6 All data in excess of the limit prescribed by Eq 1 of 7.5 are considered invalid, but such values can be used in the censoring analysis that is described in 10.1.4. Invalid data developed as a part of a data set disqualifies that data set for 10.1.2 analysis.

9.2 *Pop-in Evaluation*—Test records that can be used for K_{Jc} analyses are those that show complete specimen separation due to cleavage fracture and those that show pop-in. If a load-displacement record shows a small but perceptible discontinuity without the audible click of the typical pop-in, a mid-test decision will be needed. Following Fig. 6, determine the post pop-in to initial compliance ratio, C_i/C_o, and compare this to the value of the right-hand side of the following inequality which implies that a pop-in has occurred:

$$\frac{C_i}{C_o} > \left[1 + 0.01\,\eta\left(\frac{W}{a_o} - 1\right)^{-1}\right] \tag{13}$$

where:

a_o = nominal initial crack size (high accuracy on dimension a_o is not required here), and

η = parameter based on LLD defined in 9.1.4.1.

9.2.1 Eq 13 involves the use, by approximation, of the plastic parameter, η, in an otherwise elastic equation, as suggested in Test Method E 1152. When a_o/W = 0.5, C_i/C_o shall be greater than 1.02, to follow the pop-in evaluation procedure prescribed in 8.9.5.

9.3 *Outlier*—Occasionally a K_{Jc} value will appear to be well below the general population of K_{Jc} data. It is useful to examine such a value to determine if it belongs to the same population as the other data. At least 12 replicate K_{Jc} values are needed to evaluate an outlier. Determine $K_{Jc(med)}$ including the outlier; then determine the 2 % lower-tolerance bound value of K_{Jc} as follows:

$$K_{Jc(02)} = 0.429\,K_{Jc(med)} + 11.44\,MPa\sqrt{m} \tag{14}$$

9.3.1 An individual value from a data set of 12 or more specimens that is less than $(K_{Jc})_{02}$ can be regarded as an outlier.[8] The fact that an outlier datum has been identified and discarded shall be reported. The median K_{Jc} derived from the remaining data can be used to characterize reference temperature, T_o.

[8] Data rejection is a risky practice since outliers potentially could be the result of a serious material inhomogeneity problem.

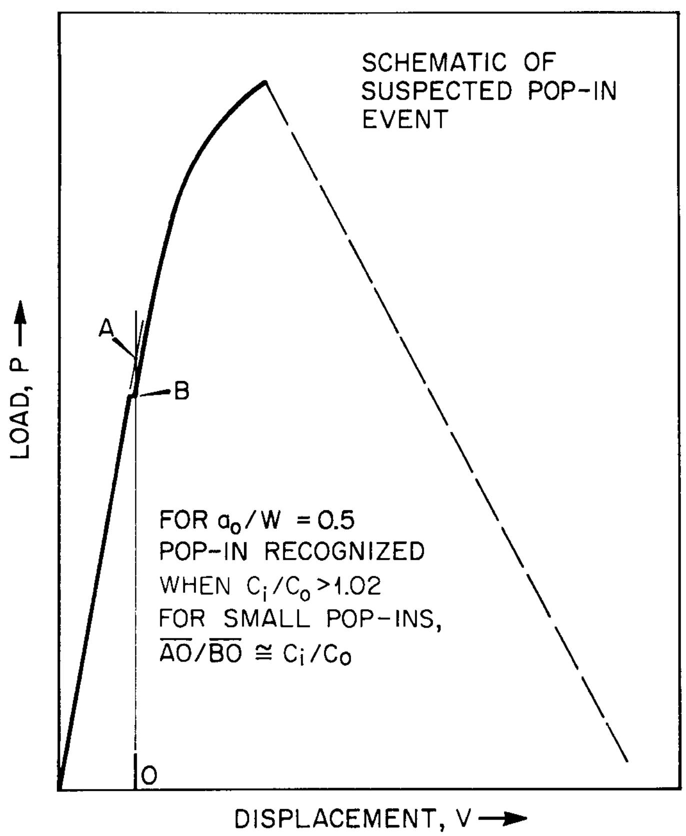


FIG. 6 Schematic of Pop-in Magnitude Evaluation

10. Prediction of Size Effects and Transition Temperature

10.1 *Weibull Fitting of Data Sets*:

10.1.1 *Test Replication*— A data set consists of at least six valid replicate test results determined at one test temperature; see also 8.5.

10.1.2 *Determination of Scale Parameter, K_o, and median K [$K_{Jc(med)}$]*—The three-parameter Weibull model is used to define the relationship between K_{Jc} and the cumulative probability for failure, p_f. The term p_f is the probability for failure at or before K_{Jc} for an arbitrarily chosen specimen taken from a large population of specimens. Data samples of six or more specimens are used to estimate the true value of scale parameter, K_o, in the following Weibull model:

$$p_f = 1 - \exp\{-[(K_{Jc} - K_{min})/(K_o - K_{min})]^b\} \quad (15)$$

10.1.2.1 Ferritic steels of yield strengths ranging from 275 to 825 MPa (40 to 120 ksi) will have fracture toughness cumulative probability distributions of nearly the same shape, independent of specimen size and test temperature, when K_{min} is set at 20 MPa$\sqrt{m}$ (18.2 ksi$\sqrt{in.}$). The distribution shape is defined by the Weibull exponent, *b*, which tends to be near 4. Scale parameter, K_o, is the data-fitting parameter, and the following Eq 16 can be used for a sample that consists of six or more valid K_{Jc} values.[9] Invalid K_J data cannot be discarded (ignored) to make an all-valid data set. Instead, the censoring procedure of 10.1.4 shall be used **(17)**.

$$K_o = \left[\sum_{i=1}^{N} (K_{Jc(i)} - K_{min})^4/(N - 0.3068)\right]^{1/4} + K_{min}, \quad (16)$$

where:
N = number of specimens.

10.1.2.2 An example solution is given in Appendix X1. The estimated median K_{Jc} value of the population can be obtained from K_o using the following equation:

$$K_{Jc(med)} = (K_o - K_{min})\,[ln(2)]^{1/4} + K_{min}, \quad (17)$$

where:
K_{min} = 20 MPa$\sqrt{m}$ (18.2 ksi$\sqrt{in.}$)

10.1.3 *Plotting Data in Three-Parameter Weibull Coordinates*—Eq 15 can be rearranged into a graphically linear Weibull format for visual presentation of test results. Coordinates of the linear Weibull plot are as follows:

$$x = \ln(K_{Jc} - K_{min}) \quad (18)$$

and

$$y = \ln\{\ln[1/(1 - \hat{p}_f)]\},$$

10.1.3.1 Probability values $\hat{p}_f$ are assigned to K_{Jc} values after they are ranked in order of increasing magnitude. In the following equation, $i = 1$ is assigned to the lowest ranked K_{Jc} value and so forth, and ending with $i = N$ assigned to the highest ranked K_{Jc} value. Cumulative probability values for failure, p_f, are assigned to each ranked K_{Jc} value using the following equation:

$$\hat{p}_f = \frac{i - 0.3}{N + 0.4} \quad (19)$$

10.1.3.2 The transformed data usually produce an approximately linear plot with a Weibull slope (b in Eq 15) near 4.[10] The line that represents the Weibull function, Eq 15, is developed from K_o calculated by maximum likelihood determination (see Appendix X1).

10.1.4 *Data Censoring*— Weibull fitting can be performed on data sets that contain invalid K_{Jc} values. An individual datum that fails the validity requirements of 8.9.2, K_J, shall be censored and replaced by the $K_{Jc(limit)}$ toughness value of Eq 1 in 7.5. All the data shall be obtained from one specimen size, that is, there shall be at least six valid K_{Jc} values in the data set, see 8.5 and 8.9. It is correct to presume that, if censoring is necessary, in almost all cases the K_{Jc} values of highest fracture toughness rank will be censored. To determine the scale parameter, K_o, use the following:

$$K_o = \left[\sum_{i=1}^{N} (K_{Jc(i)} - K_{min})^4/(r - 0.3068)\right]^{1/4} + K_{min}, \quad (20)$$

where:
r = number of valid data, and
N = total number of valid K_{Jc} and invalid K_J values.

See the example case in Appendix X1.

10.2 *Prediction of Specimen Size Effects on $K_{Jc(med)}$ or Single K_{Jc} Datum*—The statistical dependence of fracture toughness data on specimen size is predicted using a weakest-link theory. Such size effects exist in the transition region but not for fracture toughness values on the lower shelf as defined in 10.2.2. The following Eq 21 can be used to size adjust $K_{Jc(med)}$, or individual K_{Jc} values. $K_{Jc(med)}$ serves as an example case.

$$K_{(med)x} = K_{min} + [K_{Jc(med)} - K_{min}]\left(\frac{B_o}{B_x}\right)^{1/4}, \quad (21)$$

where:
$K_{Jc(med)}$ = median K_{Jc} for test data,
B_o = full thickness of test specimens (presence of side grooves ignored), and
B_x = full thickness of prediction (presence of side-grooving ignored).

10.2.1 *Upper Limit*— At high values of fracture toughness relative to specimen size and material-flow properties, the values of K_{Jc} that meet the requirement of Eq 1 may not always provide a unique description of the crack-front stress-strain fields due to some loss of constraint caused by excessive plastic flow **(2)**. This condition may develop in materials with low strain hardening. When this occurs, the highest K_{Jc} values of the valid data set may cause the value of T_o to be lower than the value that would be obtained from testing specimens with higher constraint.

10.2.2 *Lower Toughness Limit*—At low temperatures, specimen size effects diminish due to a change in the cleavage crack triggering mechanism **(10)**. This condition develops when plastic deformation at the crack tip is highly localized. Size effects can be considered to have vanished when $K_{Jc(med)}$ of the data set is 50 MPa$\sqrt{m}$ or below. The use of Eq 21 in this range of fracture toughness is not advised.

[9] The estimator method for K_o is from the maximum likelihood derivation **(17)**.

[10] Small data sets of the number required by this test method may not always appear to show a Weibull slope of 4. True slope is reliably converged upon when data sets contain 50 or more replicate specimens.

10.3 *Establishment of a Transition Temperature Curve (Master Curve)*—Transition temperature K_{Jc} data tend to conform to a common toughness versus temperature curve shape in the same manner as the ASME K_{Ic} and K_{IR} lower-bound design curves **(18)**. For this method, the shape of the median K_{Jc} toughness, $K_{Jc(med)}$, for 1T specimens (3.3.14) is described by:

$$K_{Jc(med)} = 30 + 70 \exp[0.019(T - T_o)], \text{MPa}\sqrt{\text{m}}, \quad (22)$$

where:
T = test temperature (°C), and
T_o = reference temperature (°C).

10.3.1 Master curve positioning involves the determination of T_o using the computational steps presented below.

10.3.2 For data sets with 100 % valid data, adjust K_{Jc} data to 1T equivalence. Data equivalent to that for a 1T specimen size, B_{1T}, can be calculated from data measured with specimens of a different size, B_x, by using the following equation:

$$K_{Jc(1T)} = 20 + [K_{Jc\,(x)} - 20]\left(\frac{B_x}{B_{1T}}\right)^{1/4}, \text{MPa}\sqrt{\text{m}}. \quad (23)$$

10.3.3 *Determine* K_o—For all valid data:

$$K_o = [\sum_{i=1}^{N}(K_{Jc(i)} - 20)^4 / (N - 0.3068)]^{1/4} + 20 \text{ MPa}\sqrt{\text{m}}. \quad (24)$$

10.3.4 For data sets with censored K_{Jc} values, set all censored values, K_J to $K_{Jc(limit)}$ using:[11]

$$K_{Jc(limit)} = (Eb_o\sigma_{ys}/30)^{1/2} \text{ MPa}\sqrt{\text{m}}. \quad (25)$$

then determine $K_{o(x)}$ for the specimen size tested using,

$$K_{o(x)} = [\sum_{i=1}^{N}(K_{Jc(i)} - 20)^4 / (r - 0.3068)]^{1/4} + 20 \text{ MPa}\sqrt{\text{m}}, \quad (26)$$

where:
N = total number of K_J and K_{Jc} values, and
r = number of valid K_{Jc} values. At least six valid K_{Jc} values are required.

10.3.4.1 Adjust K_o to 1T equivalence using Eq 23 and then proceed to 10.3.5.

10.3.5 *Determine* $K_{Jc(med)}$:

$$K_{Jc(med)} = (K_o - 20)(0.9124) + 20 \text{ MPa}\sqrt{\text{m}} \quad (27)$$

10.3.6 *Determine Reference Temperature* (T_o):

$$T_o = T - \frac{1}{0.019}\ln\left[\frac{K_{Jc(med)} - 30}{70}\right] \quad (28)$$

Units of $K_{Jc(med)}$ are in MPa$\sqrt{\text{m}}$; units of T_o are in °C.

10.3.6.1 Temperature T_o should be relatively independent of the test temperature chosen. If multiple values of T_o are obtained using different test temperatures, determine an average T_o value.

10.3.7 When tests are made at one selected test temperature, the number of specimens required for a valid sample will equal or exceed six, depending on $K_{Jc(med)}$, as given in 8.5. The determination of reference temperature, T_o, has some uncertainty when there are small numbers of replicate specimens used. It is optional to cover this uncertainty by adding a temperature adjustment, ΔT_o, to the lower tolerance bound of the master curve (Appendix X3). Otherwise, uncertainty in T_o can be reduced by testing either more specimens or more groups of specimens at other test temperatures.

10.3.8 K_{Jc} values that are developed using specimens and/or test practices that do not conform to the requirements of this method can be used to establish the temperature of 100 MPa$\sqrt{\text{m}}$ fracture toughness. Such temperatures shall be referred to as T_Q. Currently existing experimental evidence indicates that data populations developed without the controlled constraint conditions required by the present standard method are apt to have Weibull slopes that are other than 4 and, as such, the use of the equations provided here and the use of the master curve toughness trend to determine T_Q is not technically justifiable. Hence, values of T_Q are of use for unique circumstances only and are not to be regarded as provisional values of T_o.

10.4 *Uses for Master Curve*—The master curve can be used to define a transition temperature shift related to metallurgical damage mechanisms. Fixed values of Weibull slope and median K_{Jc} define the standard deviation; hence the representation of data scatter. This information can be used to calculate tolerance bounds on toughness, for the specimen reference size chosen. The data scatter characteristics modeled here can also be of use in probabilistic fracture mechanics analysis, bearing in mind that the master curve pertains to a 1T size specimen. The master curve determined by this procedure pertains to cleavage fracture behavior of ferritic steels. Extensive ductile tearing beyond the validity limit set in 8.9.2, may precede cleavage as the upper-shelf range of temperature is approached. Such data can be characterized by separate methods (see Test Methods E 813 and E 1152).

11. Report

11.1 Report the following information:

11.1.1 Specimen type, specimen thickness, B, net thickness, B_N, specimen width, W,

11.1.2 Specimen initial crack size,

11.1.3 Visually measured slow-stable crack growth to failure, if evident,

11.1.4 Crack plane orientation according to Terminology E 1823,

11.1.5 Test temperature,

11.1.6 Number of valid specimens and total number of specimens tested at each temperature,

11.1.7 Crack pop-in and compliance ratio, C_i/C_o,

11.1.8 Material yield strength and tensile strength,

11.1.9 The location of displacement measurement used to obtain the plastic component of J (load-line or crack-mouth),

11.1.10 A list of individual K_{Jc} values and the median $K_{Jc(med)}$ (MPa$\sqrt{\text{m}}$) obtained from that list,

11.1.11 Reference temperature on master curve, T_o (°C),

11.1.12 Fatigue precracking condition in terms of K_{max} for the last 0.64 mm (0.025 in.) of precrack growth, and

11.1.13 Difference between maximum and minimum crack length measurement expressed as a percentage of the initial crack size.

[11] Data obtained from specimens of a variety of sizes cannot be converted into 1T equivalence before using Eq 25 because the variability introduced through different $K_{Jc(limit)}$ values would result in random censoring. However, a K_o value obtained by censoring with *fixed* specimen size can be subsequently size-adjusted.

11.2 The report may contain the following supplementary information:

11.2.1 Specimen identification codes,

11.2.2 Measured pop-in crack extensions, and

11.2.3 Load-displacement record.

12. Precision and Bias

12.1 *Precision*—The variability of material toughness in the transition range is an accepted fact and the modeling of the data scatter is an integral feature of this test procedure. It has been observed that when K_{min} of 20 MPa$\sqrt{m}$ is used as a deterministic parameter in the three-parameter Weibull statistical model, K_{Jc} data distributions will tend to display a Weibull slope of approximately 4. Small sample sizes, such as required by 8.5, are prone at times to show slopes that vary randomly above and below 4, but such behavior does not necessarily indicate a lack-of-precision problem. This variability becomes small only with extremely large sets of specimens **(8)**. Despite slope variations with sample sizes, the median K_{Jc} will be within 20 % of the true median of the full data population and it is this value that is used to establish the reference temperature, T_o. The number of specimens required by this standard is increased for tests performed at temperatures below T_o. Tests that use more than the minimum number of six specimens have increased precision of $K_{Jc(med)}$ determination. This is required at test temperatures approaching lower shelf where more precision is needed to maintain an equal uncertainty level in the T_o determination. If reference temperatures, T_o, are calculated from $K_{Jc(med)}$ values determined at several test temperatures, some scatter can be expected. The standard deviation of this scatter is defined by Eq. X3.4 in Appendix X3. Equation X3.4 solved using the sample size required for validity and applied with a standard normal deviate for 85 % confidence suggests that T_o values determined at different temperatures can be expected to be within a scatter band of 20°C **(12, 19)**.

12.2 *Bias*—There is no accepted standard value for the fracture toughness of a specific material. In the absence of a true known value, no statement concerning bias can be made.

APPENDIXES

(Nonmandatory Information)

X1. WEIBULL FITTING OF DATA

X1.1 *Description of the Weibull Model*:

X1.1.1 The three-parameter Weibull model is used to fit the relationship between K_{Jc} and the cumulative probability for failure, p_f. The term p_f is the probability for failure at or before K_{Jc} for an arbitrarily chosen specimen from the population of specimens. This can be calculated from the following:

$$p_f = 1 - \exp\{-[(K_{Jc} - K_{min})/(K_o - K_{min})]^b\} \tag{X1.1}$$

X1.1.2 Ferritic steels of yield strengths ranging from 275 to 825 MPa (40 to 120 ksi) will have fracture toughness distributions of nearly the same shape when K_{min} is set at 20 MPa$\sqrt{m}$ (18.2 ksi$\sqrt{in.}$). This shape is defined by the Weibull exponent, b, which is assumed to be constant at 4. Scale parameter, K_o, is a data-fitting parameter. The procedure is described in X1.2.

X1.2 *Determination of Scale Parameter, K_o, and Median K_{Jc} Using the Maximum Likelihood Method*:

X1.2.1 The following example of six 4T compact specimens of A 533 grade B (–75°C) demonstrates the procedure.

Rank (i)	K_{Jc} (MPa$\sqrt{m}$)
1	59.1
2	68.3
3	77.9
4	97.9
5	100.9
6	112.4

$$K_o = [\sum_{i=1}^{N} (K_{Jc(i)} - K_{min})^4 / (N - 0.3068)]^{1/4} + K_{min} \tag{X1.2}$$

$$K_{min} = 20 \text{ MPa}\sqrt{m}$$
$$N = 6$$
$$K_o = 94.1 \text{ MPa}\sqrt{m}$$

X1.2.2 Median K_{Jc} is obtained as follows:

$$K_{Jc(med)} = (K_o - K_{min})[\ln(2)]^{1/4} + K_{min} \tag{X1.3}$$

$$K_{Jc(med)} = 87.6 \text{ MPa}\sqrt{m}$$

X1.3 *Development of Weibull Plots*:

X1.3.1 Data points are converted to Weibull coordinates using:

$$Y_i = \ln\{\ln[1/(1 - \hat{p}_{f(i)})]\}, \tag{X1.4}$$

where:

$\hat{p}_{f(i)}$ = (i − 0.3)/(N + 0.4) (see Note X1.1), and
N = number of tests,

and

$$X_i = \ln[K_{Jc(i)} - K_{min}], \tag{X1.5}$$

where:

K_{min} = 20 MPa $\sqrt{m}$.

X1.3.2 The regression line with a slope of 4 is fitted to the data points as follows:

$$Y = 4X + Y_o, \tag{X1.6}$$

where:

Y_o = –4 ln(K_o – K_{min}).

X1.3.3 For Table X1.1 data, Y_o = –17.22. Therefore, $Y = 4X - 17.22$ (see Fig. X1.1).

TABLE X1.1 Six 4T Compact Specimens of A 533 Grade B (–75°C)

Rank (i)	K_{Jc} (MPa$\sqrt{m}$)	p_f	Plotting points	
			ln (K_{Jc}– 20)	ln {ln [1/(1 – p_f)]}
1	59.1	0.109	3.667	–2.155
2	68.3	0.266	3.877	–1.175
3	77.9	0.422	4.059	–0.602
4	97.9	0.578	4.355	–0.147
5	100.9	0.734	4.393	0.282
6	112.4	0.891	4.526	0.794

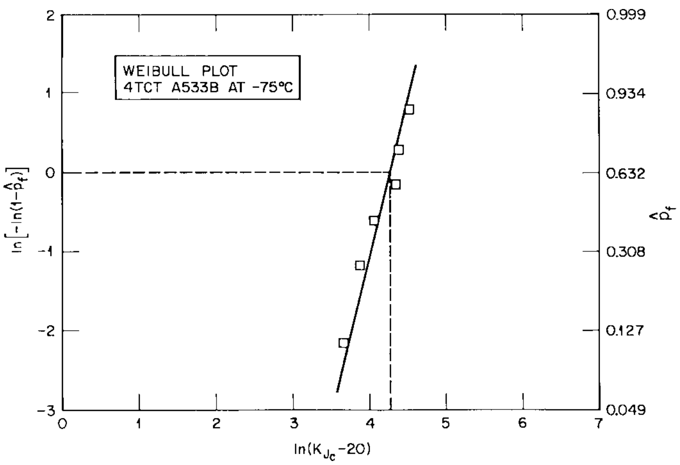


FIG. X1.1 Weibull Plot Showing Identification of (K_o – 20) MPa$\sqrt{m}$ Point

NOTE X1.1—The use of [] over variables such as p_f denotes the value is fixed with no variance.

X1.4 *Data Censoring Using the Maximum Likelihood Method*:

X1.4.1 K_{Jc} data can be invalid because of not satisfying the requirements of 8.9.2. However, such data can be used in a censoring practice. All data must come from one specimen size. Only the highest ranked data can be censored. There must be six valid K_{Jc} values in the group. An example is given in the following list of data:

X1.4.2 Determine scale parameter, K_o, using the following:

From $(Eb_o\sigma_{ys}/30)^{1/2}$; K_{Jc} (limit) = 603 MPa$\sqrt{m}$

Censor data ranked = 7, 8, 9.

Substitute K_{Jc} = 603 MPa for these in Eq X1.7.

where:

b_o = 100 mm,
r = 6,
N = 9, and
K_{min} = 20 MPa$\sqrt{m}$.

$$K_o = \left[\sum_{i=1}^{N} (K_{Jc\,(i)} - K_{min})^4/(r - 0.3068)\right]^{1/4} + K_{min} \quad \text{(X1.7)}$$

$$K_o = 594 \text{ MPa}\sqrt{m}$$

X1.5 *Weibull Slope Fit to Censored Data Set (For 4T Size)*:

$$Y_o = (\textit{see Eq X1.6 and below})\ 4\ \ln\ (K_o - K_{min}) \quad \text{(X1.8)}$$

$$K_{min} = 20 \text{ MPa}\sqrt{m}$$

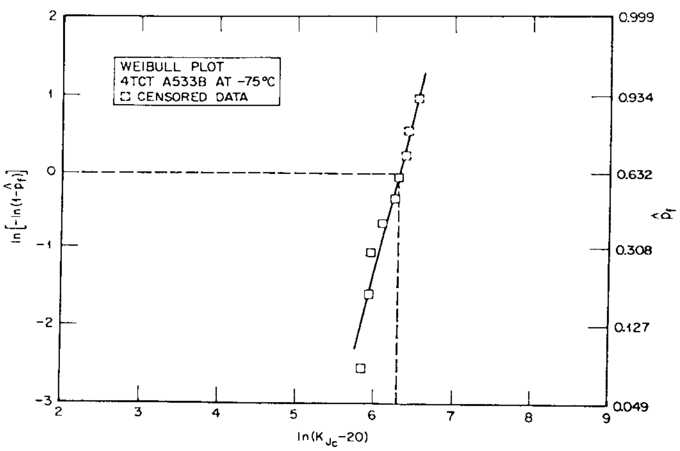
For Table X1.2 data, Y_o = –25.41 (see Fig. X1.2); therefore, $Y = 4X - 25.41$ (see Fig. X1.2).

TABLE X1.2 K_{Jc} Data on 4T Size Bend Bars of A 533 Grade B Steel Tested at 10°C

NOTE 1—Yield strength = 517 MPa (75 ksi)

Rank (i)	K_{Jc} (MPa$\sqrt{m}$)	Δa_p (mm)
1	365.5	1.2
2	403.1	1.4
3	409.6	1.8
4	470.2	2.3
5	549.8	4.5
6	572.0	4.9
7	632.3^A	6.9
8	647.1^A	10.3
9	741.3^A	15.4

^{A}Invalid, to be censored.



NOTE 1—The fitted line of Weibull slope = 4 comes from maximum likelihood derived K_o.

FIG. X1.2 Weibull Plot With Three Censored Data

X2. MASTER CURVE FIT TO DATA

X2.1 *Select Test Temperature* (see 8.4):

X2.1.1 Six ½*T* compact specimens,

X2.1.2 A 533 grade B base metal, and

X2.1.3 Test temperature, T =– 75°C.

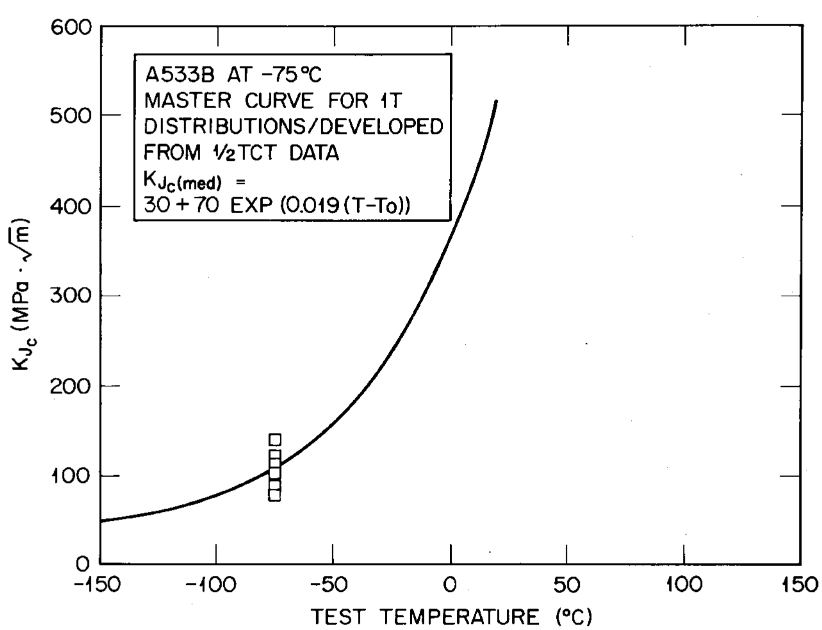
X2.2 In this data set, there are no censored data; therefore, there is no harm in first converting to K_{Jc} equivalence for 1 *T* compact size (see 10.3.1):

Rank (i)	$K_{Jc(1/2T)}$ (MPa√m)	$K_{Jc(1T)}$ (MPa√m)
1	91.4	80.0
2	103.1	89.9
3	120.3	104.3
4	133.5	115.4
5	144.4	124.6
6	164.0	141.1

X2.3 *Determine* $\boldsymbol{K_o}$ *using Eq X1.2:*
$K_{Jc} = K_o$,

K_o = 117.0 MPa√m, and

$K_{Jc(med)} = [\ln(2)]^{1/4} (K_o - 20) + 20 = 108.5$ MPa√m.



NOTE 1—Toughness data are converted to 1T equivalence.

FIG. X2.1 Master Curve for 1*T* Specimens Based on 1/2*T* Data Tabulated in Step X2.2

X2.4 *Position Master Curve*:

$$T_o = T - (0.019)^{-1} \ln[(K_{Jc(med)} - 30)/70] \quad (X2.1)$$

$$= -75 - \ln[(108.5 - 30)/70]/0.019 = -81°C.$$

X2.5 *Master Curve*:

$$K_{Jc(med)} = 30 + 70 \exp[0.019(T + 81)] \quad (X2.2)$$

X2.5.1 See Fig. X2.1.

X3. CALCULATION OF TOLERANCE BOUNDS

X3.1 The standard deviation of the fitted Weibull distribution is a mathematical function of Weibull slope, $K_{Jc(med)}$, and K_{min}, and because two of these are constant values, the standard deviation is easily determined. Specifically, with slope b of 4 and K_{min} = 20 MPa$\sqrt{m}$, standard deviation is defined by the following **(20)**:

$$\sigma = 0.28\, K_{Jc(med)} [1 - 20/K_{Jc(med)}] \quad (X3.1)$$

X3.1.1 *Tolerance Bound*— Given Eq X3.1 and the simplifying assumption of an infinite sample size, the lower-bound (1, 2, 3, 4, 5, and 10 %) and upper-bound (90, 95, 96, 97, 98, and 99 %) curves can be set up using the following:

$$K_{TB} = D_1 + D_2 \exp[0.019(T - T_o)], \quad (X3.2)$$

where T is the temperature value on the abscissa in °C, T_o is the reference temperature of the master curve, °C, and the values of D_1 and D_2 are given in Table X3.1. See Fig. X3.1 for 5 and 95 % tolerance bounds. As an example, the 5 % bound for the Appendix X2 example is:

$$K_{Jc(05)} = 25.4 + 37.8 \exp[0.019(T + 81)] \quad (X3.3)$$

TABLE X3.1 Values of D_1 and D_2

NOTE 1—The standard normal deviates used here are for single tail of normal or Gaussian distributions. These values are within 3 % of more rigorously determined values for Weibull distributions where b = 4 and K_{min} = 20 MPa$\sqrt{m}$.

Tolerance Bound (TB), %	Coefficients	
	D_1	D_2
01	23.5	24.5
02	24.3	30.0
03	24.7	33.2
04	25.1	35.7
05	25.4	37.8
10	26.4	44.9
90	33.6	95.1
95	34.6	102.2
96	34.9	104.3
97	35.3	106.8
98	35.8	110.3
99	36.5	115.5

X3.1.2 The potential error–effect of finite sample size can be considered, in terms of T_o, by calculating a margin adjustment, as described in X3.2.

X3.2 *Margin Adjustment*—The margin adjustment is an upward temperature shift of the tolerance bound curve, Eq X3.3. Margin is added to cover the uncertainty in T_o that is associated with the use of only a few specimens to establish T_o. The standard deviation on the estimate on T_o is given by:

$$\sigma = \beta / \sqrt{N} \ (°C), \quad (X3.4)$$

where:

N = total number of specimens used to establish the value of T_o.

When $K_{Jc(med)}$ is equal to or greater than 83 MPa$\sqrt{m}$, β = 18°C **(21)**. If the 1T equivalent $K_{Jc(med)}$ is below 83 MPa$\sqrt{m}$, values of β must be increased according to the following schedule:

$K_{Jc(med)}$ 1*T* equivalent[A] (MPa$\sqrt{m}$)	β (°C)
83 to 66	18.8
65 to 58	20.1
57 to 53	21.4
52 to 49	22.7

[A]Round off $K_{Jc(med)}$ to nearest whole number.

X3.2.1 To estimate the uncertainty in T_o, a standard two-tail normal deviate, Z, should be taken from statistical handbook tabulations. The selection of the confidence limit for T_o adjustment is a matter for engineering judgment. The following example calculation is for 85 % confidence (two-tail) adjustment to Eq X3.3 for the six specimens used to determine T_o.

$$\Delta T_o = \sigma(Z_{85}) = \frac{18}{\sqrt{6}}(1.44) = 10°C \quad (X3.5)$$

$$T_o(\text{margin}) = T_o + \Delta T_o = -81° + 10° = -71°C$$

Then the margin-adjusted 5 % tolerance bound of Eq X3.3 is revised to:

$$K_{Jc(05)} = 25.4 + 37.8 \exp[0.019(T + 71)] \quad (X3.6)$$

X3.2.1.1 See Fig. X3.2, dashed line (L. B.).

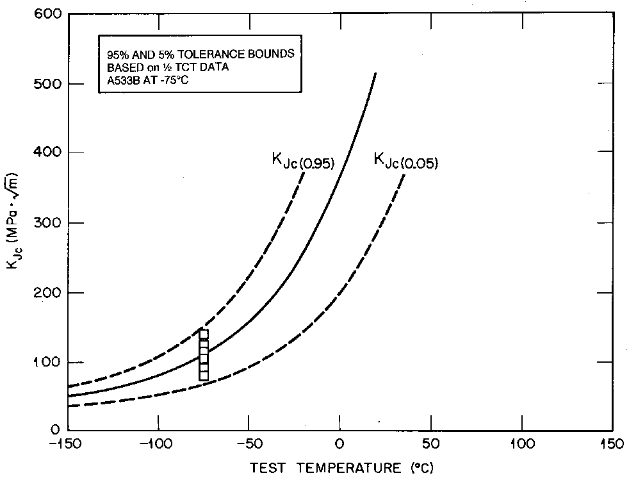


FIG. X3.1 Master Curve With Upper and Lower 95 % Tolerance Bounds

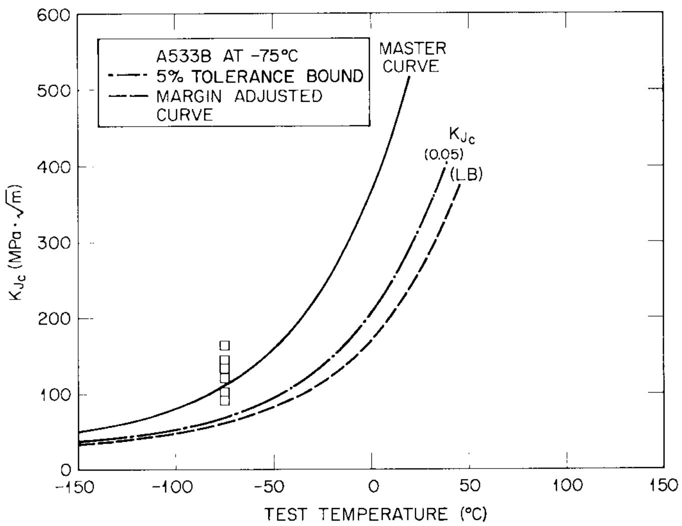


FIG. X3.2 Master Curve Showing the Difference Between 5 % Tolerance Bound and Lower Bound That Includes 85 % Confidence Margin on T_o

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