Designation: E1921 – 17a

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 E1921; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of 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 Median K_{Jc} values tend to vary with the specimen type at a given test temperature, presumably due to constraint differences among the allowable test specimens in 1.2. The degree of K_{Jc} variability among specimen types is analytically predicted to be a function of the material flow properties (**1**)[2] and decreases with increasing strain hardening capacity for a given yield strength material. This K_{Jc} dependency ultimately leads to discrepancies in calculated T_o values as a function of specimen type for the same material. T_o values obtained from C(T) specimens are expected to be higher than T_o values obtained from SE(B) specimens. Best estimate comparisons of several materials indicate that the average difference between C(T) and SE(B)-derived T_o values is approximately 10°C (**2**). C(T) and SE(B) T_o differences up to 15°C have also been recorded (**3**). However, comparisons of individual, small datasets may not necessarily reveal this average trend. Datasets which contain both C(T) and SE(B) specimens may generate T_o results which fall between the T_o values calculated using solely C(T) or SE(B) specimens. It is therefore strongly recommended that the specimen type be reported along with the derived T_o value in all reporting, analysis, and discussion of results. This recommended reporting is in addition to the requirements in 11.1.1.

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

1.5 T_o is dependent on loading rate. T_o is evaluated for a quasi-static loading rate range with $0.1 < dK/dt < 2$ MPa$\sqrt{m}$/s. Slowly loaded specimens ($dK/dt < 0.1$ MPa$\sqrt{m}$) can be analyzed if environmental effects are known to be negligible. Provision is also made for higher loading rates ($dK/dt > 2$ MPa$\sqrt{m}$/s) in Annex A1.

1.6 The statistical effects of specimen size on K_{Jc} in the transition range are treated using the weakest-link theory (**4**) 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 (**5**).

1.7 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.

1.8 This test method assumes that the test material is macroscopically homogeneous such that the materials have uniform tensile and toughness properties. The fracture toughness evaluation of nonuniform materials is not amenable to the statistical analysis methods employed in the main body of this test method. Application of the analysis of this test method to an inhomogeneous material will result in an inaccurate estimate of the transition reference value T_o and non-conservative confidence bounds. For example, multipass weldments can create heat-affected and brittle zones with localized properties that are quite different from either the bulk material or weld. Thick section steels also often exhibit some variation in

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

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

properties near the surfaces. Metallography and initial screening may be necessary to verify the applicability of these and similarly graded materials. An appendix to analyze the cleavage toughness properties of nonuniform or inhomogeneous materials is currently being prepared. In the interim, users are referred to **(6-8)** for procedures to analyze inhomogeneous materials.

1.9 *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.*

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

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E4 Practices for Force Verification of Testing Machines
E8/E8M Test Methods for Tension Testing of Metallic Materials
E23 Test Methods for Notched Bar Impact Testing of Metallic Materials
E74 Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines
E111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E208 Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels
E399 Test Method for Linear-Elastic Plan-Strain Fracture Toughness K_{Ic} of Metallic Materials
E436 Test Method for Drop-Weight Tear Tests of Ferritic Steels
E561 Test Method for K_R Curve Determination
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1820 Test Method for Measurement of Fracture Toughness
E1823 Terminology Relating to Fatigue and Fracture Testing

2.2 *ASME Standards:*[4]

ASME Boiler and Pressure Vessel Code, Section II, Part D

3. Terminology

3.1 Terminology given in Terminology E1823 is applicable to this test method.

3.2 *Definitions:*

3.2.1 *ferritic steels*—typically carbon, low-alloy, and higher alloy grades. Typical microstructures are bainite, tempered bainite, tempered martensite, and ferrite and pearlite. All ferritic steels have body centered cubic crystal structures that display ductile-to-cleavage transition temperature fracture toughness characteristics. See also Test Methods E23, E208 and E436.

3.2.1.1 *Discussion*—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.

3.2.2.1 *Discussion*—In this test method, Mode I is assumed. See Terminology E1823 for further discussion.

3.2.3 *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 (**9**). See Terminology E1823 for further discussion.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *control force, P_m [F]*—a calculated value of maximum force, used in 7.8.1 to stipulate allowable precracking limits.

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_{eff} [FL^{-2}]*—an elastic modulus that allows a theoretical (modulus normalized) compliance to match an experimentally measured compliance for an actual initial crack size, a_o.

3.3.4 *effective yield strength, σ_Y [FL^{-2}],* — an assumed value of uniaxial yield strength that represents the influence of plastic yielding upon fracture test parameters.

3.3.4.1 *Discussion*—It is calculated as the average of the 0.2 % offset yield strength σ_{YS}, and the ultimate tensile strength, σ_{TS} as follows:

$$\sigma_Y = \frac{\sigma_{YS} + \sigma_{TS}}{2}$$

3.3.5 *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 stress, $E' = E$ is used, and for plane strain, $E/(1 - \nu^2)$ is used, with E being Young's modulus and ν being Poisson's ratio.

3.3.6 *elastic plastic J_c [FL^{-1}]*—*J*-integral at the onset of cleavage fracture.

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

3.3.7.1 *Discussion*—In this test method, K_J also implies a stress intensity factor determined at the test termination point under conditions that require censoring the data by 8.9.2.

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

[4] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http://www.asme.org.

3.3.9 *equivalent value of median toughness, $K^{eq}_{Jc(med)}$ [$FL^{-3/2}$]*—an equivalent value of the median toughness for a multi-temperature data set.

3.3.10 *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 (**10**).

3.3.11 *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.

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

3.3.13 *load-line displacement rate, $\dot{\Delta}_{LL}$[LT^{-1}]*—rate of increase of specimen load-line displacement.

3.3.14 *pop-in*—a discontinuity in a force versus displacement test record (**11**).

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

3.3.15 *precracked Charpy, PCC, specimen*—SE(B) specimen with $W = B = 10$ mm (0.394 in.).

3.3.16 *provisional reference temperature, (T_{oQ}) [°C]*—Interim T_o value calculated using the standard test method described herein. T_{oQ} is validated as T_o in 10.5.

3.3.17 *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√m (91.0 ksi√in.).

3.3.18 *SE(B) specimen span, S [L]*—the distance between specimen supports (See Test Method E1820 Fig. 3).

3.3.19 *specimen thickness, B [L]*—the distance between the parallel sides of a test specimen as depicted in Fig. 1–3.

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

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

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

3.3.21 *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 at which $K_{Jc\ (med)} = 100$ MPa√m is defined as T_Q. T_Q is not a provisional value of T_o.

3.3.22 *time to control force, t_m [T],*—time to P_m.

3.3.23 *Weibull fitting parameter, K_0*—a scale parameter located at the 63.2 % cumulative failure probability level (**12**). $K_{Jc} = K_0$ when $p_f = 0.632$.

3.3.24 *Weibull slope, b*—with p_f and K_{Jc} data pairs plotted in linearized Weibull coordinates obtainable by rearranging Eq 18, *b* is the slope of a line that defines the characteristics of the typical scatter of K_{Jc} data.

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

3.3.25 *yield strength, σ_{YS} [FL^{-2}]*—the stress at which a material exhibits a specific limiting deviation from the proportionality of stress to strain at the test temperature. This deviation is expressed in terms of strain.

3.3.25.1 *Discussion*—It is customary to determine yield strength by either (1) Offset Method (usually a strain of 0.2 % is specified) or (2) Total-Extension-Under-Force Method (usually a strain of 0.5 % is specified although other values of strain may be used).

3.3.25.2 *Discussion*—Whenever yield strength is specified, the method of test must be stated along with the percent offset or total strain under force. The values obtained by the two methods may differ.

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 Force 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}. Censoring limits are based on K_{Jc} to determine the suitability of data for statistical analyses.

4.3 A minimum of six tests are required to estimate the median K_{Jc} of the Weibull distribution for the data population (**13**). 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 is assessed using weakest-link theory, thereby providing a relationship between the specimen size and K_{Jc} (**4**). Limits are placed on the fracture toughness range over which this model can be used.

4.5 For the definition of the toughness transition curve, a master curve concept is used (**14, 15**). 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√m (91.0 ksi√in.). Selection of a test temperature close to that at which the median K_{Jc} value will be 100 MPa√m is encouraged and a means of estimating this temperature is suggested. Small specimens such as precracked Charpy's may have to be tested at temperatures below T_o where $K_{Jc(med)}$ is well below 100 MPa√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 microscopically 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 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 (**16**). This results in a distribution of fracture toughness values that is amenable to characterization using the statistical methods in this test method.

5.3 The statistical methods in this test method presume that the test materials are macroscopically homogeneous such that both the tensile and toughness properties are uniform. The fracture toughness evaluation of nonuniform materials is not amenable to the statistical analysis methods employed in the main body of this test method. For example, multipass weldments can create heat-affected and brittle zones with localized properties that are quite different from either the bulk material or weld. Thick section steel also often exhibits some variation in properties near the surfaces. An appendix to analyze the cleavage toughness properties of nonuniform or inhomogeneous materials is currently being prepared. In the interim, users are referred to (**6-8**) for procedures to analyze inhomogeneous materials. Metallographic analysis can be used to identify possible nonuniform regions in a material. These regions can then be evaluated through mechanical testing such as hardness, microhardness, and tensile testing to compare with the bulk material. It is also advisable to measure the toughness properties of these nonuniform regions distinctly from the bulk material.

5.4 Distributions of K_{Jc} data from replicate tests can be used to predict distributions of K_{Jc} for different specimen sizes. Theoretical reasoning (**12**), 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 (**17**). An upper limit on constraint loss and a lower limit on test temperature are defined between which weakest-link statistics can be used.

5.5 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 (**18**). 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.

5.6 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.

5.7 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 (**5**). 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.

5.8 As discussed in 1.3, there is an expected bias among T_o values as a function of the standard specimen type. The magnitude of the bias may increase inversely to the strain hardening ability of the test material at a given yield strength, as the average crack-tip constraint of the data set decreases (**19**). On average, T_o values obtained from C(T) specimens are higher than T_o values obtained from SE(B) specimens. Best estimate comparison indicates that the average difference between C(T) and SE(B)-derived T_o values is approximately 10 °C (**2**). However, individual C(T) and SE(B) datasets may show much larger T_o differences (**3, 20, 21**), or the SE(B) T_o values may be higher than the C(T) values (**2**). On the other hand, comparisons of individual, small datasets may not necessarily reveal this average trend. Datasets which contain both C(T) and SE(B) specimens may generate T_o results which fall between the T_o values calculated using solely C(T) or SE(B) specimens.

6. Apparatus

6.1 *Precision of Instrumentation*—Measurements of applied forces and load-line displacements are needed to obtain work done on the specimen. Force versus load-line displacement shall be recorded digitally on computers or autographically on *x-y* plotters. For computers, digital signal resolution shall be at least 1/32,000 of the displacement transducer signal range and shall be at least 1/4,000 of the force transducer signal range.

6.2 *Grips for C(T) Specimens*—A clevis with flat-bottom holes is recommended. See Test Method E399, 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 E399. 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 are determined from area under force 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 E1820. 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 $0.25W$ 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) value developed specifically for the CMOD location (**22**) or infer load-point displacement from CMOD using an expression that relates the two displacements (**23**). In either case, the procedure described in 9.1.4 is used to calculate the plastic part of J. However, it is recommended that the plastic part of J be estimated from the direct CMOD or load-line displacement measurement rather than inferring load-line displacement from CMOD. Additionally, CMOD measurement is more accurate than load-line displacement for estimating crack length from compliance.

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) (**24**).

6.6 *Force Measurement:*

6.6.1 Testing shall be performed in a machine conforming to Practices of E4 and Test Methods E8/E8M. Applied force may be measured by any transducer with a noise-to-signal ratio less than 1/2,000 of the transducer signal range.

6.6.2 Calibrate force measurement instruments by way of Practice E74, 10.2. Annual calibration using calibration equipment traceable to the National Institute of Standards and Technology is a mandatory requirement.

6.7 *Temperature Control*—Specimen temperature shall be measured with thermocouple wires and potentiometers. It is recommended that the two thermocouple wires be attached to the specimen surface separately, either by welding, spot welding, or by being affixed mechanically. Mechanical attachment schemes must be verified to provide equivalent temperature measurement accuracy. The purpose is to use the test material as a part of the thermocouple circuit (see also 8.6.1). Accuracy of temperature measurement shall be within 3°C of true temperature and repeatability among specimens 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 E399; the two with cutout sections are taken from E1820. 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 $0.25W$ in front of the load-line) displacement measurements are made with the Test Method E399 design, the load-line displacement can be inferred by multiplying the measured values by the constant 0.73 (**25**). 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 $0.5W \pm 0.05W$. 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 $0.5W \pm 0.05W$. 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 $0.5W \pm 0.05W$.

7.4 *Machined Notch Design*—Three designs of fatigue crack starter notches are shown in Fig. 4. These notches can be straight through the specimen thickness or incorporate the chevron form (Fig. 4). The machined notch plus fatigue crack for all specimens shall lie within the envelope shown in Fig. 5. To facilitate fatigue cracking at low stress intensity levels, the root radius for a straight-through slot terminating in a V-notch should be 0.08 mm (0.003 in.) or less. If a chevron form of notch is used, the root radius may be 0.25 mm (0.010 in.) or less. In the case of a notch ending in a drilled hole, it will be necessary to provide a sharp stress raiser at the end of the hole.

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

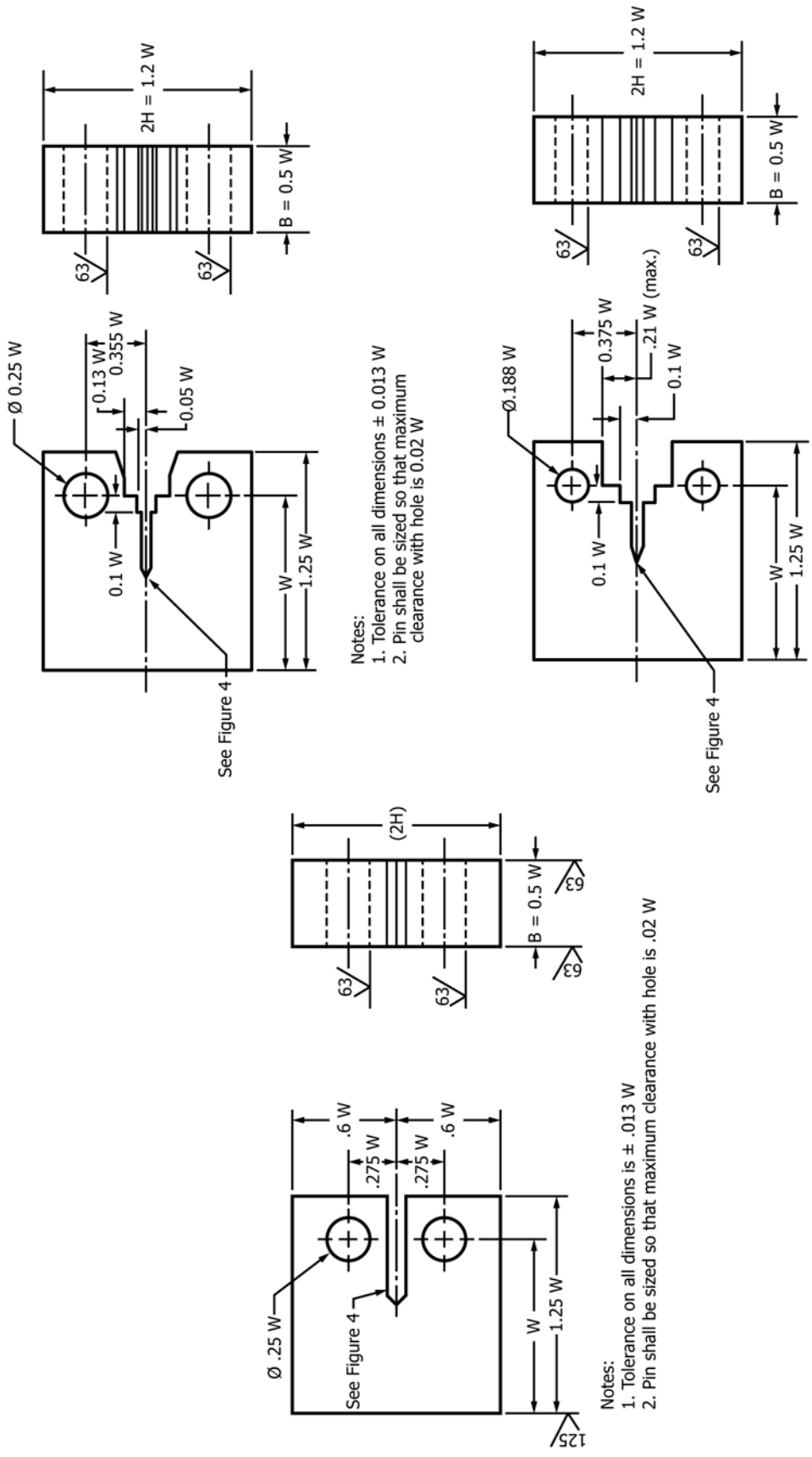
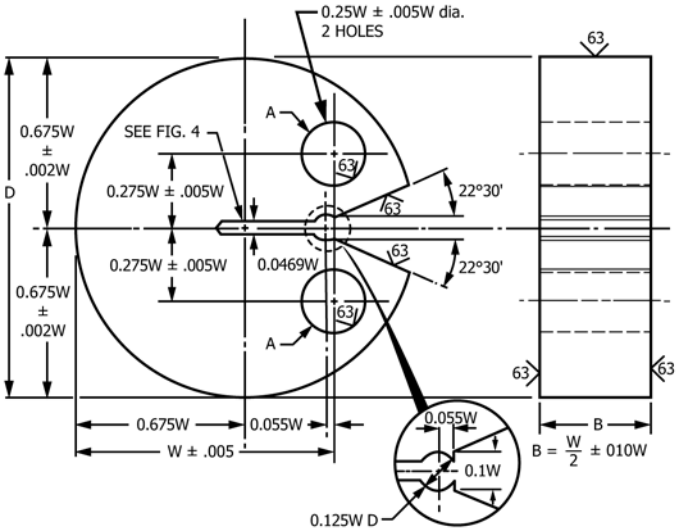


FIG. 1 Three Compact Specimen Designs That Have Been Used Successfully for Fracture Toughness Testing

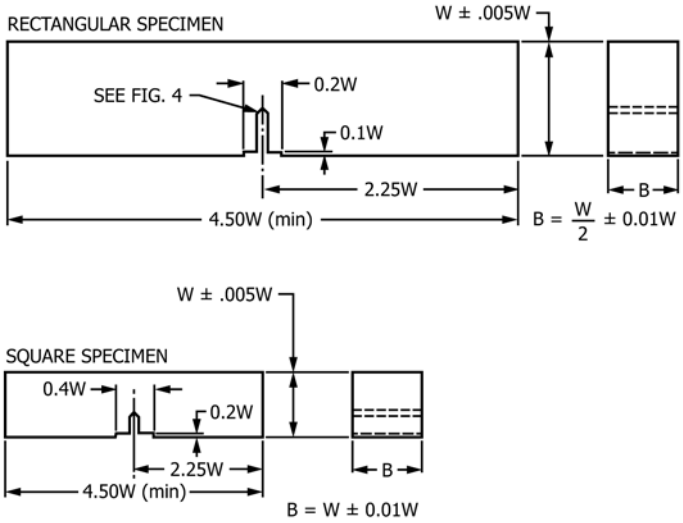


NOTE 1—A surfaces shall be perpendicular and parallel as applicable to within 0.002W TIR.

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 E399.

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

maintain a condition of high crack-front constraint at fracture. The maximum K_{Jc} capacity of a specimen is given by:

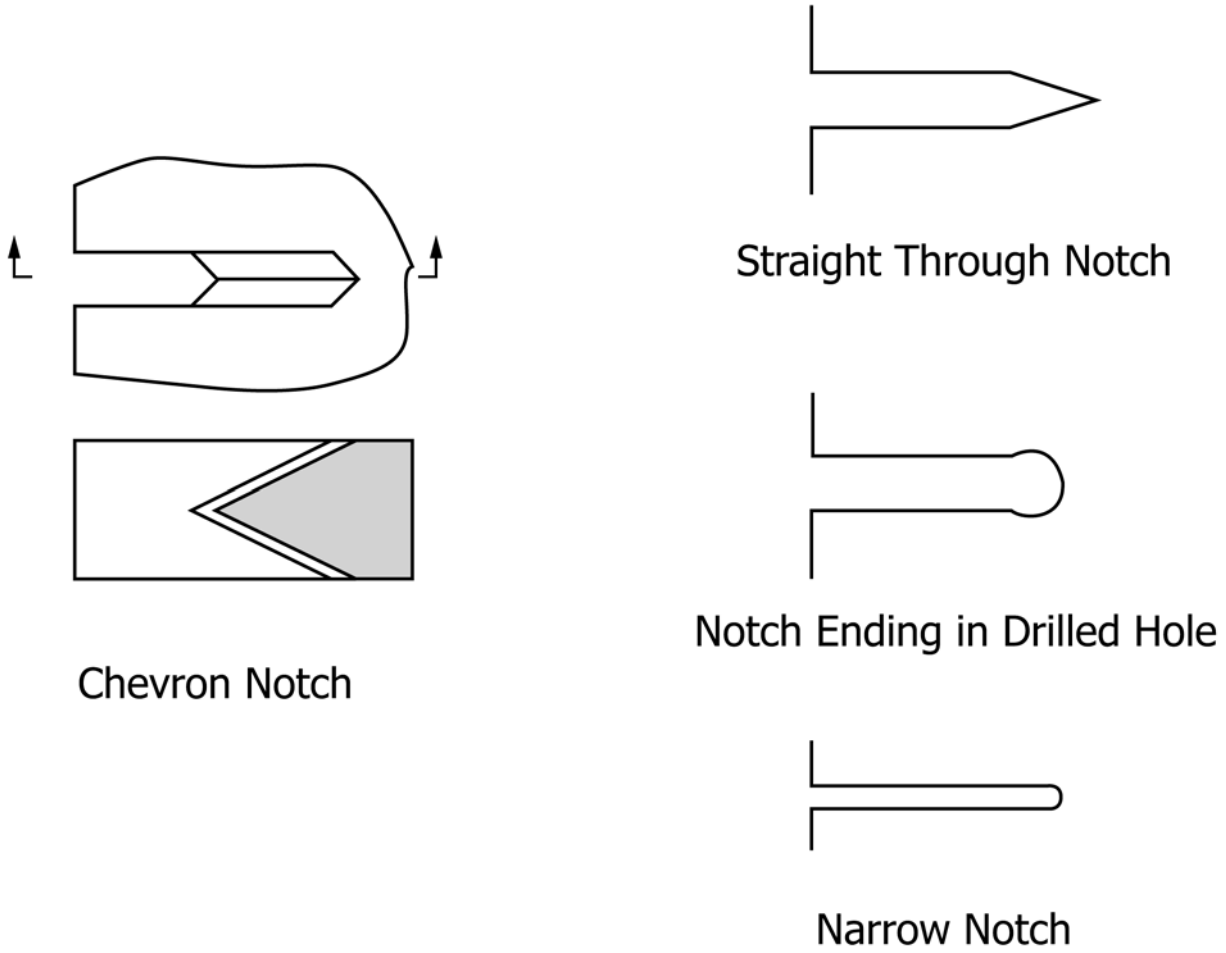
$$K_{Jclimit} = \sqrt{\frac{Eb_o\sigma_{YS}}{30(1-\nu^2)}} \quad (1)$$

where:

$b_o = W\text{-}a_o$

Measurement of σ_{ys} at the test temperature (T) using Test Methods E8/E8M is preferred for use in Eq 1. When σ_{ys} has not been measured at T, any of the following three methods are acceptable for estimating σ_{ys} at T for use in Eq 1:

(1) Using a value of σ_{ys} measured at a higher temperature than T.



NOTE 1—Notch width need not be less than 1.6mm (1⁄16 in.) but not exceed 0.063W.

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

(2) Linearly interpolating between measurements of σ_{ys} at temperatures above and below T, as long as these temperatures are within 50°C of T.

(3) Determining σ_{ys} from the following equation which can be used for temperatures between -200°C and 300°C. **(26)** See Note 1.

$$\sigma_{ys} = \sigma_{ysRT} + 10^5/(491 + 1.8\,T) - 189\,(\text{MPa}) \quad (2)$$

where:

T = test temperature (°C), and

σ_{ysRT} = the material yield strength at room temperature (MPa)

NOTE 1—Eq 2 should not be used to determine σ_{ysRT} from σ_{ys} values obtained at other temperatures.

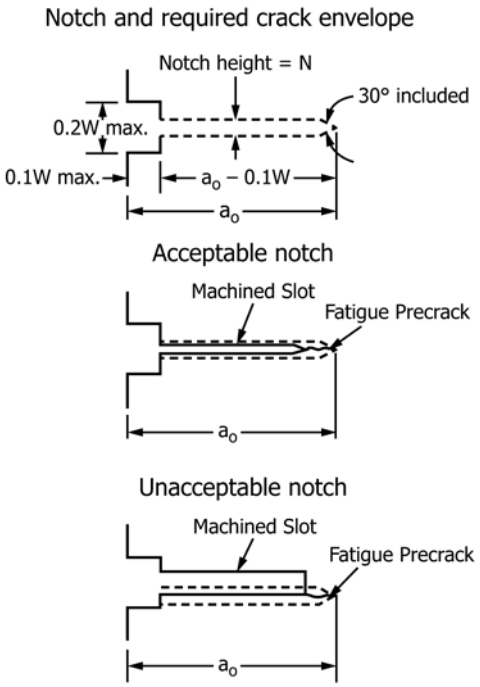
K_{Jc} data that exceed this requirement (that is, Eq 1) are used in a data censoring procedure. Details of this procedure are described in 10.2.1.

7.6 *Small Specimens*—At high values of fracture toughness relative to specimen size and material flow properties, the values of K_{Jc} that meet the requirements 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 **(5)**. This condition may develop in materials with low strain hardening. When this occurs, the highest K_{Jc} values of the data set could possibly cause the value of T_o to be lower than the value that would be obtained from testing specimens with higher constraint.

7.7 *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.

7.8 *Precracking:*

7.8.1 *Fatigue Loading Requirements*—Allowable fatigue force values are limited to keep the maximum stress intensity factor applied during precracking, K_{max}, well below the material fracture toughness measured during the subsequent test. The fatigue precracking shall be conducted with the specimen



Notch and Precrack Configurations

	Wide Notch	Narrow Notch
Maximum Notch Height	Lesser of 0.063W or 6.25 mm	Greater of 0.01W or 0.25 mm
Maximum Notch Angle	60°	As machined
Minimum Precrack Length	Greater of 0.5N or 1.3 mm	Greater of 0.5N or 0.6mm

NOTE 1—The crack-starter notch shall be centered between the top and bottom specimen edges within 0.005W.

FIG. 5 Envelope of Fatigue Crack and Crack Starter Notches

fully heat-treated to the condition in which it is to be tested. No intermediate heat treatments between precracking and testing are allowed. The combination of starter notch and fatigue precrack shall conform to the requirements shown in Fig. 5. There are several ways of promoting early crack initiation: *(1)* by providing a very sharp notch tip, *(2)* by using a chevron notch (Fig. 4), *(3)* by statically preloading the specimen in such a way that the notch tip is compressed in a direction normal to the intended crack plane (to a force not to exceed P_m), and *(4)* by using a negative fatigue force ratio; for a given maximum fatigue force, the more negative the force ratio, the earlier crack initiation is likely to occur. The peak compressive force shall not exceed P_m as defined in the equations below:

$$\text{For SE(B) specimens, } P_m = \frac{0.5Bb_o^2\sigma_Y}{S} \quad (3)$$

$$\text{For C(T) and DC(T) specimens, } P_m = \frac{0.4Bb_o^2\sigma_Y}{2W+a_o} \quad (4)$$

7.8.2 *Fatigue Precracking Procedure*—Fatigue precracking can be conducted under either force control, displacement control, or K control. If the force cycle is maintained constant, the maximum K and ΔK will increase with crack size; if the displacement cycle is maintained constant, the reverse will happen. If K is maintained constant, force has to be reduced as a function of increasing crack size. Fatigue cycling is conducted using a sinusoidal waveform and a frequency close to the highest practical value. There is no known marked frequency effect on fatigue precrack formation up to at least 100 Hz in the absence of adverse environments. The specimen shall be accurately located in the loading fixture to achieve uniform, symmetric loading. The specimen should be carefully monitored until crack initiation is observed on one side. If crack initiation is not observed on the other side before appreciable growth is observed on the first side, then fatigue cycling should be stopped to try to determine the cause and find a remedy for the unsymmetrical behavior. Sometimes, simply turning the specimen around in relation to the fixture will solve the problem.

Precracking can be performed either by some method of smoothly and continually decreasing the maximum stress intensity factor (K_{max}) or by using discrete steps. It is suggested that the reduction in K_{max} between any discrete step be no greater than 20 % because reducing K_{max} too rapidly can result in precrack growth rate retardation. It is also suggested that measurable crack extension occur before proceeding to the next step. Precracking is generally most effectively conducted using $R = P_{min}/P_{max} = 0.1$. Maximum force values shall be accurate to within ± 5 % of their target values.

Fig. 6 shows the allowable envelope for K_{max} during precracking. The precracking K_{max} and crack extension requirements are summarized in Table 1, and Table 2. Precracking can be conducted in any manner such that K_{max} remains within the envelope and the maximum fatigue force is less than P_m. The K_{max} applied to the specimen shall not exceed 25

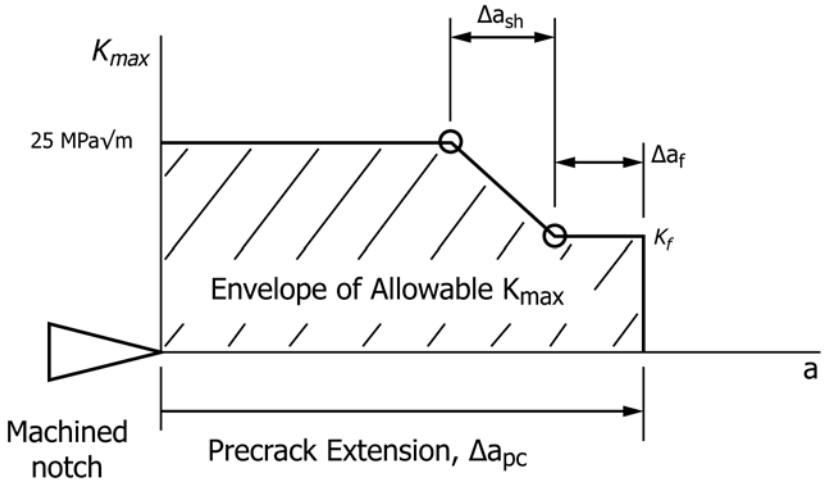


FIG. 6 Envelope of Allowable K_{max} During Precracking

TABLE 1 K_{max} Requirements

Intial: K_{max} cannot exceed 25 $MPa\sqrt{m}$ (22.8 $ksi\sqrt{in.}$) and the maximum fatigue force cannot exceed P_m.

Final: K_f depends on the test temperature:

Test Temperature	K_f throughout Δa_f
< precracking temperature	< 15$MPa\sqrt{m}$ (13.7 $ksi\sqrt{in.}$)
≥ precrackeing temperature	< 20$MPa\sqrt{m}$ (18.3 $ksi\sqrt{in.}$)

TABLE 2 Crack Extension Requirements

Wide Notch (Fig. 5)	Δa_{min}	=	1.3mm (0.050 in.)
Narrow Notch (Fig. 5)	Δa_{min}	=	0.6 mm (0.024 in.)
	Δa_{pc}	≥	Greater of 0.5N or Δa_{min}
	Δa_{sh}	≥	$r_{p1} - r_{p2}$
Where:			
	r_{pl}	=	$r_{p1} = \frac{1}{3\pi}\left(\frac{K_{max}}{\sigma_{ys}}\right)^2$ with K_{max} = 25 MPa√m (22.8 ksi√in.)
	r_{p2}	=	$r_{p2} = \frac{1}{3\pi}\left(\frac{K_f}{\sigma_{ys}}\right)^2$
	Δa_f	≥	0.2 mm (0.008 in.)

MPa√m (22.8 ksi√in) at any crack length, and may be limited by P_m for small specimens or low yield strength materials, or both. As the testing temperature decreases compared to the precracking temperature, the warm prestressing effect increases, which can elevate the measured fracture toughness. To minimize the warm prestressing effect, the maximum K that may be applied to the specimen during Δa_f (K_f in Fig. 6) shall not exceed 15 MPa√m (13.7 ksi√in), where the minimum length of Δa_f (Fig. 6) is 0.2 mm (0.008 in.). Alternatively, when the testing temperature is equal to or above the precracking temperature, K_f shall not exceed 20 MPa√m (18.3 ksi√in). Δa_{sh} is greater than or equal to the change in plastic zone size in going from a maximum K of 25 MPa√m (22.8 ksi√in) to K_f. The minimum value for Δa_{sh} defines the condition where the leading edge of the plastic zone remains stationary as K_{max} is decreased.

$$\Delta a_{sh} \geq r_{p1} - r_{p2} \tag{5}$$

where:

$$r_{p1} = \frac{1}{3\pi}\left(\frac{K_{max}}{\sigma_{ys}}\right)^2 \text{ with } K_{max}$$

$$= 25\ MPa\sqrt{m}\ (22.8\ ksi\sqrt{in.})$$

$$r_{p2} = \frac{1}{3\pi}\left(\frac{K_f}{\sigma_{ys}}\right)^2$$

NOTE 2—If the yield strength (σ_{ys}) is not known, a low estimate should be used to obtain a conservatively high estimate of Δa_{sh}.

The average length of the fatigue precrack extension from the machined notch, Δa_{pc} (determined using the measured initial crack length defined in 8.8.1) shall equal or exceed the larger of 0.5*N* or Δa_{min} (see Fig. 5), where Δa_{min} is 1.3 mm (0.050 in.) for a wide notch (Fig. 5) or 0.6 mm (0.024 in.) for a narrow notch (Fig. 5). The precrack must also meet the curvature requirement in 8.9.1 and there must be measurable crack extension from the machine notch at all points through the specimen thickness. To ensure that these criteria are met for specimens with B > 25.4 mm (1 in), it is recommended to either optically verify that crack extension has occurred at both surfaces, or ensure that Δa_{pc} is long enough that fatigue precrack extension occurs at all points through the thickness for a crack with the maximum curvature allowed in 8.9.1.

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, and the average starting crack size estimated. The average starting crack size can be estimated using a variety of techniques including precrack compliance, back-face strain, and using the average of the optical side face measurements.

NOTE 3—When side-grooving is to be used, first precrack without side grooves and then visually estimate the precrack size.

If estimates are available from multiple techniques, the user shall select the value that is believed to be most representative of the average crack size.

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.

8.2.3 Follow Test Method E1820, 8.5 for crack size measurement, 8.3.2 for testing compact specimens and 8.3.1 for testing bend specimens.

8.3 The required minimum number of K_{Jc} results that are uncensored is specified according to the value of $K_{Jc(med)}$. See also 8.5.

8.4 *Test Temperature Selection*—It is recommended that the selected temperatures be close to that at which the $K_{Jc(med)}$ value will be about 100 MPa√m for the specimen size selected.

8.4.1 *Quasi-static loading rates*—If loading rate complies with the limits stated in 8.7.1, Charpy V-notch data can be used as an aid for predicting a viable test temperature. If a Charpy transition temperature, T_{CVN}, is known corresponding to a 28 J Charpy V-notch energy or a 41 J Charpy V-notch energy, the constant C can be chosen from Table 3 corresponding to the test specimen size (defined in 3.3.20), and used to estimate[5] the test temperature from **(15, 27)**.

$$T = T_{CVN} + C \tag{6}$$

8.4.2 The procedure outlined in 8.4.1 is only appropriate for determining an initial test temperature. The iterative scheme described in 10.3.1 may be necessary to refine this test temperature in order to increase T_o accuracy. Testing below the temperature specified in Eq 6 may be appropriate for low upper-shelf toughness materials to avoid ductile crack growth before cleavage onset, and for low yield strength materials to avoid obtaining data that must be censored because it exceeds $K_{Jclimit}$ in accordance with Eq 1.[6]

8.5 *Testing Below Temperature, T_o*—When the equivalent value of $K_{Jc(med)}$ for 1T specimens is greater than 83 MPa√m, the required number of uncensored K_{Jc} values to perform the analyses covered in Section 10 is six. However, small specimens such as precracked Charpy specimens can develop excessive numbers of K_{Jc} values that exceed the $K_{Jclimit}$ (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 uncensored. 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 testing more specimens thereby increasing the $K_{Jc(med)}$ accuracy. The number of specimens required for obtaining a valid T_o measurement as a function of the test temperature is provided in 10.3 (10.4.1 for the special case of testing at a single temperature).

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 as defined in 6.7 during the conduct of the test.

[5] Standard deviation on this estimate has been determined to be 15°C.
[6] Data censoring is covered in 8.9.2 and Section 10.

TABLE 3 Constants for Test Temperature Selection Based on Charpy Results

Specimen Size, (*nT*)	Constant C (°C)	
	28 J	41 J
0.4[A]	−32	−38
0.5	−28	−34
1	−18	−24
2	−8	−14
3	−1	−7
4	2	−4

[A] For precracked Charpy specimens, use C = −50 or −56°C.

8.6.1 The most dependable method of monitoring test temperature is to weld or spot weld each thermocouple wire separately to the specimen, spaced across the crack plane. The specimen provides the electrical continuity between the two thermocouple wires, and spacing should be enough not to raise any question of possible interference with crack tip deformation processes. Alternative attachment methods can be mechanical types such as drilled hole, or by a firm mechanical holding device so long as the attachment method is verified for accuracy and these practices do not disturb the crack tip stress field of the specimen during loading.

8.6.2 To verify that the specimen is properly seated into the loading device and that the clip gage is properly seated, estimate the specimen crack size while working-in the test setup at test temperature. Working-in is accomplished via repeated preloading and unloading in the linear elastic range between force values of 0.2 P_{max} and P_{max} (where P_{max} is the largest allowable precracking force of the finishing cycles as prescribed in 7.8.2) at least three times. For each unloading/reloading sequence, estimate the precrack size using Test Method E1820, Eq A2.12 for C(T) specimens and Eq A1.12 for SE(B) specimens. The elastic modulus, E, used in these calculations shall be the nominal value for the material at the test temperature. The nominal value of E shall come from either handbook values or dedicated modulus testing per Test Method E111 or equivalent. Tensile test results do not provide accurate elastic modulus values. Alternatively, the following equation can be used to determine the nominal value of E.

$$E = 204 - T/16 \text{ GPa} \quad (7)$$

where:

T = test temperature in °C.

This equation was derived from fitting the tabular values for ferritic steels contained in ASME Section II, Part D. The fit is valid for –200°C ≤ T ≤ 300°C.

8.6.3 Check the estimated crack size slope against the average precrack size defined in 8.2. The test setup is considered acceptable when the last three consecutive estimated crack sizes are all within 10 % of the final precrack size and no individual estimated crack size differs from the mean by more than ±0.002W. To minimize the difference between the precrack size and the working-in estimated crack size, the nominal E value may be adjusted up to 10 %. Modulus adjustments should only be made when the force transducer and clip gage calibrations are known to be within acceptable limits of accuracy, see Section 6. The value of E in use for the final three acceptable working-in unloading/reloading sequences shall be used for all crack size estimates throughout the remainder of the given test. If the repeatability or the accuracy, or both of the estimated crack sizes are outside the prescribed limits, the test setup is questionable and should be thoroughly rechecked. It is essential that the specimen temperature and clip gage are stable and that the clip gage knife edges are sharp in order to meet these requirements. 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.

8.7 *Testing for K_{Jc}*—All tests shall be conducted under displacement control. Force 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 (**24**). 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 E561 contains equations that define compliance for other locations on the compact specimen.

8.7.1 *Quasi-static Loading*—Load specimens at a rate such that $\dot{K}$ during the initial elastic portion is between 0.1 and 2 MPa$\sqrt{}$m/s. Variation of the loading rate within these limits allows obtaining a T_o which is insensitive to the loading rate within 10°C (**28**). The testing machine loading rate associated with this allowable range can be determined in terms of the time to reach P_m (t_m) or the specimen load-line displacement rate $\dot{\Delta}_{LL}$. Table 4 is provided to determine the time to t_m or $\dot{\Delta}_{\mathrm{LL}}$ as a function of $\dot{K}$, W, E, and σ_{YS} for each allowable specimen geometry. P_m is nominally 40 % of limit force; see 7.8.1. The actual crosshead rate used must be adjusted to account for test machine compliance if the load-line displacement rate of Table 4 is used. The crosshead speed during periodic partial unloadings, if applied, 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 *Slow Loading Rates*—For loading rates less than 0.1 MPa$\sqrt{}$m/s, the procedures of this test method can be used if the failure mode remains cleavage. The corresponding reference temperature is then reported as $T_{o,X}$ using the convention described in A1.2.1.1.

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 size 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

TABLE 4 SE(B) Specimen Rate Estimation-C(T) Specimen Rate Estimation

SE(B) Specimen Rate Estimation			C(T) Specimen Rate Estimation		
a/W	$\frac{t_M\dot{K}}{\sigma_Y\sqrt{W}}$	$\frac{E\dot{\Delta}_{LL}}{\frac{dK}{dt}\sqrt{W}}$	a/W	$\frac{t_M\dot{K}}{\sigma_Y\sqrt{W}}$	$\frac{E\dot{\Delta}_{LL}}{\frac{dK}{dt}\sqrt{W}}$
0.45	0.346	5.064	0.45	0.412	3.475
0.50	0.333	5.263	0.50	0.386	3.829
0.55	0.318	5.522	0.55	0.361	4.212
0.60	0.302	5.851	0.60	0.336	4.635
0.65	0.283	6.267	0.65	0.312	5.118
0.70	0.263	6.798	0.70	0.287	5.696

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.).

8.8.2 *Post-Test Check*—Compare the estimated fatigue pre-crack length determined in 8.6.3 with the optical average value determined in 8.8.1. The pre-test estimate shall not differ from the post-test optical value by more than 5 %. If the error exceeds 5 %, then a unique value of E (E_i) can be found for each test to match the optical average value as closely as possible using Test Method E1820, Eq A2.12 for C(T) specimens and Eq A1.12 for SE(B) specimens. E_i values shall be within 10 % of the nominal value of E identified in 8.6.2.

8.9 *Qualification of Data:*

8.9.1 The K_{Jc} datum shall be considered invalid if any of the nine physical measurements of the starting crack size differ by more than 5 % of the thickness dimension, B, or 0.5 mm, whichever is larger, from the average defined in 8.8.1. The datum is also invalid if the calculated crack length for the test determined in 8.8.2 differs from the optical average value determined in 8.8.1 by more than 5 %.

8.9.2 A K_{Jc} datum requires censoring if the specimen exceeds the $K_{Jclimit}$ requirement of 7.5, or if a test has been discontinued at a value of K_J without cleavage fracture after surpassing $K_{Jclimit}$. Another limit, $K_{Jc\Delta a}$, is violated in tests that terminate in cleavage after slow stable crack growth that exceeds the smaller of either 0.05(W-a_o) or 1 mm (0.040 in.) at the longest crack size dimension measured by 8.8.1. A K_{Jc} datum exceeding $K_{Jc\Delta a}$ also requires censoring. Censored K_J or K_{Jc} values contain statistically useable information and are used in the evaluation as described in 10.2.1. If $K_{Jclimit}$ is violated, the $K_{Jclimit}$ datum shall be replaced with $K_{Jclimit}$ in the analysis. See, for example, X1.3.1. If $K_{Jc\Delta a}$ is violated, the K_{Jc} datum shall be replaced with $K_{Jc\Delta a}$ (as determined in 10.2.1) in the analysis. See, for example, X1.3.6. If both $K_{Jclimit}$ and $K_{Jc\Delta a}$ are violated, the lower value of the two shall be used to replace the K_{Jc} datum for data censoring purposes in the analysis.

8.9.3 For any test terminated without cleavage fracture, and for which the final K_J value does not exceed either censoring limit cited in 8.9.2, the test is judged to be a nontest, the result of which shall be discarded.

8.9.4 Data sets that contain all uncensored K_{Jc} values are used without modification in Section 10. Data sets that contain some censored data, but that meet the meet the minimum data requirements of 8.5, are used in the evaluation as described in 10.2.1. Remedies for excessive censored data points include (*1*) testing at a lower test temperature, (*2*) testing with larger specimens, or (*3*) testing more specimens to satisfy the minimum data requirements.

8.9.5 A discontinuity in a force-displacement record prior to attaining maximum force may be a pop-in event. Test equipment can, at times, introduce a discontinuity in the force-displacement record. However, a pop-in is uniquely characterized by a decrease in force and a simultaneous increase in crack opening displacement. After a pop-in event, both force and crack opening displacement continue to increase. Discontinuities in the force displacement record after attaining maximum force are not pop-in events and are not addressed in this section. If a single pop-in or multiple pop-ins are observed during testing, assess the estimated crack mouth opening compliance change by 9.2 to determine if it changes by more than 2 % as a result of the pop-ins. If the change is greater than 2 %, the pop-in shall be treated as significant and the K_{Jc} value associated with the pop-in shall be used as the result of the test. Note that an estimated compliance change of 2 % in accordance with 9.2 predicts an increase in crack size of no more than 1 % depending on the specimen type.

9. Calculation of J_c and K_{Jc} Values from the Input Data

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

$$J_c = J_e + J_p \tag{8}$$

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

$$J_e = \frac{(1-\nu^2)\,K_e^2}{E} \tag{9}$$

where:

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

$$f(a_o/W) = \frac{(2+a_o/W)}{(1-a_o/W)^{3/2}}[0.886+4.64\,(a_o/W) - 13.32(a_o/W)^{2} + 14.72(a_o/W)^{3} - 5.6(a_o/W)^{4}], \tag{10}$$

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:

$$J_e = \frac{(1-\nu^2)\,K_e^2}{E} \tag{11}$$

where:

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

$$f(a_o/W) = \frac{(2+a_o/W)}{(1-a_o/W)^{3/2}}[0.76+4.8(a_o/W) - 11.58(a_o/W)^{2} + 11.43(a_o/W)^{3} - 4.08(a_o/W)^{4}], \tag{12}$$

and a_o = initial crack size.

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

$$J_e = \frac{(1-\nu^2)\,K_e^2}{E} \tag{13}$$

where:

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

$$f(a_o/W) = \frac{3(a_o/W)^{1/2}}{2[1+2(a_o/W)]} \tag{14}$$

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

and a_o = the initial crack size.

9.1.4 The plastic component of J is calculated as follows:

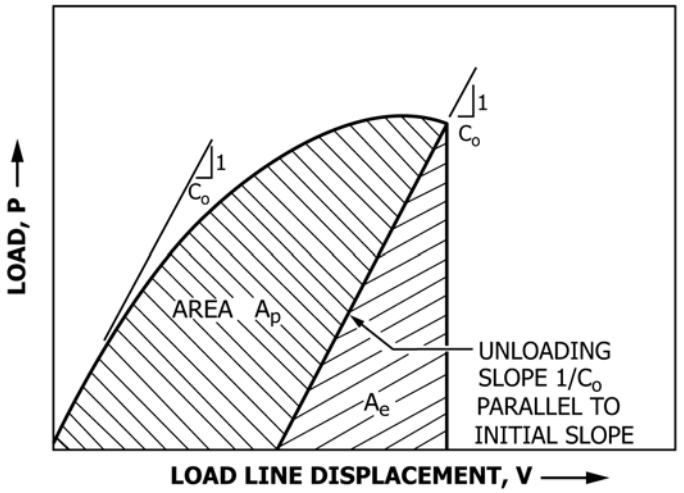


FIG. 7 Definition of the Plastic Area for J_p Calculations

$$J_p = \frac{\eta A_p}{B_N b_o} \quad (15)$$

where:

A_p = $A - 1/2C_oP^2$,
A = $A_e + A_p$ (see Fig. 7),
C_o = reciprocal of the initial elastic slope, $\Delta V/\Delta P$ (Fig. 7), 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 $B \times 2B$ 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, $\eta = 1.9$. Using CMOD, $\eta = 3.667–2.199(a/W)+ 0.4376(a/W)^2$. Determination of η for bend bars based on CMOD is also discussed in 6.5.2.

9.1.5 K_{Jc} is determined for each datum from J at onset of cleavage fracture, J_c using:

$$K_{Jc} = \sqrt{J_c \frac{E}{1 - \nu^2}} \quad (16)$$

The nominal value of E identified in 8.6.2 for each test temperature shall be used in the conversion of J_c to K_{Jc}.

9.2 *Pop-in Evaluation*—Test records used for K_{Jc} analyses are those that exhibit complete specimen separation due to cleavage fracture and those that exhibit significant pop-ins. As discussed in 8.9.5, if a force-displacement record exhibits a small but perceptible discontinuity that is characterized by a drop in force with a simultaneous increase in crack opening displacement, a pop-in may have occurred. As depicted in Fig. 8, the accumulated change in crack mouth opening compliance before and after single or multiple pop-in events are estimated[7] as:

$$1 - C_o \cdot \left(\frac{P_n - y_n}{v_n + x_n} \right) \quad (17)$$

where:

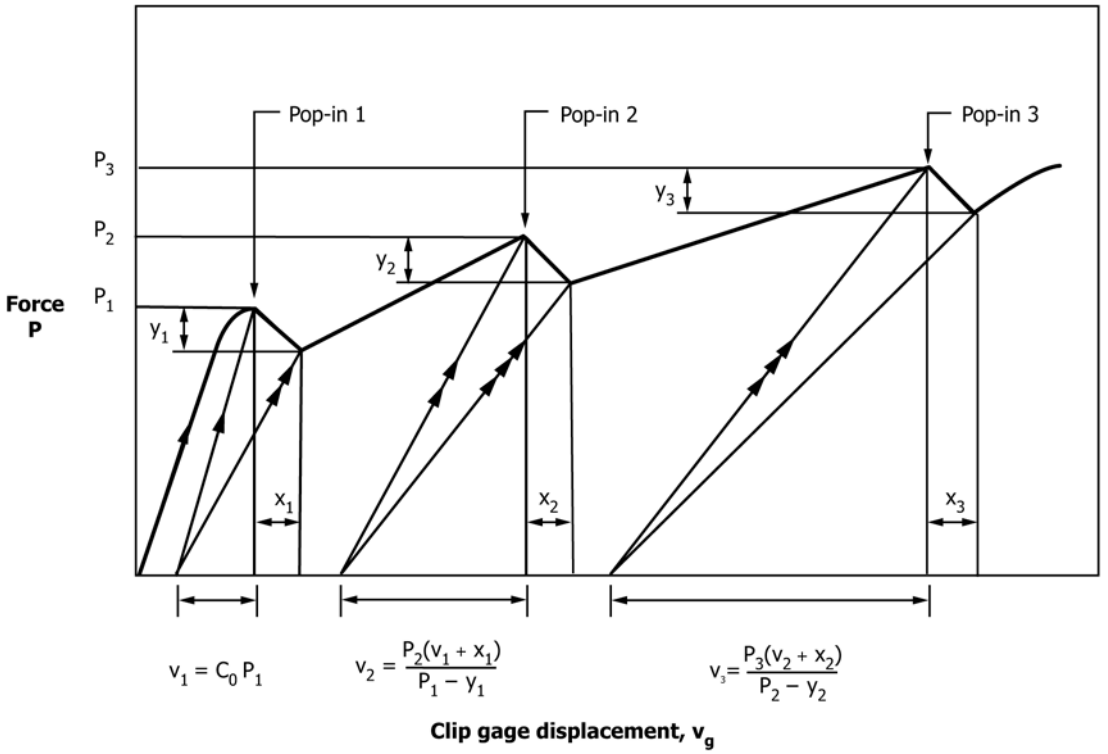
n = sequential number (see Fig. 8) of the last of the particular series of pop-ins being assessed (When only one pop-in occurs, $n = 1$.),
v_1 = elastic displacement at pop-in No. 1 (see Fig. 8),
P_n = force at the n^{th} pop-in, and
v_n = elastic displacement at the n^{th} pop-in. (v_n may be determined graphically or analytically, see Fig. 8).
y_n = force drop at the n^{th} pop-in, and
x_n = displacement increase at the n^{th} pop-in. [8]

For a single pop-in, if $1 - C_o \cdot \left(\frac{P_1 - y_1}{v_1 + x_1} \right) \geq 0.02$ the pop-in shall be considered significant. When multiple pop-in events occur, $1 - C_o \cdot \left(\frac{P_i - y_i}{v_i + x_i} \right)$ shall be assessed sequentially for each pop-in. The K_{Jc} value corresponding to the pop-in that causes $1 - C_o \cdot \left(\frac{P_i - y_i}{v_i + x_i} \right)$ to exceed 0.02 shall be used as the test result. If $1 - C_o \cdot \left(\frac{P_n - y_n}{v_n + x_n} \right) < 0.02$, then the K_{Jc} value at the final specimen fracture shall be used as the test result.

9.3 *Outlier*—Occasionally, an individual K_{Jc} datum will appear to deviate greatly from the remainder of the data set. It may be possible to reduce the influence of the outlier datum on $K_{Jc(med)}$ by testing additional specimens. However, no valid K_{Jc} data shall be discarded from the data utilized to calculate $K_{Jc(med)}$ unless justification is provided by the tester that this data is not representative of the intended test material.

[7] Machine compliance can result in differences between this estimated crack mouth opening compliance and the actual specimen compliance. However, the estimated compliance change is always equal to or greater than the specimen compliance.

[8] Although an individual pop-in may be ignored on the basis of these criteria, this does not necessarily mean that the lower bound of fracture toughness has been measured. For instance, in an inhomogeneous material such as a weld, a small pop-in may be recorded because of fortuitous positioning of the fatigue precrack tip. Thus, a slightly different fatigue precrack position may give a larger pop-in, which could not be ignored. In such circumstances the specimens should be sectioned after testing, and examined metallographically to ensure that the crack tips have sampled the weld or base metal region of interest (**29**).



NOTE—C_o is the initial compliance
NOTE—The pop-ins have been exaggerated for clarity.

FIG. 8 Schematic of Pop-in Magnitude Evaluation

10. Data Analysis and Evaluation of the Reference Temperature, T_o

10.1 *Evaluation of Data Sets Based on Weibull Model:*

10.1.1 *Test Replication*—A data set consists of at least six uncensored K_{Jc} test results.

10.1.2 *Relationship between the Scale Parameter, K_o and K_{Jc} Test Results*—The three-parameter Weibull model is used to define the relationship between individual K_{Jc} results 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, for the following Weibull model:

$$p_f = 1 - \exp\{-[(K_{Jc} - 20)/(K_o - 20)]^4\} \quad (18)$$

10.1.3 Ferritic steels with 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. Scale parameter, K_o, is the data fitting parameter determined when using the maximum likelihood statistical method of data fitting (**30**). When K_{Jc} and K_o in Eq 18 are equal, $p_f = 0.632$.

10.1.4 *Size Effect Predictions*—The statistical weakest-link theory is used to model specimen size effects in the transition range between lower shelf and upper shelf fracture toughness. The following relationship shall be used to size-adjust individual K_{Jc} values, $K_{Jc(med)}$, or K_o. K_{Jc} serves as the example case:

$$K_{Jc(x)} = 20 + [K_{Jc(o)} - 20]\left(\frac{B_o}{B_x}\right)^{1/4} \quad (19)$$

where:

$K_{Jc(x)}$ = K_{Jc} for a specimen size B_x,
$K_{Jc(o)}$ = K_{Jc} for a specimen size B_o,
B_o = gross thickness of test specimens (side grooves ignored), and
B_x = gross thickness of prediction (side grooves ignored).

10.2 *Computing T_o from K_{Jc} Test Results:*

10.2.1 *Data Censoring*—Replace all censored K_{Jc} values with appropriate K_{Jc} limit values (8.9.2). If censoring is required due to violation of $K_{Jclimit}$, Eq 1, the experimental K_{Jc} value shall be replaced by $K_{Jclimit}$ for the specimen sizes used. Determine $K_{Jclimit}$ at each test temperature using the material yield strength corresponding to that temperature. If censoring is required due to violation of $K_{Jc\Delta a}$, the K_{Jc} test value shall be replaced with the highest uncensored K_{Jc} in the data set obtained at any specimen size and test temperature because $K_{Jc\Delta a}$ should be size independent and also largely insensitive to test temperature. The K_{JIc} value defined in E1820 can also be used for $K_{Jc\Delta a}$, if J_{Ic} is known for the test material. As specified in 8.9.2, if both $K_{Jclimit}$ and $K_{Jc\Delta a}$ are violated, replace the K_{Jc} test value with the lower of the two limits.

10.2.2 *Size Correction of K_{Jc} Data*—If the data are generated from specimens of other than 1T size, all data, including uncensored and censored values, shall be converted to 1T size equivalence using Eq 19 (see 3.3.20). For determining $K_{Jc(1T)}$ using Eq 19, B_o and $K_{Jc(o)}$ are the measured specimen thickness and K_{Jc} test result (either censored or uncensored), respectively, and $B_x = 25.4$ mm.

10.2.3 *Calculation of Provisional T_o Value, T_{oQ}*—After censoring the K_{Jc} input values and converting the uncensored

or censored K_{Jc} results to 1T equivalence using Eq 19, the following equality shall be used to determine the provisional T_{oQ} using an iterative procedure **(30, 31)**.

$$\sum_{i=1}^{N} \delta_i \frac{\exp[0.019\,(T_i - T_{oQ})]}{11.0+76.7\exp[0.019\,(T_i - T_{oQ})]} \tag{20}$$

$$-\sum_{i=1}^{N} \frac{(K_{Jc(i)} - 20)^4 \exp[0.019\,(T_i - T_{oQ})]}{\{11.0+76.7\exp[0.019\,(T_i - T_{oQ})]\}^5} = 0$$

where:

N = number of specimens tested,
T_i = test temperature corresponding to $K_{Jc(i)}$,
$K_{Jc(i)}$ = either an uncensored K_{Jc} datum or a datum replaced with a censoring value (8.9.2),
δ_i = 1.0 if the datum is uncensored or zero if the datum is a censored value,
11.0 = approximation of $10/(\ln 2)^{1/4}$ MPa√m to 3 significant digits, and
76.7 = approximation of $70/(\ln 2)^{1/4}$ MPa√m to 3 significant digits.

Solve Eq 20 for T_{oQ} temperature by iteration.

10.3 *Requirement for Size of Data Set*—Data generated at test temperatures in the range of T_o - 50°C to T_o - 14°C are considered to make reduced accuracy contribution to T_o determinations. As a consequence, more data development within the aforementioned temperature range is required. The following weighting system specifies the required number of data:

$$\sum_{i=1}^{3} r_i\, n_i \geq 1 \tag{21}$$

where r_i is the number of uncensored data within the i-th temperature range, $(T–T_o)$, and n_i is the specimen weighting factor for the same temperature range as shown in Table 5.

TABLE 5 Weighting Factors for Multi-Temperature Analysis

$(T - T_o)$ range[A] (°C)	1T $K_{Jc(med)}$ range[A] (MPa√m)	Weighting factor n_i
50 to –14	212 to 84	1/6
–15 to –35	83 to 66	1/7
–36 to –50	65 to 58	1/8

[A] Rounded off to the closest integer.

10.3.1 Since the valid test temperature range is only known after T_{oQ} has been determined, the following iterative scheme may be helpful for identifying proper test temperature. Choose an initial test temperature as described in 8.4.1 using the value of "C" appropriate for the test specimen size. Conduct tests at this temperature to obtain 3–4 uncensored results. Evaluate an estimated T_{oQ} value ($T_{oQ(est)}$) value using Eq 20. Base all subsequent test temperatures on $T_{oQ(est)}$. See Appendix X3 for an example calculation.

10.3.2 Certain data sets may result in an oscillating iteration between two (or more) distinct T_{oQ} values upon satisfying the T_{oQ} ± 50°C limit required by 10.5.5. In these instances, the T_{oQ} value reported shall be the average of the calculated values. One example is for hypothetical data with toughness values such that the initial T_{oQ} estimation requires that data at one temperature be excluded. The second iteration then results in the inclusion of this same data. Subsequent T_{oQ} iterations will then oscillate between the original first and second estimations. This phenomenon is more likely for sparse data sets when test results exist near the T_{oQ} ± 50°C limit. More testing near the average T_{oQ} will likely resolve this problem.

10.4 *Single Temperature Analysis*—In the special case that all tests are conducted at a single temperature, T, the iterative solution of Eq 20 can be replaced with a direct evaluation of K_o, $K_{Jc(med)}$, and T_{oQ} using the following relationships:

$$K_o = \left[\sum_{i=1}^{N} \frac{(K_{Jc(i)} - 20)^4}{r}\right]^{1/4} + 20,\ \text{MPa}\sqrt{\text{m}} \tag{22}$$

where:

r = number of uncensored data as determined in 8.9.2, and
N = total number of uncensored and censored data.

$$K_{Jc(med)} = 20 + (K_o - 20)\,[\ln(2)]^{1/4},\ \text{MPa}\sqrt{\text{m}} \tag{23}$$

and

$$T_{oQ} = T - \left(\frac{1}{0.019}\right)\ln\left(\frac{(K_{Jc(med)} - 30)}{70}\right) \tag{24}$$

10.4.1 *Single Temperature Test Sample Size Requirements*—For the special case where all tests are conducted at a single temperature, Eq 21 and Table 5 in 10.3, which provide the number of uncensored K_{Jc} test results required to evaluate T_o, can be simplified according to Table 6 below. If $K_{Jc(med)}$ of a data set is lower than 58 MPa√m, then the T_o determination using that data set shall not be allowed.

See Appendix X1 and Appendix X2 for example calculations.

10.5 *Validation of T_{oQ} as T_o*—$T_o = T_{oQ}$ if all of the following requirements are met:

10.5.1 The apparatus requirements of Section 6 are met or exceeded,

10.5.2 The specimen configuration and dimensions meet the requirements of Section 7,

10.5.3 The specimen precracking was completed within the requirements of 7.8,

10.5.4 The specimens were tested according to the requirements of Section 8, including qualification of the data according to 8.9, and

10.5.5 The number of specimens tested within the allowable temperature range T_{oQ} ± 50°C, meets the requirements of 10.3 or 10.4.1 as applicable.

TABLE 6 Number of Uncensored K_{Jc} Test Results Required to Evaluate T_o

$(T - T_o)$ range (°C)	$K_{Jc(med)}$ range[A] (MPa√m)	Number of uncensored K_{Jc} results required	Possible number of censored K_{Jc} results by Eq 1[B]
50 to –14	212 to 84	6	3
–15 to –35	83 to 66	7	1
–36 to –50	65 to 58	8	0

[A] Convert $K_{Jc(med)}$ to 1T equivalence using Eq 19. Round off to nearest whole digit.
[B] Established specifically for precracked Charpy specimens. Use this column for total specimen needs.

10.6 *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 (**30, 32**). For this method, the shape of the median K_{Jc} toughness, $K_{Jc(med)}$, for 1T specimens (3.3.20) is described by:

$$K_{Jc(med)} = 30+70 \quad \exp[0.019(T - T_o)], \text{ MPa}\sqrt{\text{m}} \tag{25}$$

where:

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

The Weibull scale parameter, K_o, is given by:

$$K_o = \frac{[K_{Jc(med)} - 20]}{[\ln(2)]^{1/4}} + 20, \text{ MPa}\sqrt{\text{m}} \tag{26}$$

10.7 *Standard Deviation*—The standard deviation of the fitted Weibull distribution is a mathematical function of $K_{Jc(med)}$ and is given by:

$$\sigma = 0.28K_{Jc(med)}[1 - 20/K_{Jc(med)}] \tag{27}$$

10.8 *Tolerance Bounds*—Upper and lower tolerance bounds for the master curve can be calculated using the following equation:

$$K_{Jc(0.xx)} = 20+\left[ln\left(\frac{1}{1-0.xx} \right) \right]^{1/4} \{11+77 \exp[0.019(T - T_o)]\} \tag{28}$$

where $0.xx$ represents the selected cumulative probability level; for example, for the 2 % tolerance bound, $0.xx$ = 0.02.

10.9 *Margin Adjustment*—The margin adjustment is an upward temperature shift of the tolerance bound curve, Eq 28. 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. Additional uncertainty can result from other sources including material inhomogeneity and experimental errors. The standard deviation on the estimate on T_o which incorporates sample size and experimental uncertainties is given by:

$$\sigma = \sqrt{\frac{\beta^2}{r} + \sigma_{exp}^2} \tag{29}$$

where:

β = sample size uncertainty factor,
r = total number of uncensored data used to establish the value of T_o, and
σ_{exp} = contribution of experimental uncertainties. If standard calibration practices are followed, σ_{exp} = 4°C may be used.

10.9.1 An equivalent value of the median toughness for a data set, $K^{eq}_{Jc(med)}$, is defined as (**33**):

$$K^{eq}_{Jc(med)} = \left[\frac{1}{r} \sum_{i=1}^{r} 30+70 \exp(0.019 \quad (T_i - T_o)) \right] \tag{30}$$

When $K^{eq}_{Jc(med)}$ is equal to or greater than 83 MPa$\sqrt{\text{m}}$, β = 18°C (**34**). If the 1T equivalent $K^{eq}_{Jc(med)}$ is below 83 MPa$\sqrt{\text{m}}$, values of β must be increased according to the following table:

$K^{eq}_{Jc(med)}$ 1T equivalent[A] (MPa$\sqrt{\text{m}}$)	β (°C)
83 to 66	18.8
65 to 58	20.1

[A] Round off $K^{eq}_{Jc(med)}$ to the nearest whole number.

10.9.2 To estimate the uncertainty in T_o, a standard two-tail normal deviate, Z, shall be taken from statistical handbook tabulations. The selection of the confidence limit for T_o adjustment is a matter for engineering judgment.

10.10 *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 censoring limits 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 Method E1820).

11. Report

11.1 Report the following information for each specimen:

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

11.1.2 Crack plane orientation according to Terminology E1823,

11.1.3 Number of uncensored data, r, and number of specimens tested at each temperature,

11.1.4 Crack pop-in and compliance ratio, C_i/C_o, if applicable,

11.1.5 Material yield strength and tensile strength, at each test temperature,

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

11.1.7 A list of individual data for each specimen including:

11.1.7.1 $K_{Jc(i)}$, $K_{Jclimit}$, $K_{Jc\Delta a}$, $a_{o(i)}$, $T_{(i)}$, and the extent of visually measured slow-stable crack growth prior to the onset of cleavage, if present,

11.1.7.2 Difference between maximum and minimum initial crack size expressed as a percentage of the initial specimen thickness, B,

11.1.8 Weibull scale parameter, K_o and the master curve reference temperature, T_o (°C) or $T_{o,X}$ (°C), and

11.1.9 Fatigue precracking K_{max} for the final precracking step (see 7.8.2).

11.1.10 Values for the nominal elastic modulus, E, used to convert J_c to K_{Jc} at each test temperature.

11.1.11 Values for E_i and the associated calculated crack size for each test from 8.8.2.

11.2 The report may contain the following supplementary information:

11.2.1 Specimen identification codes,

11.2.2 Measured pop-in crack extensions for applicable test results,

11.2.3 Provisional value T_{oQ} (°C) and reason for invalidity, if applicable, and

11.2.4 Force-displacement records.

12. Precision and Bias

12.1 *Precision*—The precision of T_o measurements has been examined through an interlaboratory round-robin study with nine participating laboratories. A nuclear grade pressure vessel weld metal was tested using precracked Charpy-type (PCC) specimens **(35)**. All the values of T_o used for the calculations satisfy the validity requirements of this test method. Values of T_o were originally calculated and reported by participants using the single-temperature approach (that is, one value of T_o per test temperature). However, test results obtained by each laboratory at different temperatures have also been analyzed using the multi-temperature approach (that is, one value of T_o per laboratory). While the data for this interlaboratory study do not strictly conform to the requirements of Practice E691 (that is, the reported reference temperatures and their standard errors do not represent typical means and standard deviations based on repeated measurements), alternative definitions that satisfy the intent of Practice E691 have been used. The results are summarized in 12.1.1.2 and 12.1.2.2. For more details, see ASTM Research Report RR:E08-1008.[9]

12.1.1 *Analysis of Single-Temperature Estimates of T_o:*

12.1.1.1 *Justification and Theoretical Background*—For the analysis of single-temperature estimates of T_o, laboratories reported values of T_o and their associated standard errors based on Eq 29 at different test temperatures. The number of test temperatures varied for each laboratory. The arithmetic average of the single T_o values is the laboratory's estimated reference temperature. In addition, the standard errors associated with each single T_o value were combined to obtain an estimate of the standard deviation for each laboratory. The use of Practice E691 for computing repeatability and reproducibility standard deviations for this case is not applicable due to the differing number of test temperatures for each laboratory. Instead, the repeatability standard deviation and the reproducibility standard deviation are defined as follows. The repeatability standard deviation is the square root of the average of the estimated laboratory variances obtained from Eq 29. The reproducibility standard deviation is the standard deviation of the reference temperatures reported for each laboratory. For the analysis of single-temperature estimates of T_o, the reported values of repeatability and reproducibility standard deviations provide some general insights, but do not strictly correspond to the definitions provided in Practice E691.

12.1.1.2 *Results*—The statistics reported in Table 7 were calculated for the single-temperature (that is, single-T) approach from test results obtained at various temperatures. Individual T_o values are based on the number of uncensored data points reported by each laboratory at each test temperature. The number of uncensored data points ranged from 6 to 11. Note that the statistics reflecting the precision of the test method from this interlaboratory study (Table 7) also incorporate any variability resulting from estimating T_o at different test temperatures.

NOTE 4—Repeatability and reproducibility limits have been calculated by multiplying the respective standard deviations by 2.8, as recommended by Practice E177. Repeatability and reproducibility limits are considered general guides, and the associated 95th percentiles provide an estimate of the differences that may be expected when comparing test results from laboratories similar to those in the study.

12.1.2 *Analysis of Multi-Temperature Estimates of T_o:*

12.1.2.1 *Justification and Theoretical Background*—For the analysis of multi-temperature estimates of T_o, each laboratory provided a single value of the reference temperature based on differing numbers of uncensored test results, and Eq 29 from this test method was used to estimate the standard error of the reported reference temperature. Although the data do not strictly comply with Practice E691, the definitions of repeatability standard deviation and reproducibility standard deviation from Appendix X1.1 of Practice E691 remain applicable. It is assumed in this analysis that the standard error of the reference temperature, Eq 29, is equal to the standard deviation of the measurement. Because the standard errors of the reference temperatures were similar, they could be combined to obtain the repeatability standard deviation.

12.1.2.2 *Results*—The statistics reported in Table 8 were calculated for the multi-temperature (multi-T) approach. Eq 29 of this Test Method was used to determine the repeatability standard deviation n, and reproducibility standard deviation was computed using Practice E691 Eq 8, where n=1.

NOTE 5—Repeatability and reproducibility limits have been calculated by multiplying the respective standard deviations by 2.8, as recommended by E177. Repeatability and reproducibility limits are considered general guides, and the associated 95th percentiles provide an estimate of the differences that may be expected when comparing test results from

[9] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E08-1008.

TABLE 7 Precision using PCC Specimens (Single-T Analysis)

Parameter	Type of Analysis	Number of Determinations	Average	Repeatability Standard Deviation, S_r	Reproducibility Standard Deviation, S_R	Repeatability Limit, r	Reproducibility Limit, R
T_o, °C	Single-T	9	-75	7.8[A]	7.8[B]	21.8	21.8

[A] The Repeatability Standard Deviation used in this analysis does not strictly correspond to the repeatability standard deviation as defined in Practice E691. Standard errors for each laboratory are given in ASTM Research Report RR:E08-1008.

[B] The provisional reproducibility standard deviation is defined as the standard deviation of the laboratory averages. Since the provisional reproducibility standard deviation of 6.3 °C is less than the repeatability standard deviation, the "Reproducibility Standard Deviation" is set to be equivalent to the repeatability standard deviation. The reproducibility standard deviation used in this analysis does not strictly correspond to the reproducibility standard deviation as defined in Practice E691.

TABLE 8 Precision using PCC Specimens (Multi-T Analysis)

Parameter	Type of Analysis	Number of Determinations	Average	Repeatability Standard Deviation, S_r	Reproducibility Standard Deviation, S_R	Repeatability Limit, *r*	Reproducibility Limit, *R*
T_o, °C	Multi-T	9	-74	5.7[A]	7.6	16.0	21.3

[A]These values do not strictly correspond to the repeatability standard deviation as defined in Practice E691. Individual within-laboratory standard deviations for each laboratory are given in ASTM Research Report RR:E08-1008.

laboratories similar to those in the study.

12.1.3 The terms repeatability and reproducibility are used as specified in Practice E177.

12.2 *Bias*—Since there is no accepted reference material, method, or laboratory suitable for determining the bias in T_0 using the procedure in this test method, no statement of bias is being made.

ANNEX

(Mandatory Information)

A1. SPECIAL REQUIREMENTS FOR DETERMINING THE REFERENCE TEMPERATURE, $T_{o,X}$, AT ELEVATED LOADING RATES

A1.1. Scope

A1.1.1 This annex covers the determination of the rate-dependent reference temperature, $T_{o,X}$, under conditions where the loading rate exceeds the limit allowed for conventional quasi-static loading in 1.5 and when the minimum test time is greater than the limit defined in A14.3.1.4 in Test Method E1820, Annex A14 "Special Requirements for Rapid-Load J-integral Fracture Toughness Testing".

A1.1.2 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

A1.2. Terminology

A1.2.1 *Definitions of Terms Specific to This Standard:*

A1.2.1.1 *reference temperature,$T_{o,X}$*—Reference temperature analogous to T_o determined from testing performed at a rate higher than the quasi-static range specified in 1.5. The index *X* quantifies the order of magnitude of $\dot{K}_I$, which means that *X* corresponds to log ($\dot{K}_I$), rounded to the integer.

A1.2.1.2 *test loading rate $\dot{K}_I$ [$FL^{-3/2}T^{-1}$]*—rate of increase of applied stress intensity factor.

A1.2.1.2.1 *Discussion*—It is generally evaluated as the ratio between K_{Jc} and the corresponding time to cleavage. For tests where partial unloading/reloading sequences are used to measure compliance, an equivalent time to cleavage t_c shall be used to calculate the loading rate. The value of t_c is calculated as the ratio between the value of load-line displacement at cleavage and the load-line displacement rate applied during the monotonic loading portions of the test (that is, the periods between partial unloading/reloading sequences used for compliance measurement).

A1.2.1.3 *Elevated loading rate test*—A test where the specimen loading rate in terms of $\dot{K}_I$ exceeds 2 MPa√m/s.

A1.2.1.4 *Estimated reference temperature, $T_{o,X}^{est}$ [°C]*—estimated value of the reference temperature corresponding to an elevated loading rate, *X*, to be used only for test temperature selection in accordance with A1.4.2.

A1.3 General Considerations

A1.3.1 This annex describes how to obtain data measured at a nominally constant loading rate, $\dot{K}_I$, from tests conducted at either multiple or single temperature and calculates a rate-dependent measure of T_o, called $T_{o,X}$, where *X* corresponds to the order of magnitude of the average test $\dot{K}_I$. $\dot{K}_I$ values are considered to be nominally constant if they deviate by no more than a factor of 3 from the average $\dot{K}_I$ value.

A1.3.2 The summary of test method (Section 4) and significance and use (Section 5) are applicable to elevated loading rate data. The apparatus (Section 6), and specimen configuration, dimensions, and preparation (Section 7) are also generally applicable. However, if the time taken to reach P_m is less than 0.1 minutes as stipulated in Test Method E1820, Annex A14, additional considerations pertaining to the test apparatus in Test Method E1820, Annex A14 are also applicable and modifications to the test specimens may be necessary to accommodate the test apparatus as discussed in Test Method E1820, Annex A14.

A1.4. Procedure

A1.4.1 *General*—The procedures described in Section 8 for quasi-static testing are applicable, unless superseded by the procedures in this section. To evaluate $T_{o,X}$, the loading rate for all tests shall be of the same order of magnitude (that is, correspond to the same X) and shall be higher than the quasi-static range specified in 1.5.

A1.4.2 *Initial Test Temperature Selection*—If the value of T_o under quasi-static loading rate conditions is known, the following relationship can be used to derive an estimated value of $T_{o,X}$ ($T_{o,X}^{est}$) to facilitate test temperature selection (**36**).

$$T_{o,X}^{est} = \frac{(T_o + 273.15)\cdot\Gamma}{\Gamma - \ln\left(\dot{K}_I\right)} - 273.15 \qquad \text{(A1.1)}$$

where:

$\dot{K}_I$ = in MPa√m/s and T_o is in °C.

The function Γ is given by:

$$\Gamma = 9.9\cdot exp\left[\left(\frac{T_o + 273.15}{190}\right)^{1.66} + \left(\frac{\sigma_{ys}^{T_o}}{722}\right)^{1.09}\right] \qquad \text{(A1.2)}$$

$\sigma_{ys}^{T_o}$ = yield strength measured (as per Test Methods E8/E8M) or estimated at T_o and at quasi-static rates (~ 10^{-6} to 10^{-4} s^{-1}).

Eq A1.1 and Eq A1.2 shall not be used for calculating and reporting values of reference temperatures corresponding to elevated loading rates.

A1.4.2.1 While testing is allowed at any temperature within $T_{o,X} \pm 50$°C, the most accurate estimates of $T_{o,X}$ are obtained by testing as close to $T_{o,X}$ as possible. One recommended strategy is to conduct initial testing at $T_{o,X}^{est}$, determine an initial value of $T_{o,X}$, and then conduct subsequent testing as close as possible to $T_{o,X}$ to increase the overall accuracy of the $T_{o,X}$ estimation.

A1.4.3 *Testing Procedure*—If the time taken to reach P_m is greater than 0.1 min., specimen testing shall be conducted as per Test Method E1820. Testing at higher loading rates, as stipulated in Test Method E1820, Annex A14, shall be conducted as per Test Method E1820, Annex A14. The corresponding requirements of Test Method E1820, Annex A14, including transition time and data smoothness requirements, shall be fulfilled in order for a test result to be considered valid.

A1.4.3.1 Testing shall proceed beyond the point of specimen instability due to cleavage to be considered a valid test. If a single or multiple pop-ins occur prior to the final specimen instability point, the significance of the pop-ins should be evaluated using 8.9.5 and 9.2 to determine the point in the load-displacement record used to calculate $J_{Qc}(t)$ for this method.

A1.4.3.2 After the test, measure the initial crack size and the extent of any slow stable crack growth prior to either final specimen instability or a significant pop-in event (9.2), as applicable, as per 8.8.1.

A1.4.3.3 Determine the specimen compliance from the test record and estimate the initial crack size based on this compliance using Test Method E1820, equation A1.12 for SE(B) specimens, Test Method E1820, equation A2.12 for C(T) or Test Method E1820, equation A3.11 for DC(T) specimens. Compare, and adjust if needed, the estimated initial crack size with the measured initial crack size as described in 8.8.2.

A1.4.3.4 Calculate $J_{Qc}(t)$ for each specimen in the data set at the point of instability as per either Test Method E1820, Section 9 or Test Method E1820, Annex A14 as applicable for the test loading rate. The J-estimation formulas for the basic method provided in Test Method E1820, Annex A1 – A3 for each applicable specimen type shall be used.

A1.4.4 *Qualification of $J_{Qc}(t)$ Data*—For $J_{Qc}(t)$ to be a valid $J_c(t)$, the following requirements shall be met:

A1.4.4.1 Requirements on testing equipment in Test Method E1820, Section 6.

A1.4.4.2 Requirements pertaining to specimen configuration, dimensions, and machining tolerances in Test Method E1820, Section 7.

A1.4.4.3 Specimen precracking requirements in 7.8.

A1.4.4.4 Requirements on fixture alignment in Test Method E1820, Section 8.

A1.4.4.5 Requirements on specimen test temperature control and measurement in 8.6.

A1.4.4.6 Requirements on the accuracy of the post-test check of the estimated crack size in 8.8.2.

A1.4.4.7 Requirements on initial crack size measurement in 8.9.1.

A1.4.4.8 Specimen size and ductile crack extension requirements in Test Method E1820, Annex 6.

A1.4.4.9 For testing conducted as per Test Method E1820, the requirements on test rate in Test Method E1820, Section 8.

A1.4.4.10 For testing conducted as per Test Method E1820, Annex A14, the requirements in Test Method E1820, Annex A14 on qualification of data.

A1.4.5 *Determination of $K_{Jc}(t)$ data for $T_{o,X}$ calculation.*

A1.4.5.1 Calculate $K_{Jc}(t)$ for each $J_c(t)$ datum using Eq 16 in 9.1.5.

A1.4.5.2 $K_{Jc}(t)$ data that exceed the $K_{Jclimit}$ or $K_{Jc\Delta a}$ requirements specified in 8.9.2 are considered to be censored data that are still analyzed as described in 10.2.1.

A1.4.5.2.1 The use of the material's quasi-static yield strength in the $K_{Jclimit}$ equation (Eq 1 in 7.5) is conservative since the quasi-static yield strength will always be lower than the dynamic yield strength. Alternatively, the dynamic yield strength can be measured at the strain rate corresponding to $\dot{K}_I$ for the fracture test and used in the $K_{Jclimit}$ equation. The corresponding dynamic tensile testing strain rate, $\dot{\varepsilon}$, is calculated by (**37**, **38**):

$$\dot{\varepsilon} = \frac{2\sigma_{YS}\dot{K}_I}{\overline{K_{Jc}}\cdot E} \qquad \text{(A1.3)}$$

σ_{YS} = the average quasi-static yield strength at the test temperature

E = Young's modulus at the test temperature,

$\overline{K_{Jc}}$ = average cleavage toughness value of the elevated rate tests

$\dot{K}_I$ = average loading rate of the elevated rate tests.

The tensile test shall then be conducted at the strain rate calculated by Eq A1.3 to obtain the dynamic yield strength.

A1.4.6 *Calculation of* $T_{Qo,X}$—Calculate a provisional $T_{o,X}$ ($T_{Qo,X}$) according to Section 10 with X = order of magnitude of the average loading rate $\dot{K}_I$ for all tests performed (in MPa$\sqrt{m}$/s). For example, if the average calculated loading rate is 3×10^4 MPa$\sqrt{m}$/s, the corresponding reference temperature shall be designated $T_{o,4}$. As indicated in A1.3.1, the loading rate for all specimens used in the calculation must deviate by no more than a factor of 3 from the average $\dot{K}_I$ value for the data set.

A1.4.7 *Qualification of* $T_{Qo,X}$—The provisional value of $T_{Qo,X}$ is equal to $T_{o,X}$ if the following requirements are met.

A1.4.7.1 The number of test specimens meets the minimum data set size requirements in Table 5.

A1.4.7.2 The test temperatures, T, for all test specimens satisfy $-50°C \le T - T_{o,X} \le 50$ °C.

A1.4.7.3 Once $T_{o,X}$ has been determined, the provisions in 10.6, 10.7, 10.8, and 10.9 can be followed to determine a transition temperature curve, standard deviation, tolerance bounds, and a margin adjustment for $T_{o,X}$. The uses of the transition temperature curve in 10.10 are also applicable.

A1.5. Report

A1.5.1 The report shall include the information required in Test Method E1820, 10.2.1 – 10.2.7, and 10.2.9.

A1.5.2 If testing was conducted as per Test Method E1820, Annex A14 the report shall include the information required in Test Method E1820, A14.9

A1.5.3 The report shall include the information required in Section 11.

A1.5.4 The report shall also include the following:

A1.5.4.1 Load-line displacement rate $\dot{\Delta}_{LL}$, and

A1.5.4.2 Test loading rate, $\dot{K}_I$

A1.5.5 The report may contain the following supplementary information:

A1.5.5.1 Force-time and force-displacement records.

A1.6. Precision and Bias

A1.6.1 An interlaboratory study (**35**) for the determination of the master curve reference temperature, T_o, from precracked Charpy-type specimens tested at impact loading rates, was conducted in ten laboratories using a reactor pressure vessel steel denominated JRQ (ASTM A533B Cl.1).[10]

A1.6.1.1 *Justification and Theoretical Background*—The data analyzed for this interlaboratory study do not strictly conform to the requirements of Practice E691 because the reported reference temperatures and their standard deviations do not represent typical means and standard deviations based on repeated measurements. Each laboratory provides a single value of the reference temperature based on differing numbers of valid measurements, and Eq 29 from this test method is used to estimate the standard deviation of the reported reference temperature. Although the data do not comply with Practice E691, the definitions of repeatability and reproducibility from Practice E691, Appendix X1.1 remain applicable. Each reference temperature is considered to be based on a sample of size 1 for analysis purposes. The standard deviations of the reference temperatures were very similar, so these estimates were "pooled" to obtain the repeatability standard deviation.

A1.6.1.2 *Statistical Analysis of the Interlaboratory Study Results*—The statistics reported in Table A1.1 were calculated using the standard deviation of the laboratory reference temperatures (when single values are reported for each laboratory, this is the provisional reproducibility standard deviation) and Eq 29 of this test method (repeatability standard deviation). Note that the statistics in Table A1.1 also reflect any contributions from test temperature effects on the precision of the test method. Individual T_o values are based on a number of valid data points ranging from 7 to 10. One of the data sets was excluded after being statistically classified as an outlier.

A1.6.1.3 The terms repeatability and reproducibility are used as specified in Practice E177.

NOTE A1.1—Repeatability and reproducibility limits have been calculated by multiplying the respective standard deviations by 2.8, as recommended by Practice E177. Repeatability and reproducibility limits are considered general guides, and the associated 95 % probability is a rough indicator of what can be expected when comparing two test results from laboratories similar to those participating in the study.

A1.6.2 *Bias*—Since there is no accepted reference material, method, or laboratory suitable for determining the bias in T_o using the procedure described in this annex, no statement of bias is being made.

[10] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E08-1011. Contact ASTM Customer Service at service@astm.org.

TABLE A1.1 Precision using impact-tested PCC specimens

Parameter	Type of Analysis	Number of Determinations	Average	Repeatability Standard Deviation, S_r	Reproducibility Standard Deviation, S_R	Repeatability Limit, r
T_o, °C	Multi-T	9	7.4[A]	7.4[B]	20.7	20.7

[A] The repeatability standard deviation is the square root of the pooled laboratory variances that were computed using Eq 29 of this test method. These values do not strictly correspond to the repeatability standard deviation as defined in Practice E691. Individual within-laboratory standard deviations for each laboratory are given in ASTM Research Report RR:E08-1011.

[B] The provisional reproducibility standard deviation (the standard deviation of the reference temperatures reported by each laboratory) was estimated to be 5.63. Since the reproducibility standard deviation is less than the repeatability standard deviation, the reproducibility standard deviation is set equal to the repeatability standard deviation as specified in Practice E691.

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:

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

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√m (18.2 ksi√in.). This shape is defined by the Weibull exponent, b, which is constant at 4. The 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 $K_{Jc(med)}$*—The following example illustrates the analysis of all uncensored data tested at a single temperature. The data came from tests that used 4T compact specimens of A533 grade B steel all tested at -75°C. None of the data require censoring so $r = N = 6$, and the next step is to convert all data to the 1T equivalent specimen size for analysis:

Rank (i)	$K_{Jc(4T)}$ (MPa√m)	$K_{Jc(1T)}$ Equivalent (MPa√m)
1	59.1	75.3
2	68.3	88.3
3	77.9	101.9
4	97.9	130.2
5	100.9	134.4
6	112.4	150.7

Eq 22 gives the Weibull scale parameter as:

$$K_o = \left[\sum_{i=1}^{N} \frac{(K_{Jc(i)} - 20)^4}{N}\right]^{1/4} + 20,\ \text{MPa}\sqrt{\text{m}} \quad (X1.2)$$

Since $N = r = 6$, Eq X1.2 gives $K_o = 123.4$ MPa√m.

The median K_{Jc} is obtained as:

$$K_{Jc(med)} = 20 + (K_o - 20)\,(0.9124) = 114.3\ \text{MPa}\sqrt{\text{m}} \quad (X1.3)$$

and the reference temperature (°C) is:

$$T_o = T_{oQ} = T - \left(\frac{1}{0.019}\right) \ln\left[\frac{K_{Jc(med)} - 30}{70}\right] \quad (X1.4)$$

$$= -85°C$$

X1.3 *Data Censoring Examples*:

X1.3.1 *Censoring When $K_{Jclimit}$ is Violated*—The following example illustrates the analysis of censored data when all tests have been conducted at a single test temperature.

X1.3.2 The example data is artificially generated with the following assumptions:

Material yield strength = σ_{YS} = 482 MPa
T_o temperature = 0°C
Test temperature T = 38°C
Six 1/2T and six 1T specimens, all with $a/W = 0.5$

X1.3.3 $K_{Jclimit}$ values in MPa√m from Eq 1.

	0.5T	1T
Specimen size	206	291
1T equivalent	176	291

X1.3.4 *Simulated Data Set:*

Raw Data (K_{Jc}, MPa√m)		Size Adjusted ($K_{Jc(1T)}$, MPa√m)	
1/2T	1T	1/2T[A]	1T
138.8	119.9	119.9	119.9
171.8	147.6	147.6	147.6
195.2	167.3	167.3	167.3
(216.2)	185.0	(176)	185.0
(238.5)	203.7	(176)	203.7
(268.3)	228.8	(176)	228.8

[A] $K_{Jc(1T)} = (K_{Jc(0.5T)} - 20)\,(1/2\ /\ 1)^{1/4} + 20$ MPa√m

X1.3.5 Calculations using the censored, size-adjusted data and the relationships of section 10.4 with $N = 12$ and $r = 9$ give: $K_o = 188$ MPa√m, $K_{Jc(med)} = 174$ MPa√m and $T_o = T_{oQ} = 0°C$.

X1.3.6 *Censoring When Ductile Crack Extension Limit is Violated*—The following example also illustrates the analysis of censored data where all tests have been conducted at a single test temperature of 38°C. The test material has properties as defined in X1.3.2 and toughness data as defined in X1.3.4. However, for this example assume that the steel has a low upper shelf. The crack growth limit (see 8.9.2) is 0.64 mm and 1 mm for the 0.5T and 1T specimens, respectively. The K_J value after 0.64 mm of slow-stable growth is 197 MPa√m and after 1 mm of slow-stable growth is 202 MPa√m. Therefore, the crack growth limit controls all censoring. In this case, the value to use for crack growth censoring, as per 10.2.1, is the highest K_{Jc} result that does not require censoring, regardless of specimen size:

Raw Data				1T Size Adjusted Data	
0.5T		1T		0.5T[A]	1T
Δa_p, mm	K_{Jc}, Mpa√m	Δa_p, mm	K_{Jc}, Mpa√m	K_{Jc}, Mpa√m	
0.00	138.8	0.00	119.9	119.9	119.9
0.25	171.8	0.15	147.6	147.6	147.6
0.50	195.2	0.20	167.3	167.3	167.3
0.67	(216.2)	0.55	185.0	(167.3)	185
0.70	(238.5)	1.10	(203.7)	(167.3)	(185)
0.71	(268.3)	1.15	(228.8)	(167.3)	(185)

[A] $K_{Jc(1T)} = K_{Jc(0.5T)} - 20)\,(0.5\ /\ 1)^{1/4} + 20$ MPa√m

X1.3.7 Calculations using the censored, size-adjusted data and the relationships of section 10.4 with $N = 12$ and $r = 7$ give: $K_o = 186$ MPa√m, $K_{Jc(med)} = 171$ MPa√m and $T_o = T_{oQ} = 1°C$.

X2. MASTER CURVE FIT TO DATA

X2.1 The data set for this example is defined by:

X2.1.1 Six 0.5*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.

Rank (*I*)	$K_{Jc(1/2T)}$ (MPa√m)	$K_{Jc(1T)}$ Equivalent (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

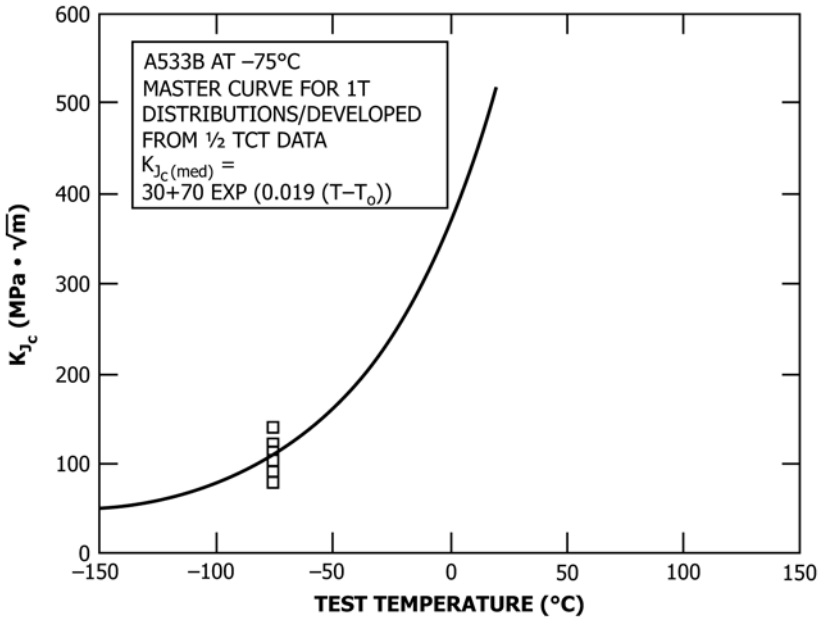
X2.3 Determine K_o, $K_{Jc(med)}$ and T_{oQ} using 10.4 to obtain:

K_o = 115.8 MPa√m,

$K_{Jc(med)}$ = 20 + (K_o – 20)[ln(2)]$^{1/4}$ = 107.4 MPa√m, and

T_o = T_{oQ} = -75 - ln[(107.4 - 30)/70]/0.019 = -80.3°C = -80°C.

X2.4 *Master Curve*—The master curve of Eq 25 with T_o = -80°C for this case is presented in Fig. X2.1 along with the 1T adjusted data.



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

FIG. X2.1 Master Curve for 1T Specimens Based on 0.5*T* Data Tabulated in X2.2

X3. EXAMPLE T_o DETERMINATION WITH DATA OBTAINED AT MULTIPLE TEST TEMPERATURES

X3.1 *Material and Specimen Geometries:*

A533 Grade B plate
Quenched and tempered
900°C WQ (water quench); and 440°C (5 h) temper
Specimen types:
0.5T C(T) with $a_o/W = 0.5$
1T SE(B) with $a_o/W = 0.5$

X3.2 *Mechanical Properties:*

Yield strength: 641 MPa (93 ksi)
Tensile strength: 870 MPa (117.5 ksi)
Charpy V:
28-J temperature T_{28J} = −5°C (23°F)
41-J temperature T_{41J} = 16°C (61°F)
NDT: 41°C (106°F)

X3.3 $K_{Jclimit}$ *Values from Eq 1:*

Test Temperature (°C)	Yield Strength (MPa)	$K_{Jclimit}$ (MPa$\sqrt{m}$)	
		1/2T	1T
−10	651	239	338
−5	649	238	337
0	648	238	337
23	641	237	335

X3.4 *Slow-stable Crack Growth Limits:*

$$K_{Jc(1\ mm)} = 263\ \text{MPa}\sqrt{\text{m}}\ \text{for 1T SE(B) specimen;}$$
$$K_{Jc(0.64\ mm)} = 255\ \text{MPa}\sqrt{\text{m}}\ \text{for 1/2T C(T) specimen}$$

X3.5 *Estimation Procedure #1 from Charpy Curve:*

$$T_{o(est)} = T_{28J} + C = -5° - 18° = -23°C$$
$$T_{o(est)} = T_{41J} + C = 16° - 24° = -8°C$$

Conduct four 1T SE(B) tests at −20°C.

X3.6 T_o *Estimation Procedure #2 from Results of First Four Tests:*

First four test results at T = −20°C:

K_{Jc}, MPa$\sqrt{m}$
135.1
108.9
177.1
141.7

Calculate preliminary $T_{o(est)\#2}$ from data to determine allowable test temperature range using 10.4:

$$K_{Jc(med)} = 137\ MPa\sqrt{m};$$
$$T_{0(est)\#2} = -42°C$$

Estimated temperature range or usable data:

$$= T_{0(est)\#2} \pm 50°C$$
$$= -92°C < T_i < +8°C$$

Now conduct additional testing within this range for T_o determination. Data is presented in Table X3.1.

X3.7 *Calculation of* T_{oQ}—Based on $T_{o(est)\#2}$, data is valid between −92°C and 8°C. Using data from -80°C to 0°C, with N = 53 and r = 48, Eq 20 gives T_{oQ} = -48°C. Based on this result the valid test temperature range is –98°C to 2°C. Since calculations were performed with data within this range, no iteration is required.

TABLE X3.1 Data Tabulation

Test temperature, (°C)	Specimen		K_{Jc} (MPa$\sqrt{m}$)		δ_j
	Type	Size	Raw data	1T equivalent	
−130	C(T)	1/2T	59.5	53.2	1
			85.1	74.7	1
			55.3	49.7	1
			56.4	50.6	1
−80	C(T)	1/2T	51.3	46.3	1
			87.9	77.1	1
			113.4	98.5	1
−65	SE(B)	1T	73.9	73.9	1
			126.8	126.8	1
−55	C(T)	1/2T	167.7	144.2	1
			88.5	77.6	1
			115.2	100.0	1
			81.4	71.6	1
			121.9	105.7	1
			145.0	125.1	1
			104.2	90.8	1
			64.4	57.3	1
			96.8	84.6	1
			114.5	99.5	1
			107.4	93.5	1
			81.0	71.3	1
			70.0	62.0	1
			131.8	114.0	1
			69.5	61.6	1
			67.5	59.9	1
−30	C(T)	1/2T	102.3	89.2	1
			194.0	166.3	1
			170.4	146.5	1
			129.5	112.1	1
			118.2	102.6	1
			147.9	127.5	1
			178.8	153.5	1
			95.9	83.8	1
−20	SE(B)	1T	135.1	135.1	1
			108.9	108.9	1
			177.1	177.1	1
			141.7	141.7	1
			174.4	174.4	1
			84.8	84.8	1
			132.1	132.1	1
−10	C(T)	1/2T	211.4	180.9	1
			179.9	154.5	1
			171.8	147.6	1
			153.0	131.8	1
			236.9	(204)	0
			156.8	135	1
−5	C(T)	1/2T	121.5	105.3	1
			194.2	166.5	1
			110.4	96.0	1
			197.0	168.8	1
			134.7	116.5	1
			264.4	(203)	0
0	C(T)	1/2T	277.8	(198.9)	0
			218.9	187.2	1
			107.7	93.7	1
			269.3	(203)	0
			327.1	(203)	0
23	C(T)	1/2T	325[A]	(202)	0
			328[A]	(202)	0
			227	194	1

[A] R-curve (no cleavage instability).

X3.8 *Qualified Data Summation*:

($T - T_o$) range (°C)	Number of uncensored results, r_i	Weighting factor, n_i	$r_i \cdot n_i$
50 to –14	43	1/6	7.2
–15 to –35	5	1/7	0.7
–36 to –50	0	1/8	0

X3.9 *Validity Check*:

$$\Sigma r_i n_i = 7.9 > 1.0$$

Therefore, $T_{oQ} = T_o$

X4. CALCULATION OF TOLERANCE BOUNDS

X4.1 As an example, the 5 % and 95 % bounds on the Appendix X2 master curve with T_o = -80°C, are:

$$K_{Jc(0.95)} = 34.5 + 101.3\ \exp[0.019(T+80)] \quad \text{(X4.1)}$$

$$K_{Jc(0.05)} = 25.2 + 36.6\ \exp[0.019(T+80)]$$

These tolerance bounds are illustrated in Fig. X4.1.

X4.1.1 The potential error due to finite sample size can be considered, in terms of T_o, by calculating a margin adjustment, as described in X4.2.

X4.2 *Margin Adjustment*—The margin adjustment is an upward temperature shift of the tolerance bound curve, Eq X4.1. 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. Additional uncertainty can result from other sources including material inhomogeneity and experimental errors. The standard deviation on the estimate on T_o which incorporates sample size and experimental uncertainties is given by:

$$\sigma = \sqrt{\frac{\beta^2}{r} + \sigma_{exp}^2} \quad \text{(X4.2)}$$

where:

β = sample size uncertainty factor
r = total number of uncensored data used to establish the value of T_o.
σ_{exp} = contribution of experimental uncertainties. If standard calibration practices are followed, σ_{exp}=4°C may be used.

X4.2.1 An equivalent value of the median toughness for a data set, $K^{eq}_{Jc(med)}$, is defined as (**33**):

$$K^{eq}_{Jc(med)} = \frac{1}{r}\sum_{i=1}^{r} 30 + 70\ \exp(0.019\,(T_i - T_o)) \quad \text{(X4.3)}$$

When $K^{eq}_{Jc(med)}$ is equal to or greater than 83 MPa√m, β = 18°C (**34**). If the 1T equivalent $K^{eq}_{Jc(med)}$ is below 83 MPa√m, values of β must be increased according to the following schedule:

$K^{eq}_{Jc(med)}$ 1T equivalent[A] (MPa√m)	β (°C)
83 to 66	18.8
65 to 58	20.1

[A] Round off $K^{eq}_{Jc(med)}$ to nearest whole number.

X4.2.2 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 X4.1 for the six specimens used to determine T_o.

$$\Delta T_o = \sigma(Z_{85}) = \sqrt{\frac{18^2}{6} + 4^2}\,(1.44) = 12°\text{C} \quad \text{(X4.4)}$$

$$T_o(\text{margin}) = T_o + \Delta T_o = -80° + 12° = -68°\text{C}$$

Then the margin-adjusted 5 % tolerance bound of Eq X4.1 is revised to:

$$K_{Jc(05)} = 25.2 + 36.6\ \exp[0.019(T+68)] \quad \text{(X4.5)}$$

Eq X4.5 is plotted in Fig. X4.2 as the dashed line (LB).

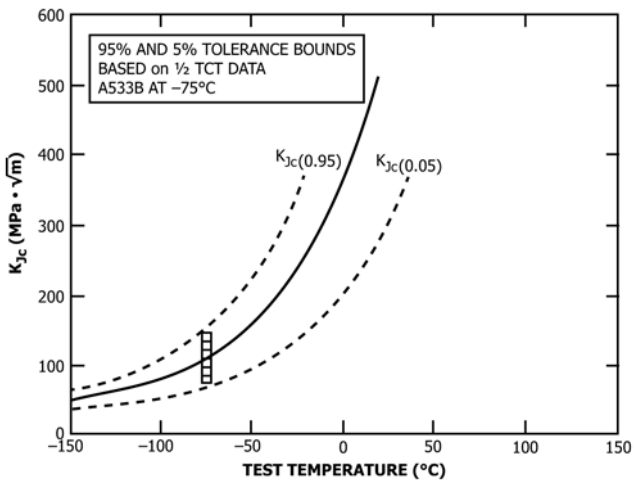


FIG. X4.1 Master Curve With Upper and Lower 95 % Tolerance Bounds

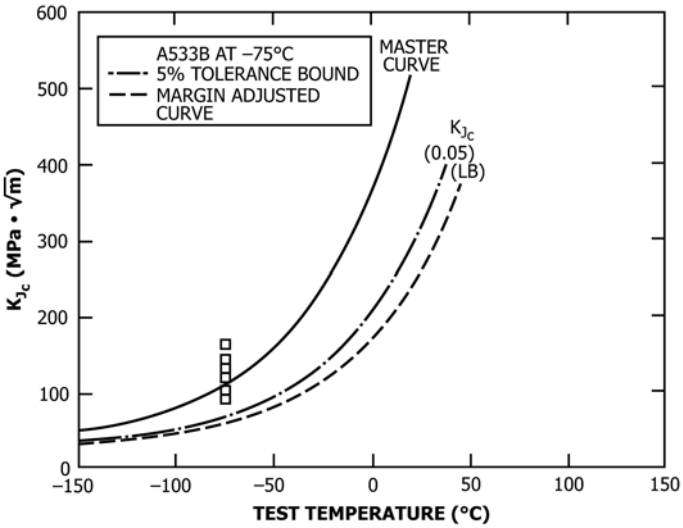


FIG. X4.2 Master Curve Showing the Difference Between 5 % Tolerance Bound and Lower Bound That Includes 85 % Confidence Margin on T_o

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