



Standard Test Method for Determination of Reference Temperature, T_o , for Ferritic Steels in the Transition Range¹

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 $\sqrt{m/s}$).

1.6 The statistical effects of specimen size on K_{Jc} in the transition range are treated using 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 The fracture toughness evaluation of nonuniform material is not amenable to the statistical analysis methods employed in this standard. Materials must have macroscopically uniform tensile and toughness properties. For example, multi-pass 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. Metallography and initial screening may be necessary to verify the applicability of these and similarly graded materials. Particular notice should be given to the 2% and 98% tolerance bounds on K_{Jc} presented

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.

in 9.3. Data falling outside these bounds may indicate nonuniform material properties.

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.*

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
- 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 Plane-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

3. Terminology

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

3.2 Definitions:

3.2.1 *ferritic steels*—are 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.

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

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

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

3.2.4 *J-integral, $J[FL^{-1}]$* —a mathematical expression; a line or surface integral that encloses the crack front from one crack surface to the other; used to characterize the local stress-strain field around the crack front (6). 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 Test Method E1820, Eqs. A1.1 and A2.1 to stipulate allowable precracking limits.

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

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

3.3.3 *effective modulus, $E_{eff}[FL^{-2}]$* —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, $\sigma_Y[FL^{-2}]$* , — 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 determined to be invalid 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 .

3.3.9 *equivalent value of median toughness, $K_{Jc}^{eq}[FL^{-3/2}]$* —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 (7).

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 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.

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 (8).

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

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}) [$^{\circ}\text{C}$]—Interim T_o value calculated using the standard test method described herein. If all validity criteria are met then $T_o = T_{oQ}$.

3.3.17 *reference temperature*, T_o [$^{\circ}\text{C}$]—The test temperature at which the median of the K_{Jc} distribution from 1T size specimens will equal 100 MPa $\sqrt{\text{m}}$ (91.0 ksi $\sqrt{\text{in.}}$).

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 Figs. 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*, $T_{o,X}^{\text{est}}$ [$^{\circ}\text{C}$]—estimated value of the reference temperature corresponding to an elevated loading rate X , to be used only for test temperature selection in accordance with 8.4.2.

3.3.22 *temperature*, T_Q [$^{\circ}\text{C}$]—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 $K_{Jc}(\text{med}) = 100$ MPa $\sqrt{\text{m}}$ is defined as T_Q . T_Q is not a provisional value of T_o .

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

3.3.23.1 *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).

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

3.3.25 *Weibull fitting parameter*, K_o —a scale parameter located at the 63.2 % cumulative failure probability level (9). $K_{Jc} = K_o$ when $p_f = 0.632$.

3.3.26 *Weibull slope*, b —with p_f and K_{Jc} data pairs plotted in linearized Weibull coordinates obtainable by rearranging Eq 19, b is the slope of a line that defines the characteristics of the typical scatter of K_{Jc} data.

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

3.3.27 *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.

3.3.27.1 *Discussion*—1 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).

3.3.27.2 *Discussion*—2 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

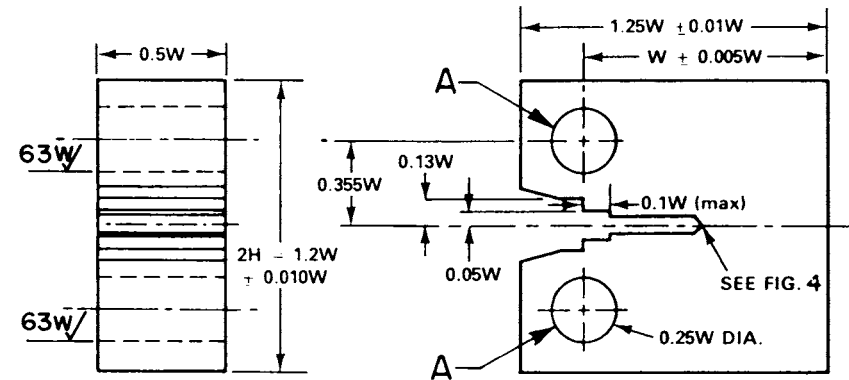
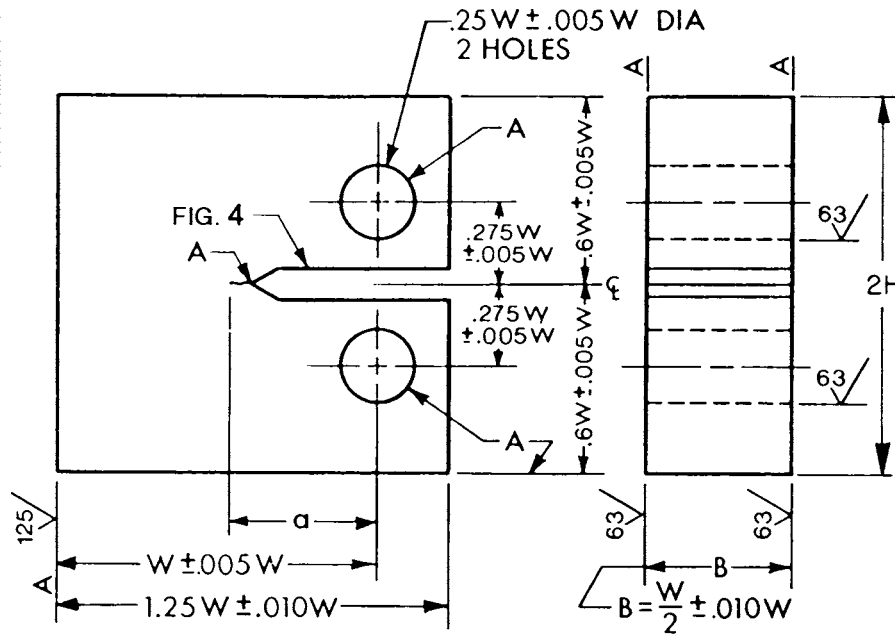
4.1 This test method involves the testing of notched and fatigue precracked bend or compact specimens in a temperature range where either cleavage cracking or crack pop-in develop during the loading of specimens. Crack aspect ratio, a/W , is nominally 0.5. Specimen width in compact specimens is two times 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} . Validity limits are set on the suitability of data for statistical analyses.

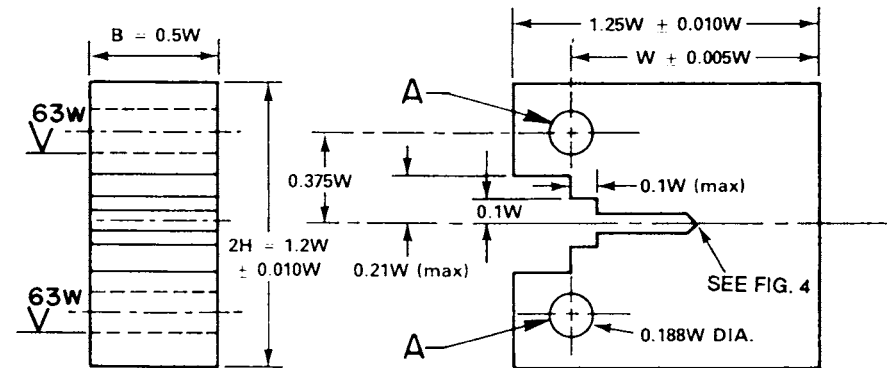
4.3 Tests that are replicated at least six times can be used to estimate the median K_{Jc} of the Weibull distribution for the data population (10). Extensive data scatter among replicate tests is expected. Statistical methods are used to characterize these data populations and to predict changes in data distributions with changed specimen size.

4.4 The statistical relationship between specimen size and K_{Jc} fracture toughness can be assessed using weakest-link theory, thereby providing a relationship between the specimen size and K_{Jc} (4). Limits are placed on the fracture toughness range over which this model can be used.

4.5 For definition of the toughness transition curve, a master curve concept is used (11, 12). The position of the curve on the temperature coordinate is established from the experimental determination of the temperature, designated T_o , at which the median K_{Jc} for 1T size specimens is 100 MPa $\sqrt{\text{m}}$ (91.0 ksi $\sqrt{\text{in.}}$). Selection of a test temperature close to that at which the median K_{Jc} value will be 100 MPa $\sqrt{\text{m}}$ is encouraged and a means of estimating this temperature is suggested. Small specimens such as precracked Charpy's may have to be tested



COMPACT TEST SPECIMEN FOR PIN OF 0.24W (+0.000W/ -0.005W) DIAMETER

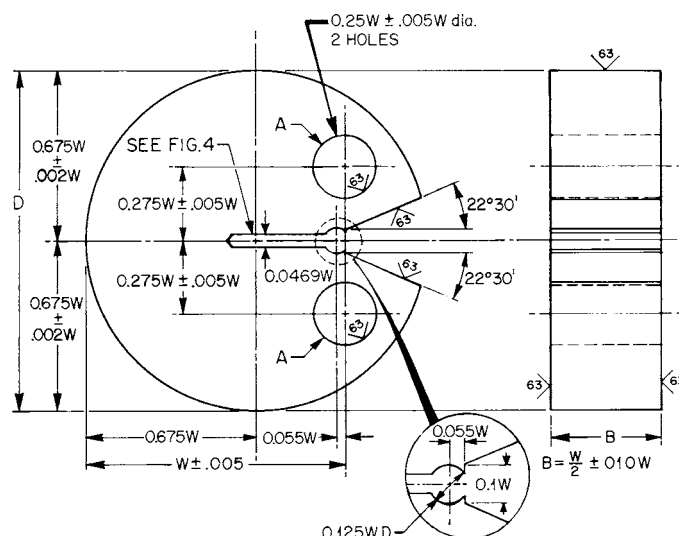


COMPACT TEST SPECIMEN FOR PIN OF 0.1875W (+0.000W/ -0.001W) DIAMETER

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

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

FIG. 1 Recommended Compact Specimen Designs

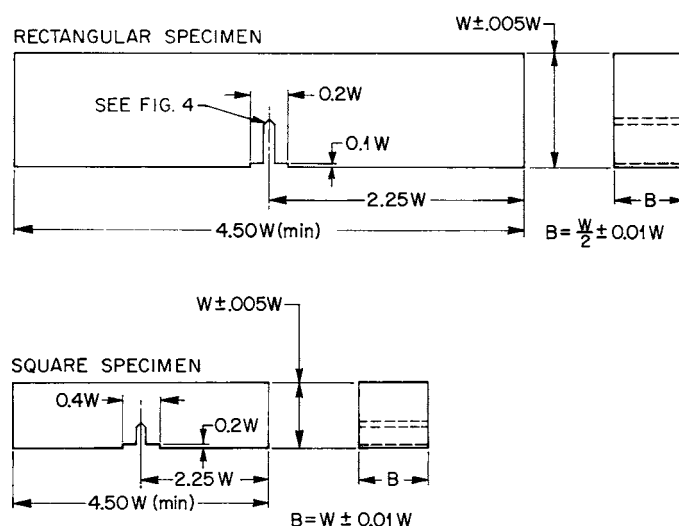


NOTE 1—A surfaces shall be perpendicular and parallel as applicable to within 0.002W TIR.

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

NOTE 3—Integral or attached knife edges for clip gage attachment may be used. See also Fig. 6, Test Method 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 $\pm 2^\circ$.

FIG. 3 Recommended Bend Bar Specimen Design

at temperatures below T_o where $K_{Jc(med)}$ is well below 100 MPa $\sqrt{m}$. In such cases, additional specimens may be required as stipulated in 8.5.

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

5. Significance and Use

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

5.2 Ferritic steels are inhomogeneous with respect to the orientation of individual grains. Also, grain boundaries have properties distinct from those of the grains. Both contain carbides or nonmetallic inclusions 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 (13). This results in a distribution of fracture toughness values that is amenable to characterization using statistical methods.

5.3 Distributions of K_{Jc} data from replicate tests can be used to predict distributions of K_{Jc} for different specimen sizes.

Theoretical reasoning (9), 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 (14). An upper limit on constraint loss and a lower limit on test temperature are defined between which weakest-link statistics can be used.

5.4 The experimental results can be used to define a master curve that describes the shape and location of median K_{Jc} transition temperature fracture toughness for 1T specimens (15). The curve is positioned on the abscissa (temperature coordinate) by an experimentally determined reference temperature, T_o . Shifts in reference temperature are a measure of transition temperature change caused, for example, by metallurgical damage mechanisms.

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

5.6 For some materials, particularly those with low strain hardening, the value of T_o may be influenced by specimen size due to a partial loss of crack-tip constraint (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.

5.7 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 (16). 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, 17, 18), 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 displacements may be recorded digitally on computers or autographically on x-y plotters. For computers, digital signal resolution should be 1/32,000 of the displacement transducer signal range and 1/4,000 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 can be 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 (19) or infer load-point displacement from CMOD using an expression that relates the two displacements (20). 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) (21).

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 $\pm 1^\circ\text{C}$ 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 (22). 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 maintain a condition of high crack-front constraint at fracture. The maximum K_{Jc} capacity of a specimen is given by:

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

where:

$$b_o = W - a_o$$

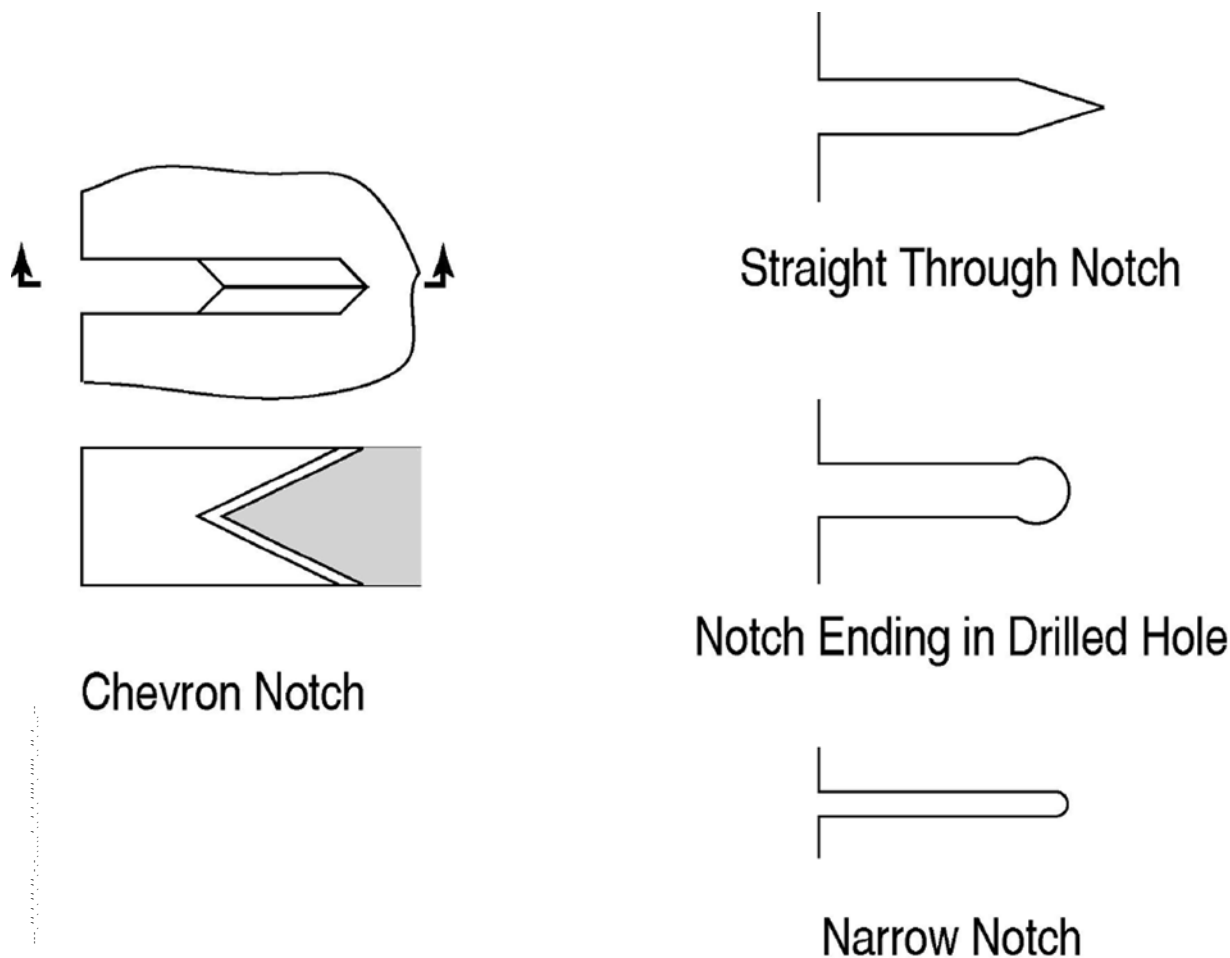
K_{Jc} data that exceed this requirement may be used in a data censoring procedure. Details of this procedure are described in section 10.2.2 for single-temperature data and 10.4.2 for multi-temperature data.

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 valid 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 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



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

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 E1820, Annex A1-Annex A3.

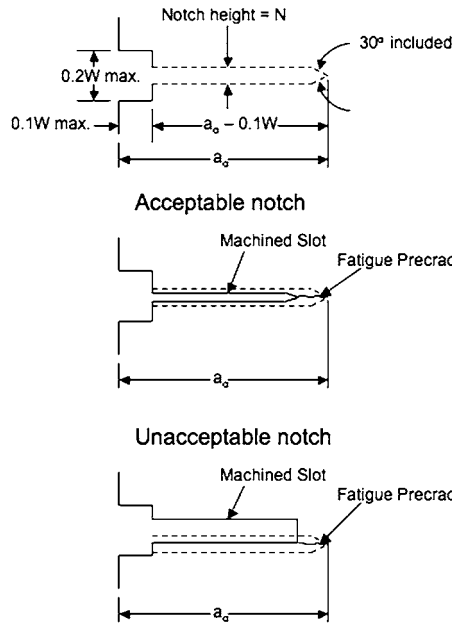
7.8.2 *Fatigue Precracking Procedure*—Fatigue precracking can be conducted under either force control, displacement control, or K control. If the force cycle is maintained constant, the maximum K and ΔK will increase with crack size; if the displacement cycle is maintained constant, the reverse will 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 $\pm 5\%$ 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

Notch and required crack envelope



Notch and Precrack Configurations

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

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

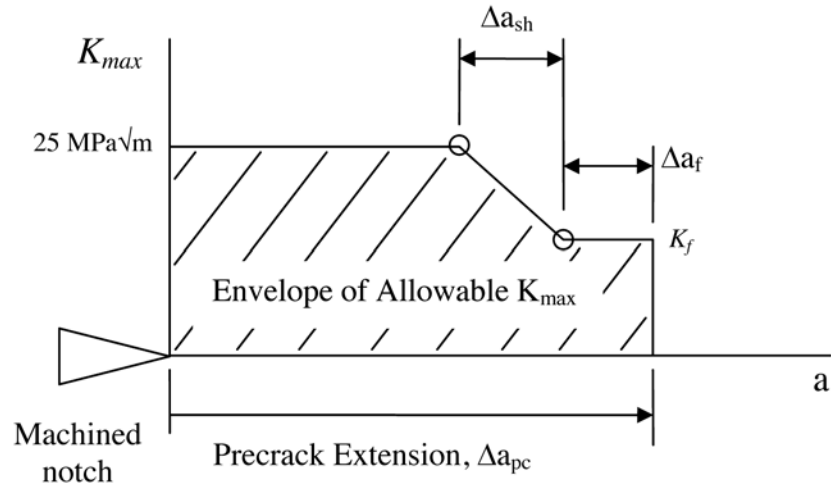


FIG. 6 Envelope of Allowable K_{max} During Precracking

TABLE 1 K_{max} Requirements

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

Final: K_f depends on the test temperature:

Test Temperature
 $<$ precracking temperature
 $\geq$ precracking temperature

K_f throughout Δa_f
 $< 15 \text{ MPa}\sqrt{\text{m}}$ ($13.7 \text{ ksi}\sqrt{\text{in.}}$)
 $< 20 \text{ MPa}\sqrt{\text{m}}$ ($18.3 \text{ ksi}\sqrt{\text{in.}}$)

TABLE 2 Crack Extension Requirements

Wide $\Delta a_{\min}$	=	1.3 mm (0.050 in.)
Notch ($N \geq 0.01W$)		
Narrow $\Delta a_{\min}$	=	0.6 mm (0.024 in.)
Notch ($N < 0.01W$)		
Δa_{pc}	$\geq$	0.5N and $\Delta a_{\min}$
Δa_{sh}	$\geq$	$r_{p1} - r_{p2}$
Where:		
r_{p1}	=	$r_{p1} = \frac{1}{3\pi} \left(\frac{K_{\max}}{\sigma_{ys}} \right)^2$ with $K_{\max} = 25 \text{ MPa}\sqrt{\text{m}}$ (22.8 ksi $\sqrt{\text{in.}}$)
r_{p2}	=	$r_{p2} = \frac{1}{3\pi} \left(\frac{K_f}{\sigma_{ys}} \right)^2$
Δa_f	$\geq$	0.2 mm (0.008 in.)

within the envelope and the maximum fatigue force is less than P_m . The $K_{\max}$ applied to the specimen shall not exceed 25 MPa $\sqrt{\text{m}}$ (22.8 ksi $\sqrt{\text{in.}}$) 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 $\sqrt{\text{m}}$ (13.7 ksi $\sqrt{\text{in.}}$), 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 $\sqrt{\text{m}}$ (18.3 ksi $\sqrt{\text{in.}}$). Δa_{sh} is greater than or equal to the change in plastic zone size in going from a maximum K of 25 MPa $\sqrt{\text{m}}$ (22.8 ksi $\sqrt{\text{in.}}$) 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.

$$\Delta a_{sh} \geq r_{p1} - r_{p2} \quad (2)$$

where:

$$r_{p1} = \frac{1}{3\pi} \left(\frac{K_{\max}}{\sigma_{ys}} \right)^2 \text{ with } K_{\max} = 25 \text{ MPa}\sqrt{\text{m}} \text{ (22.8 ksi}\sqrt{\text{in.}})$$

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

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 0.5N and $\Delta a_{\min}$ (see Fig. 5), where $\Delta a_{\min}$ is 1.3 mm (0.050 in.) for a wide notch ($N \geq 0.01W$) or 0.6 mm (0.024 in.) for a narrow notch ($N \leq 0.01W$). The precrack must also meet the curvature requirement in 8.9.1 and there must be measur-

able crack extension from the machine notch at all points through the specimen thickness. To ensure that these criteria are met for specimens with $B > 25.4 \text{ mm}$ (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, the clip gage checked, and the starting crack size estimated from the average of the optical side face measurements.⁴

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.

⁴ When side-grooving is to be used, first precrack without side grooves and optically measure the fatigue crack growth on both surfaces.

8.3 The required minimum number of valid K_{Jc} tests 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 temperature 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 28J Charpy V-notch energy or a 41J Charpy V-notch energy, a constant C can be chosen from Table 1 corresponding to the test specimen size (defined in 3.3.20), and used to estimate⁵ the test temperature from (12, 23).

TABLE 3 Constants for Test Temperature Selection Based on Charpy Results

$T = T_{CVN} + C$ (3)	
Specimen Size, (nT)	Constant C (°C)
	28J 41J
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.

8.4.2 *Elevated loading rates*—If tests at elevated loading rates (8.7.2) are performed and if the value of T_o under the 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 (24).

$$T_{o,X}^{est} = \frac{(T_o + 273.15) \cdot \Gamma}{\Gamma - |n(X)|} - 273.15 \quad (4)$$

Where: X = $\dot{K}$ in MPa√m/s and temperature is in °C. The function of Γ is given by:

$$\Gamma = 9.9 \cdot \exp \left[\left(\frac{T_o + 273.15}{190} \right)^{1.66} + \left(\frac{\sigma_{ys}^{T_o}}{722} \right)^{1.09} \right] \quad (5)$$

$\sigma_{ys}^{T_o}$ = yield strength measured or estimated at T_o and at quasi-static rates ($\sim 10^{-6}$ to 10^{-4} s^{–1}).

See Test Methods E8/E8M for additional guidance. Eq 4 and Eq 5 shall not be used for calculating and reporting values of reference temperatures corresponding to elevated loading rates.

8.4.3 The procedures outlined 8.4.1 and 8.4.2 are only appropriate for determining an initial test temperature. The iterative scheme described in 10.4.3 may be necessary to refine this test temperature in order to increase T_o accuracy. Testing below the temperature specified in Eq 3 or Eq 4 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 specimen size invalidity (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 valid 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 invalid K_{Jc} values by Eq 1 when testing close to the T_o temperature. In such cases it is advisable to test at temperatures below T_o , where most, if not all, K_{Jc} data developed can be valid. The disadvantage here is that the uncertainty in T_o determination increases as the lower-shelf toughness is approached. This increase in uncertainty can be countered by testing more specimens thereby increasing the $K_{Jc(med)}$ accuracy. Table 2 establishes the number of valid K_{Jc} test results required to evaluate T_o according to this test method. 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.

TABLE 4 Number of Valid K_{Jc} Test Results Required to Evaluate T_o

(T – T_o) _i range (°C)	$K_{Jc(med)}$ range ^A (MPa√m)	Number of valid K_{Jc} required	Possible number of invalid tests 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 20. Round off to nearest whole digit.

^B Established specifically for precracked Charpy specimens. Use this column for total specimen needs.

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.

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, repeated preloading and unloading in the linear elastic range shall be applied. Load and unload the specimen between force values of 0.2 P_{max} and P_{max} (where P_{max} is the top precracking force of the finishing cycles) at least three times. Check the calculated crack size from each unloading slope against the average precrack size defined in 8.2. Refer also to Test Method E1820, Eq. A2.12 for C(T) specimens and to Eq. A1.10 for SE(B) specimens. Be aware that ice buildup at the loading clevis hole between tests can affect accuracy. Therefore, the loading pins and devices should be dried before each test. For working-in fixtures, the elastic modulus to be used should be the nominally known value, E , for the material, and for side-grooved specimens, the effective thickness for compliance calculations is defined as:

$$B_e = B_N(2 - B_N/B) \quad (6)$$

8.6.3 For J calculations in Section 9, B_N is used as the thickness dimension. All calculated crack sizes should be within 10 % of the visual average and replicate determinations

⁵ Standard deviation on this estimate has been determined to be 15°C.

⁶ Data validation is covered in 8.9.2 and Section 10.

within 1 % of each other. If the repeatability of determination is outside this limit, the test setup is suspect and should be thoroughly rechecked. After working-in the test fixtures, the force shall be returned to the lowest practical value at which the fixture alignment can be maintained.

8.7 Testing for K_{Jc} —All tests shall be conducted 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 (21). 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(25). 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 5 is provided to determine the time to t_m or $\dot{\Delta}_{LL}$ 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 Test Method E1820 Eqs. A1.1 and A2.1. The actual crosshead rate used must be adjusted to account for test machine compliance if the load-line displacement rate of Table 5 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 Elevated Loading Rates—For loading rates that exceed 2 MPa $\sqrt{m/s}$, tests shall be performed and results shall be calculated according to Annex 14 of Test Method E 1820. The corresponding requirements of this test method, including

transition time and data smoothness requirements, shall be fulfilled in order for a test result to be considered valid.

8.7.2.1 The use of quasi-static tensile properties to fulfill the requirements of this test method will lead to a conservative estimate of the dynamic yield strength. Alternatively, dynamic tensile test results can be used provided that the testing is conducted at the corresponding strain rate for each group of fracture mechanics tests performed at a nominally constant loading rate. The dynamic tensile testing strain rate is calculated by (26, 27):

$$\dot{\epsilon} = \frac{2\sigma_{YS}\dot{K}}{K_{Jc}E} \quad (7)$$

where σ_{YS} and E are the average quasi-static yield strength and Young's modulus over the temperature range of the fracture toughness test, K_{Jc} is the average cleavage toughness value of the tests and $\dot{K}$ is the average loading rate of the test. The tensile test shall then be conducted at this strain rate calculated by Eq 7 to obtain the dynamic yield strength.

8.7.2.2 Calculate K_{Jc} according to Annex 14 of Test Method E1820. The number of specimens shall meet the requirements of Table 2. Only tests having $\dot{K}$ values within the same order of magnitude shall be used in the calculation of T_o corresponding to the average $\dot{K}$.

8.7.2.3 Calculate $T_{o,X}$ according to Section 10 with X = the order of magnitude of the average loading rate $\dot{K}$ for all test 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 $T_{o,4}$.

8.7.3 Slow Loading Rates—For loading rates less than 0.1MPa $\sqrt{m/s}$, the procedures of this test method can be used if the failure mode remains cleavage. The corresponding reference temperature should also be indicated as $T_{o,X}$ using the convention described in 8.7.2.3.

8.7.4 Partial unloadings that are initiated between force levels P_m and $1.5P_m$ can be used to establish an “effective” elastic modulus, E_e , such that the modulus-normalized elastic compliance predicts an initial crack size within 0.001W of the actual initial crack size. The resulting E_e should not differ from an expected or theoretical E of the material by more than 10 % (see also Practice E561-05^{e1}, Section 10). A minimum of two such unloadings should be made and the slopes should be repeatable within 1 % of the mean value. Slow-stable crack growth usually develops at loads well above $1.5P_m$ and the spacing of partial unloadings depends on judgement. As an aim, every 0.01 a_o increment of crack growth is suitable. Use E_e in place of E and B_e for thickness to calculate crack growth.

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

8.8.1 When the failure event is full cleavage fracture, determine the initial fatigue precrack size, a_o , as follows: measure the crack 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 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

TABLE 5 SE(B) Specimen Rate Estimation-C(T) Specimen Rate Estimation

SE(B) Specimen Rate Estimation			C(T) Specimen Rate Estimation		
a/W	$\frac{t_M \dot{K}}{\sigma_Y \sqrt{W}}$	$\frac{E \dot{\Delta}_{LL}}{dK/dt \sqrt{W}}$	a/W	$\frac{t_M \dot{K}}{\sigma_Y \sqrt{W}}$	$\frac{E \dot{\Delta}_{LL}}{dK/dt \sqrt{W}}$
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

average of those eight values. Measure the extent of slow-stable crack growth if it develops applying the same procedure. The measuring instruments shall have an accuracy of 0.025 mm (0.001 in.).

8.9 Qualification of Data:

8.9.1 The K_{Jc} datum shall be considered a non-test and discarded if any of the nine physical measurements of the starting crack size differ by more than 5 % of thickness dimension, B , or 0.5 mm, whichever is larger, from the average defined in 8.8.1.

8.9.2 A K_{Jc} datum is invalid if the specimen exceeds $K_{Jc\text{limit}}$ requirement of 7.5, or if a test has been discontinued at a value of K_J without cleavage fracture after surpassing $K_{Jc\text{limit}}$. 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 $K_{Jc\Delta a}$ is also invalid. When K_J or K_{Jc} values are invalid, these data contain statistically useable information that can be applied as censored data in 10.2.2 or 10.4.2 as appropriate. If $K_{Jc\text{limit}}$ is violated, the $K_{Jc\text{limit}}$ value should be used for censoring purposes. If $K_{Jc\Delta a}$ is violated, the $K_{Jc\Delta a}$ value should be used for censoring purposes. Should both $K_{Jc\text{limit}}$ and $K_{Jc\Delta a}$ be violated, the lower value of the two shall prevail for data censoring purposes.

8.9.3 For any test terminated with no cleavage fracture, and for which the final K_J value does not exceed either validity limit, cited in 8.9.2, the test record is judged to be a nontest, the result of which shall be discarded.

8.9.4 Data sets that contain all valid K_{Jc} values can be used without modification in Section 10. Data sets that contain some invalid data but that meet the requirements of 8.5 can be used with data censoring (10.2.2). Remedies for excessive invalid data include (1) testing at a lower test temperature, (2) testing with larger specimens, or (3) testing more specimens to satisfy 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 the crack opening displacement. After a pop-in event, both the 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 should be treated as significant and the K_{Jc} value should 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 greater than 1 % depending on the specimen type.

9. Calculations

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

$$J_c = J_e + J_p \quad (8)$$

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

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

where:

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

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

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:

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

where:

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

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

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:

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

where:

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

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

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

and a_o = the initial crack size.

9.1.4 The plastic component of J is calculated as follows:

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

where:

$$A_p = A - 1/2 C_o P^2,$$

$$A = A_e + A_p \text{ (see Fig. 7),}$$

$$C_o = \text{reciprocal of the initial elastic slope, } \Delta V/\Delta P \text{ (Fig. 7),}$$

and

$$b_o = \text{initial remaining ligament.}$$

9.1.4.1 For standard and disk-shaped compact specimens, A is based on load-line displacement (LLD) and $\eta = 2 + 0.522 b_o^p/W$. 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.

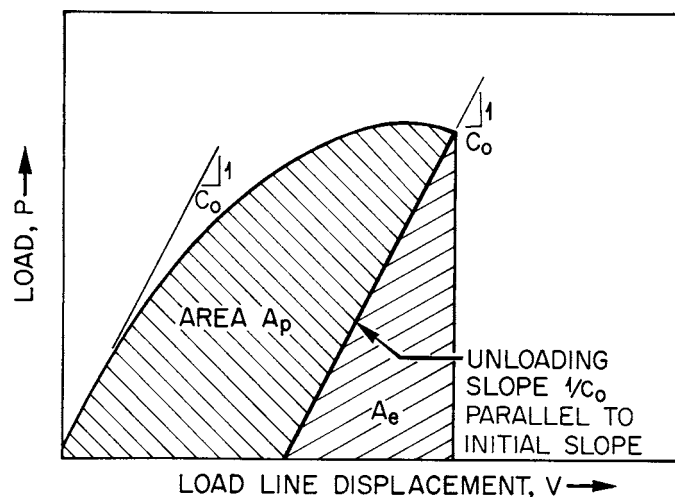


FIG. 7 Definition of the Plastic Area for J_p Calculations

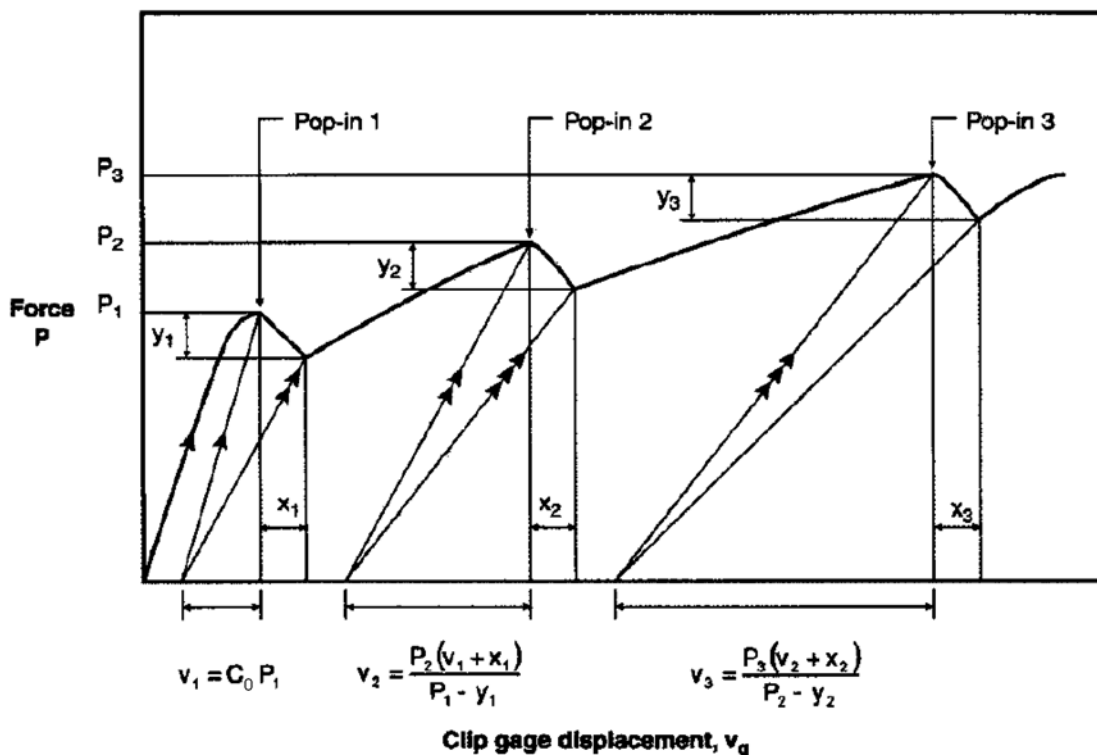
9.1.5 K_{Jc} is determined for each datum from J at onset of cleavage fracture, J_c . Assume plane strain for elastic modulus, E :

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

9.1.6 All data with K_{Jc} in excess of the limits prescribed in 8.9.2 are considered invalid, but values can be used in the censoring analysis that is described in 10.2.2 or 10.4.2 as

appropriate. Invalid data developed as a part of a data set disqualifies that data set for analysis by 10.2.1.

9.2 *Pop-in Evaluation*—Test records that can be used for K_{Jc} analyses are those that show complete specimen separation due to cleavage fracture and those that show pop-ins. As discussed in 8.9.5, if a force-displacement record shows a small but perceptible discontinuity that is characterized by a drop in force with a simultaneous increase in crack opening



NOTE— C_0 is the initial compliance

NOTE—The pop-ins have been exaggerated for clarity.

FIG. 8 Schematic of Pop-in Magnitude Evaluation

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 can be estimated⁷ 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 assessed⁸,
- 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.⁹
- y_n = force drop at the n th pop-in, and
- x_n = displacement increase at the n th pop-in.¹⁰

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 should be considered to be significant. When multiple pop-in events occur, $1 - C_o \cdot \left(\frac{P_i - y_i}{v_i + x_i} \right)$ should 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 should 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. The impact and character of this datum can be evaluated as follows. First determine the 2 % and 98 % tolerance bounds using the equations below:

$$K_{Jc(0.02)} = 0.415 K_{Jc(med)} + 11.70 \text{ MPa}\sqrt{\text{m}} \quad (18)$$

$$K_{Jc(0.98)} = 1.547 K_{Jc(med)} - 10.94 \text{ MPa}\sqrt{\text{m}}$$

If the suspected datum is outside the tolerance bounds dictated by Eqs. 17 (for example, $K_{Jc} < K_{Jc(0.02)}$ or $K_{Jc} > K_{Jc(0.98)}$) it may be possible to reduce the influence of the outlier datum on $K_{Jc(med)}$ by testing additional specimens. Typically, a total of 12 replicate specimens is sufficient. However, outliers shall not be discarded from the data utilized to calculate $K_{Jc(med)}$. The emergence of additional outliers may indicate that the test material is not homogeneous.

10. Prediction of Size Effects and Transition Temperature

10.1 Weibull Fitting of Data Sets:

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 When only one pop-in occurs, $n = 1$.

⁹ v_n may be determined graphically or analytically (see Fig. 8).

¹⁰ 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 (28).

10.1.1 Test Replication—A data set consists of at least six valid replicate test results determined at one test temperature, or the equivalent thereof; see also 8.5 for single temperature and 10.4 for multi-temperature requirements.

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

$$p_f = 1 - \exp\{ -[(K_{Jc} - K_{min})/(K_o - K_{min})]^b \} \quad (19)$$

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, when K_{min} is set at 20 MPa $\sqrt{\text{m}}$ (18.2 ksi $\sqrt{\text{in.}}$). The shape of the distribution is defined by the Weibull exponent, b , which tends to be near 4. Scale parameter, K_o , is the data fitting parameter determined when using the maximum likelihood statistical method of data fitting (29). When K_{Jc} and K_o in Eq 19 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 Eq 20 can be used to size adjust individual K_{Jc} values, $K_{Jc(med)}$, or K_o . K_{Jc} serves as the example case:

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

where:

- $K_{Jc(o)}$ = K_{Jc} for a specimen size B_o ,
- B_o = gross thickness of test specimens (side grooves ignored),
- B_x = gross thickness of prediction (side grooves ignored), and
- K_{min} = 20 MPa $\sqrt{\text{m}}$ (18.2 ksi $\sqrt{\text{in.}}$).

10.2 If K_{Jc} data replication is performed at a single test temperature, tests should be conducted as near as possible to an estimated T_o temperature. However, all data obtained at temperatures within the range $-50^\circ\text{C} \leq (T - T_o) \leq 50^\circ\text{C}$ shall be considered in the determination of T_o . Therefore, if testing is performed at more than one temperature, the multi-temperature procedure described in 10.4.2 shall be used. In this case, the combination of valid specimen numbers and test temperatures shall satisfy Eq 26 in 10.4.1. Iteration in terms of testing additional specimens may be required. For single-temperature tests, use 8.4 or 8.5 for test temperature estimation assistance. The following sections 10.2.1 and 10.2.2 can be used to calculate the scale parameter, K_o , for data developed at a single test temperature and consisting of at least six valid K_{Jc} values, or the equivalent thereof, see also 8.5. Data sets containing only valid data (as defined in 8.9.2) shall be analyzed as per 10.2.1. Paragraph 10.2.2 shall be applied if any invalid data (as defined in 8.9.2) exist.

10.2.1 *Determination of K_o with all Valid Data*—If the data are generated from specimens of other than 1T size, the data must first be converted to 1T size equivalence using Eq 20 (see section 3.3.20). The following Eq 21 shall be then applied to determine K_o :

$$K_o = \left[\sum_{i=1}^N \frac{(K_{Jc(i)} - K_{\min})^4}{N} \right]^{1/4} + K_{\min} \quad (21)$$

where:

N = number of specimens tested as defined in 8.9, and
 $K_{\min}$ = 20 MPa√m (18.2 ksi√in.).

See X1.2 for an example solution.

10.2.2 *Determination of K_o with Censored Data*—Replace all invalid K_{Jc} values with appropriate K_{Jc} censoring limits (8.9.2). If invalidity was due to violation of $K_{Jc\text{limit}}$, Eq. 1, the experimental K_{Jc} value shall be replaced by $K_{Jc\text{limit}}$ for the specimen sizes used. Determine $K_{Jc\text{limit}}$ at the test temperature using the material yield strength corresponding to that temperature. If invalidity was due to violation of $K_{Jc\Delta a}$, the K_{Jc} test value shall be replaced with the highest valid K_{Jc} in the data set for any specimen size because $K_{Jc\Delta a}$ should be size independent and also largely insensitive to test temperature. The K_J value corresponding to J_{Ic} also can be used for $K_{Jc\Delta a}$, if J_{Ic} is known for the test material. As specified in 8.9.2, if both $K_{Jc\text{limit}}$ and $K_{Jc\Delta a}$ are violated, replace the K_{Jc} test value with the lower of the two limits. All K_{Jc} data, including valid and censored values, must first be converted to 1T equivalence using Eq 20. The Weibull scale parameter, K_o , shall then be calculated using the following Eq 22. See section X1.3 for an example solution.

$$K_o = \left[\sum_{i=1}^N \frac{(K_{Jc(i)} - K_{\min})^4}{r} \right]^{1/4} + K_{\min} \quad (22)$$

where:

r = number of valid data as defined in 8.9,
 $K_{\min}$ = 20 MPa√m (18.2 ksi√in.), and
 N = number of data (valid and invalid).

10.2.3 *K_o to $K_{Jc(\text{med})}$ Conversion*—The scale parameter, K_o , calculated according to either, 10.2.1 or 10.2.2, corresponds to a 63 % cumulative probability level for specimen failure by cleavage. The median K_{Jc} of a data population corresponds to 50 % cumulative probability for fracture and $K_{Jc(\text{med})}$ can be determined from K_o using the following:

$$K_{Jc(\text{med})} = K_{\min} + (K_o - K_{\min}) [\ln(2)]^{1/4} \quad (23)$$

where:

$K_{\min}$ = 20 MPa√m (18.2 ksi√in.).

10.3 *Establishment of a Transition Temperature Curve (Master Curve)*—Transition temperature K_{Jc} data tend to conform to a common toughness versus temperature curve shape in the same manner as the ASME K_{Ic} and K_{IR} lower-bound design curves (30, 31). For this method, the shape of the median K_{Jc} toughness, $K_{Jc(\text{med})}$, for 1T specimens (3.3.20) is described by:

$$K_{Jc(\text{med})} = 30 + 70 \exp[0.019(T - T_o)], \text{ MPa}\sqrt{\text{m}}, \quad (24)$$

where:

T = test temperature (°C), and

T_o = reference temperature (°C).

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

10.3.2 *Determine Provisional Reference Temperature (T_{oQ})*—Use only 1T $K_{Jc(\text{med})}$ values, converted by Eq 20 if necessary.

$$T_{oQ} = T - \left(\frac{1}{0.019} \right) \ln \left[\frac{K_{Jc(\text{med})} - 30}{70} \right] \quad (25)$$

Units of $K_{Jc(\text{med})}$ are in MPa√m; units of T_{oQ} are in °C.
 $T_o = T_{oQ}$ if all validity requirements specified in this standard are satisfied as outlined in 10.5.

10.4 *Multi-temperature Option*—The reference temperature, T_o , should be relatively independent of the test temperature that has been selected. Hence, data that are distributed over a restricted temperature range, namely $T_o \pm 50^\circ\text{C}$, can be used to determine T_o . As it is with the single test temperature option, a minimum of six valid K_{Jc} data (8.9.2) or the equivalence, by weight factor, described in 10.4.1 below is required. In the case of data generated at test temperatures from 14°C below T_o to 50°C above T_o , the minimum requirement of six valid data will be satisfactory.

10.4.1 Data generated at test temperatures in the range of $T_o - 50$ to $T_o - 14^\circ\text{C}$ 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:

$$\sum_{i=1}^3 r_i n_i \geq 1 \quad (26)$$

where r_i is the number of valid specimens 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 6.

10.4.2 Replace all invalid K_{Jc} values with appropriate K_{Jc} censoring limits (8.9.2). If invalidity was due to violation of $K_{Jc\text{limit}}$, Eq. 1, the experimental K_{Jc} value shall be replaced by $K_{Jc\text{limit}}$ for the specimen sizes used. Determine $K_{Jc\text{limit}}$ at each test temperature using the material yield strength corresponding to that temperature. If invalidity was due to violation of $K_{Jc\Delta a}$, the K_{Jc} test value shall be replaced with the highest valid 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_J value corresponding to J_{Ic} also can be used for $K_{Jc\Delta a}$, if J_{Ic} is known for the test material. As specified in 8.9.2, if both $K_{Jc\text{limit}}$ and $K_{Jc\Delta a}$ are violated, replace the K_{Jc} test value with the lower of the two limits. All K_{Jc} data, including valid and censored values, must

TABLE 6 Weight Factors for Multi-Temperature Analysis

$(T - T_o)$ range ^A (°C)	1T $K_{Jc(\text{med})}$ range ^A (MPa√m)	Weight 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.

first be converted to 1T equivalence using Eq 20. The following equality shall then be used to determine the provisional T_{oQ} for tests conducted at multiple temperatures (29, 31):

$$\sum_{i=1}^N \delta_i \frac{\exp[0.019 (T_i - T_{oQ})]}{11 + 77 \exp[0.019 (T_i - T_{oQ})]} - \sum_{i=1}^N \frac{(K_{Jc(i)} - 20)^4 \exp[0.019 (T_i - T_{oQ})]}{\{11 + 77 \exp[0.019 (T_i - T_{oQ})]\}^5} = 0 \quad (27)$$

where:

- N = number of specimens tested,
- T_i = test temperature corresponding to $K_{Jc(i)}$,
- $K_{Jc(i)}$ = either a valid K_{Jc} datum or dummy value substitute for an invalid datum (8.9.2). All K_{Jc} input values, valid or dummy K_{Jc} , must be converted to 1T equivalence (3.3.20) before entry,
- δ_i = 1.0 if the datum is valid or zero if the datum is a dummy substitute value,
- 11 = integer equivalent of $10/(\ln 2)^{1/4}$ MPa $\sqrt{m}$, and
- 77 = integer equivalent of $70/(\ln 2)^{1/4}$ MPa $\sqrt{m}$.

Solve Eq 27 for T_{oQ} temperature by iteration.

10.4.3 Since the valid test temperature range is only known after T_o 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 using the value of “C” appropriate for the test specimen size. Conduct 3-4 valid tests at this temperature and evaluate an estimated T_o value ($T_{o(est)}$) value using 10.2 to determine K_o . Base all subsequent test temperatures on $T_{o(est)}$. See Appendix X3 for an example calculation.

10.4.4 Certain multi-temperature data sets may result in an oscillating iteration between two (or more) distinct T_o values upon satisfying the $T_o \pm 50^\circ\text{C}$ limit of 10.4. In these instances, the T_o value reported shall be the average of the calculated values. One example is for hypothetical data with toughness values such that the initial T_o estimation requires that data at one temperature be excluded. The second iteration then results in the inclusion of this same data. Subsequent T_o 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 $T_o \pm 50^\circ\text{C}$ limit. More testing near the average T_o will likely resolve this problem.

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 within 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 $T_{oQ} \pm 50^\circ\text{C}$, meets the requirement of Table 4 for single temperature testing. For multi-temperature analysis, the equivalent requirement is set by Eq 26 and the corresponding Table 6.

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

11.1.3 Visually measured slow-stable crack growth prior to onset of cleavage, if present,

11.1.4 Crack plane orientation according to Terminology E1823,

11.1.5 Test temperature or test temperatures as applicable,

11.1.6 Number of valid specimens (r) and total number of specimens (N) tested at each temperature,

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

11.1.8 Material yield strength and tensile strength, at the test temperatures,

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

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

11.1.11 Load-line displacement rate Δ and test loading rate $\dot{K}$ for testing rates outside the range defined in 8.7.1,

11.1.12 Reference temperature for master curve, T_o ($^\circ\text{C}$) or $T_{o,X}$ ($^\circ\text{C}$), and method used for calculation (single temperature or multi-temperature),

11.1.13 Fatigue precracking K_{max} for the final precracking step. The length is prescribed in 7.8.2, and

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

11.2 The report may contain the following supplementary information:

11.2.1 Specimen identification codes,

11.2.2 Measured pop-in crack extensions,

11.2.3 Provisional value T_{oQ} ($^\circ\text{C}$) and reason for invalidity, if applicable, and

11.2.4 Force-displacement, or for elevated loading rate tests, force-time and 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. A nuclear grade pressure vessel weld metal was tested using precracked Charpy, PCC, specimens (32,33). The results are summarized in 12.1.2. All the values of T_o used for the calculations satisfy the validity requirements of this test method.

12.1.1 *Justification and Theoretical Background*—The interlaboratory study analyzed here violates the following three fundamental assumptions of Practice E691:

- (1) Data are normally distributed.
- (2) Sample sizes within each laboratory are equal.
- (3) Standard deviations within each laboratory are equal.

Therefore, it is not appropriate to use this standard to determine the precision of this method. For the determination of T_o using data at a single temperature, the Paule-Mandel method (34) is used for analyzing the data since no assumptions about the statistical nature of the data (as in (1) – (3) above) are required. However, this method does not produce a single value of repeatability that is representative of all participating laboratories because equal within-laboratory standard deviations are not assumed. Thus, the minimum and maximum observed within-laboratory standard deviations among the participating laboratories are reported to provide repeatability information. For the determination of T_o using data at multiple temperatures, two statistical approaches have been used, the Paule-Mandel method and a statistical bootstrap technique. For the Paule-Mandel method (34), the within-laboratory standard deviations are estimated using Eq X4.4 of this test method. The statistical bootstrap technique (35, 36) is an alternate approach that used sub-sampling of the results from each individual laboratory to create subsets of data that have an equivalent number of test results. For the analysis of the multiple temperature data, the minimum and maximum values of the within-laboratory standard deviations are reported for both the Paule-Mandel and bootstrap methods.

12.1.2 An interlaboratory study (32, 33) for the determination of the Master Curve reference temperature, T_o , in accordance with ASTM Test Method E1921 was conducted among nine laboratories. The test material was weld 72W and all participants tested precracked Charpy-type (PCC) specimens. 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). For more details, see ASTM Research Report RR:E08-1008.¹¹

12.1.2.1 *Analysis of Single-Temperature Estimates of T_o* —The statistics reported in Table 7 were calculated for the single-temperature (that is, single-T) approach from test results obtained at various temperatures. The statistics reported have been calculated using the Paule-Mandel method (34). Individual T_o values are based on the number of valid data points reported by each laboratory at each test temperature. The number of valid 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 3—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 laboratories similar to those in the study.

12.1.2.2 *Analysis of Multi-Temperature Estimates of T_o* —The statistics reported in Table 8 were calculated for the multi-temperature (that is, multi-T) approach. The Paule-Mandel Method (34) was used to determine the reproducibility standard deviation and Eq X4.4 of this Test Method was used to determine the repeatability standard deviation.

NOTE 4—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 laboratories similar to those in the study.

In Table 9, repeatability and reproducibility measures for the multi-T analysis are based on a statistical bootstrap technique (35, 36). Subsampling of the data from each individual laboratory was performed until $\sum_{i=1}^3 r_i, n_i=1$ or $\sum_{i=1}^3 r_i, n_i=2$ for each subset of data (see 10.4.1 for details of the weighting system). Ten thousand subsets were generated for each laboratory. Using this technique, 2.5th and 97.5th percentiles (corresponding to two standard deviation limits) of the distribution of T_o values are reported instead of the standard reproducibility and repeatability limits.

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

¹¹ 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_p	Repeatability Limit, r	Reproducibility Limit, R
T_o , °C	Single-T	9	-75	(1.05, 12.05) ^A	5.05	(2.94, 33.74)	14.15

^AThe “Repeatability Standard Deviation” column contains minimum and maximum values of within-laboratory standard deviation observed for the data. These values do not strictly correspond to the repeatability standard deviation as defined in Practice E691. The mean within-laboratory standard deviation is 7.43. Individual within-laboratory standard deviations for each laboratory are given in ASTM Research Report RR:E08-1008.

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	-75	(3.42, 5.58) ^A	6.03	(9.58, 15.62)	17.21

^AMinimum and maximum values of within-laboratory standard deviation are based on Eq X4.4 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:E08-1008.

TABLE 9 Precision using PCC Specimens (Multi-T Analysis-Statistical Bootstrap)

Parameter	Type of Analysis	Number of Determinations	$\sum_{i=1}^3 r_i, n_i$	Repeatability Standard Deviation, s_r	2.5 th Percentile	97.5 th Percentile	Reproducibility Standard Deviation, s_R	2.5 th Percentile	97.5 th Percentile
T_o , °C	Multi-T	9	1	3.9 ^A 10.0 ^A	-81.6 ^B -75.8 ^B	-66.8 ^B -53.2 ^B	9.6	-90.7	-55.8
			2	2.3 ^A 5.8 ^A	-77.1 ^B -90.3 ^B	-68.5 ^B -70.1 ^B	7.6	-88.7	-60.4

^AThe “Repeatability Standard Deviation” column contains minimum and maximum values of within-laboratory standard deviation observed for the data. 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.

^BTwo values are reported for the 2.5th and 97.5th percentile respectively. These values correspond to the laboratories having the minimum and maximum repeatability standard deviation. Individual values for within-laboratory standard deviations and percentiles are provided in ASTM Research Report RR:E08-1008.

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

APPENDIXES

(Nonmandatory Information)

X1. WEIBULL FITTING OF DATA

X1.1 Description of the Weibull Model:

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

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

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. Scale parameter, K_o , is a data-fitting parameter. The procedure is described in X1.2.

X1.2 Determination of Scale Parameter, K_o , and Median

K_{Jc} —The following example illustrates the use of 10.2.1. The data came from tests that used 4T compact

specimens of A533 grade B steel tested at -75°C. All data are valid and the chosen equivalent specimen size for analysis will be 1T.

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

$$K_{o(1T)} = \left[\sum_{i=1}^N \frac{(K_{Jc(i)} - 20)^4}{N} \right]^{1/4} + 20 \quad (X1.2)$$

$$N = 6$$

$$K_{o(1T)} = 123.4 \text{ MPa}\sqrt{\text{m}}$$

X1.2.1 Median K_{Jc} is obtained as follows:

$$K_{Jc(\text{med})} = 20 + (K_{o(1T)} - 20) (0.9124) \text{ MPa}\sqrt{\text{m}} \quad (\text{X1.3})$$

$$= 114.4 \text{ MPa}\sqrt{\text{m}}$$

X1.2.2

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

$$= -85^\circ\text{C}$$

X1.3 Data Censoring Using the Maximum Likelihood Method:

X1.3.1 *Censoring When $K_{Jc\text{limit}}$ is Violated*—The following example uses 10.2.2 where all tests have been made at one test temperature. The example data set is artificially generated for a material that has a T_o reference temperature of 0°C . Two specimen sizes are 1/2T and 1T with six specimens of each size. Invalid K_{Jc} values and their dummy replacement $K_{Jc\text{limit}}$ values will be within parentheses.

X1.3.2 The data distribution is developed with the following assumptions:

Material yield strength = 482 MPa or 70 ksi
 T_o temperature = 0°C
 Test temperature = 38°C
 1/2T and 1T specimens; all $a/W = 0.5$

X1.3.3 $K_{Jc\text{limit}}$ values in $\text{MPa}\sqrt{\text{m}}$ from Eq 1.

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

X1.3.4 Simulated Data Set:

Raw Data (K_{Jc} , $\text{MPa}\sqrt{\text{m}}$)		Size Adjusted ($K_{Jc(1T)}$, $\text{MPa}\sqrt{\text{m}}$)	
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

$$^A K_{Jc(1T)} = (K_{Jc(0.5T)} - 20) (1/2 / 1)^{1/4} + 20 \text{ MPa}\sqrt{\text{m}}$$

$$K_{o(1T)} = \left[\sum_{i=1}^N \frac{(K_{Jc(i)} - 20)^4}{r} \right]^{1/4} + 20 \quad (\text{X1.5})$$

where:

$$\begin{aligned} N &= 12, \\ r &= 9, \\ K_{o(1T)} &= 188 \text{ MPa}\sqrt{\text{m}}, \\ K_{Jc(\text{med})} &= 174 \text{ MPa}\sqrt{\text{m}}, \text{ and} \\ T_o = T_{oQ} &= 0^\circ\text{C}. \end{aligned}$$

X1.3.5 *Censoring When $\Delta a_p \leq 0.05(W - a_p)$, not to Exceed 1 mm Limit is Violated*—The following example uses 10.2.2 where all tests have been made at a single test temperature of 38°C . Assume that 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 0.5T and 1T specimen respectively. The K_{Jc} value after 0.64 mm of slow-stable growth is only 197 $\text{MPa}\sqrt{\text{m}}$ and after 1 mm of slow-stable growth is only 202 $\text{MPa}\sqrt{\text{m}}$. Therefore, the crack growth limit controls all censoring. The K_{Jc} - R curve is specimen size independent so that both 0.5T and 1T specimens will have censored data. In this case the dummy replacement value as per 10.2.2 is the highest ranked valid K_{Jc} value.

Raw Data				1T Size Adjusted Data	
0.5T		1T		0.5T ^A	1T
Δa_p , mm	K_{Jc} , $\text{MPa}\sqrt{\text{m}}$	Δa_p , mm	K_{Jc} , $\text{MPa}\sqrt{\text{m}}$	K_{Jc} , $\text{MPa}\sqrt{\text{m}}$	
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)

$$^A K_{Jc(1T)} = K_{Jc(0.5T)} - 20) \cdot (0.5 / 1)^{1/4} + 20 \text{ MPa}\sqrt{\text{m}}$$

$$K_{o(1T)} = \left[\sum_{i=1}^N \frac{(K_{Jc(i)} - 20)^4}{r} \right]^{1/4} + 20 \quad (\text{X1.6})$$

where:

$$\begin{aligned} N &= 12, \\ r &= 7, \\ K_{o(1T)} &= 186 \text{ MPa}\sqrt{\text{m}}, \\ K_{Jc(\text{med})} &= 171 \text{ MPa}\sqrt{\text{m}}, \text{ and} \\ T_o = T_{oQ} &= 1^\circ\text{C}. \end{aligned}$$

X2. MASTER CURVE FIT TO DATA

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

X2.1.1 Six $\frac{1}{2}$ T compact specimens,

X2.1.2 A533 grade B base metal, and

X2.1.3 Test temperature, $T = -75^\circ\text{C}$.

X2.2 In this data set, there are no censored data.

Rank (<i>i</i>)	$K_{Jc(1/2T)}$ (MPa $\sqrt{\text{m}}$)	$K_{Jc(1T)}$ Equivalent (MPa $\sqrt{\text{m}}$)
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 using Eq X1.2:*

$K_{o(1T)} = 115.8 \text{ MPa}\sqrt{\text{m}}$, and

$K_{Jc(\text{med})} = [\ln(2)]^{1/4} (K_o - 20) + 20 = 107.4 \text{ MPa}\sqrt{\text{m}}$.

X2.4 *Position Master Curve:*

$$T_o = T_{oQ} = T - \left(\frac{1}{0.019} \right) \ln \left[\frac{K_{Jc(\text{med})} - 30}{70} \right] \quad (\text{X2.1})$$

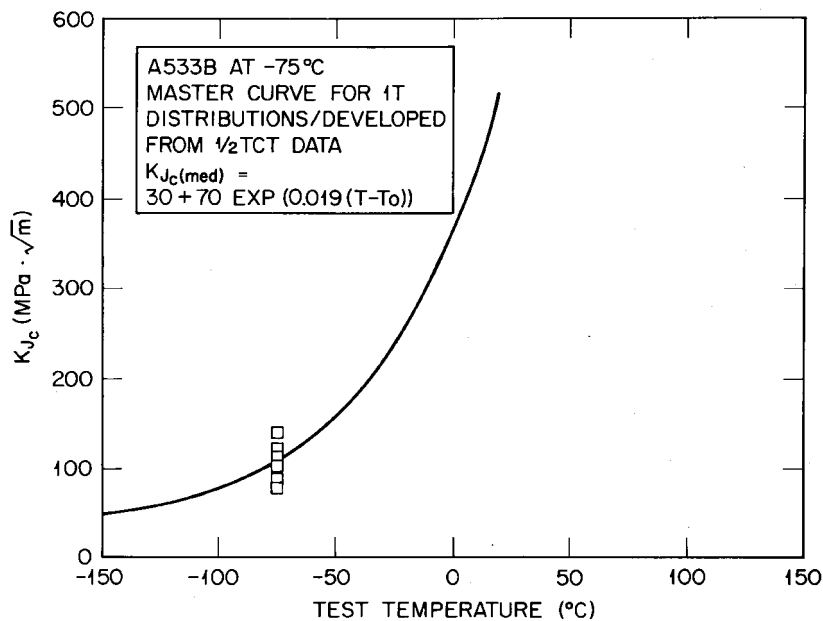
$$= -75 - \ln[(108.5 - 30)/70]/0.019 = -80^\circ\text{C}.$$

X2.5 *Master Curve:*

$$K_{Jc(\text{med})} = 30 + 70 \exp[0.019(T + 80)] \quad (\text{X2.2})$$

X2.5.1 See Fig. X2.1.

X3. EXAMPLE MULTITEMPERATURE T_o DETERMINATION



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

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

X3.1 *Material:*

A533 Grade B plate

Quenched and tempered

900°C WQ; and 440°C (5 h) temper

X3.2 *Mechanical Properties:*

Yield strength: 641 MPa (93 ksi)

Tensile strength: 870 MPa (117.5 ksi)

Charpy V:

28-J temperature = -5°C (23°F)

41-J temperature = 16°C (61°F)

NDT: 41°C (106°F)

X3.3 *K_{Jc} Limit Values:*

Specimen Types:

1/2T C(T) with $a_o/W = 0.5$

1T SE(B) with $a_o/W = 0.5$

Test Temperature (°C)	Yield Strength (MPa)	$K_{Jc\text{limit}}$ (MPa $\sqrt{\text{m}}$)	
		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:*

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

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

X3.5 Estimation Procedure #1 from Charpy Curve:

$$T_{o(est)} = T_{28J} + C = -5^{\circ} - 18^{\circ} = -23^{\circ}\text{C}$$

$$T_{o(est)} = T_{41J} + C = 16^{\circ} - 24^{\circ} = -8^{\circ}\text{C}$$

Conduct four 1T SE(B) tests at -20°C .

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

First four tests at -20°C :

$$K_{Jc}, \text{ MPa}\sqrt{\text{m}}$$

135.1
108.9
177.1
141.7

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

$$K_{Jc(\text{med})} = 137 \text{ MPa}\sqrt{\text{m}};$$

$$T_{0(est)\#2} = -42^{\circ}\text{C}$$

Estimated temperature range or usable data:

$$= T_{0(est)\#2} \pm 50^{\circ}\text{C}$$

$$= -92^{\circ}\text{C} < T_i < +8^{\circ}\text{C}$$

Now conduct additional testing within this range for T_o determination. Data is contained in [Table X3.1](#).

X3.7 Calculation of T_{oQ} :

Use data between -92°C and 8°C based on $T_{o(est)\#2}$

$$\text{From } e00002 \text{ } T_{oQ} = -48^{\circ}\text{C}$$

The valid test temperature range is -98°C to 2°C . Original calculations were performed with data in this regime. Therefore, no iteration is required.

TABLE X3.1 Data Tabulation

Test temperature, (°C)	Specimen		K_{Jc} (MPa√m)		δ_i
	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
			73.9	73.9	1
-65	SE(B)	1T	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
-30	C(T)	1/2T	70.0	62.0	1
			131.8	114.0	1
			69.5	61.6	1
			67.5	59.9	1
			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
			211.4	180.9	1
-10	C(T)	1/2T	179.9	154.5	1
			171.8	147.6	1
			153.0	131.8	1
			236.9	(204)	0
			156.8	135	1
			121.5	105.3	1
			194.2	166.5	1
			110.4	96.0	1
-5	C(T)	1/2T	197.0	168.8	1
			134.7	116.5	1
			264.4	(203)	0
			277.8	(198.9)	0
			218.9	187.2	1
			107.7	93.7	1
			269.3	(203)	0
			327.1	(203)	0
0	C(T)	1/2T	325 ^A	(202)	0
			328 ^A	(202)	0
			227	194	1
23	C(T)	1/2T			

^A R-curve (no cleavage instability).

X3.8 Qualified Data Summation:

($T - T_o$) range (°C)	Number of valid tests, r_i	Weight 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

Validity check:

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

Therefore, $T_{oQ} = T_o$

X4. CALCULATION OF TOLERANCE BOUNDS

X4.1 The standard deviation of the fitted Weibull distribution is a mathematical function of Weibull slope, $K_{Jc(med)}$, and K_{min} , and because two of these are constant values, the standard deviation is easily determined. Specifically, with slope b of 4 and $K_{min} = 20 \text{ MPa}\sqrt{\text{m}}$, standard deviation is defined by the following (37):

$$\sigma = 0.28 K_{Jc(med)} [1 - 20/K_{Jc(med)}] \quad (\text{X4.1})$$

X4.1.1 *Tolerance Bounds*—Both upper and lower tolerance bounds can be calculated using the following equation:

$$K_{Jc(0.xx)} = 20 + \left[\ln \left(\frac{1}{1 - 0.xx} \right) \right]^{1/4} \{ 11 + 77 \exp[0.019(T - T_o)] \} \quad (\text{X4.2})$$

where the temperature “T” is the independent variable of the equation; xx represents the selected cumulative probability level; for example, for 2 % tolerance bound, $0.xx = 0.02$. As an example, the 5 and 95 % bounds on the Appendix X2 master curve are:

$$K_{Jc(0.05)} = 25.2 + 36.6 \exp[0.019(T + 80)] \quad (\text{X4.3})$$

$$K_{Jc(0.95)} = 34.5 + 101.3 \exp[0.019(T + 80)]$$

X4.1.2 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 X4.3. Margin is added to cover the uncertainty in T_o that is associated with the use of only a few specimens to establish T_o . 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:

$$\sigma = \sqrt{\frac{\beta^2}{r} + \sigma_{exp}^2} \quad (\text{X4.4})$$

where:

- β = sample size uncertainty factor
- r = total number of valid specimens used to establish the value of T_o .
- σ_{exp} = contribution of experimental uncertainties. If standard calibration practices are followed, $\sigma_{exp} = 4^\circ\text{C}$ may be used.

X4.2.1 An equivalent value of the median toughness for a data set, $K_{Jc(med)}^{eq}$, is defined as (38):

$$K_{Jc(med)}^{eq} = \frac{1}{r} \sum_{i=1}^r 30 + 70 \exp(0.019(T_i - T_o)) \quad (\text{X4.5})$$

When $K_{Jc(med)}^{eq}$ is equal to or greater than $83 \text{ MPa}\sqrt{\text{m}}$, $\beta = 18^\circ\text{C}$ (39). If the 1T equivalent $K_{Jc(med)}^{eq}$ is below $83 \text{ MPa}\sqrt{\text{m}}$, values of β must be increased according to the following schedule:

$K_{Jc(med)}^{eq}$ 1T equivalent ^A ($\text{MPa}\sqrt{\text{m}}$)	β ($^\circ\text{C}$)
83 to 66	18.8
65 to 58	20.1

^A Round off $K_{Jc(med)}^{eq}$ 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

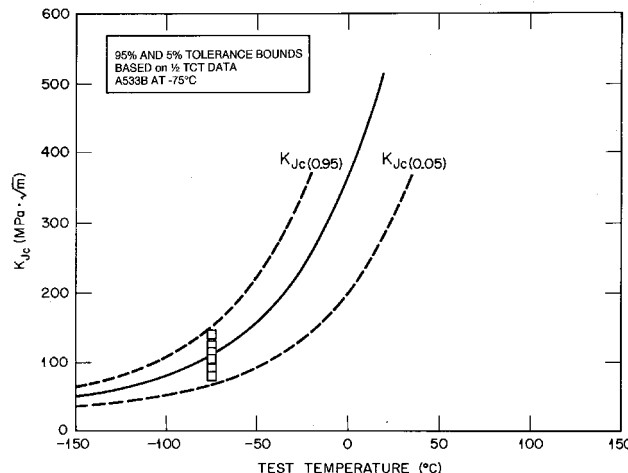


FIG. X4.1 Master Curve With Upper and Lower 95 % Tolerance Bounds

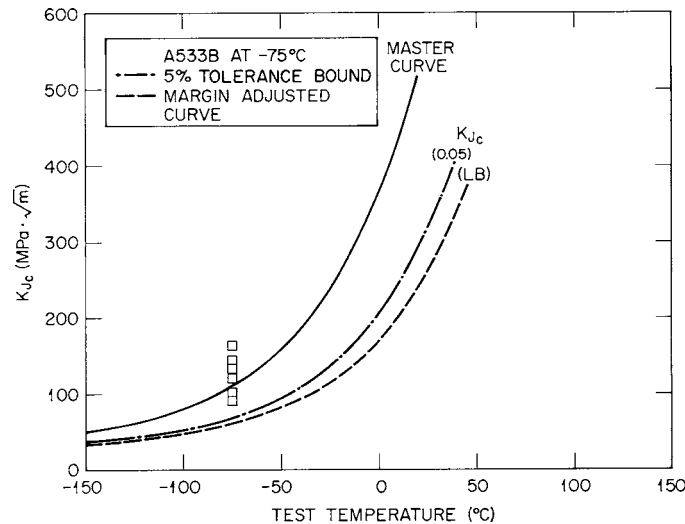


FIG. X4.2 Master Curve Showing the Difference Between 5 % Tolerance Bound and Lower Bound That Includes 85 % Confidence Margin on T_o

example calculation is for 85 % confidence (two-tail) adjustment to Eq X4.3 for the six specimens used to determine T_o .

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

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

Then the margin-adjusted 5 % tolerance bound of Eq X4.3 is revised to:

$$K_{Ic(05)} = 25.2 + 36.6 \exp[0.019(T + 68)] \quad (\text{X4.7})$$

Eq X4.7 is plotted in Fig. X4.2 as the dashed line (L.B.).

REFERENCES

- (1) Gao, X, and Dodds, R. H., "Constraint Effects on the Ductile-to-Cleavage Transition Temperature of Ferritic Steels: A Weibull Stress Model," *International Journal of Fracture*, 102, 2000, pp. 43-69.
- (2) Wallin, K., Planman, T., Valo, M., and Rintamaa, R., "Applicability of Miniature Size Bend Specimens to Determine the Master Curve Reference Temperature T_o ," *Engineering Fracture Mechanics*, Vol 68, 2001, pp. 1265-1296.
- (3) Joyce, J. A., and Tregoning, R. L., "Investigation of Specimen Geometry Effects and Material Inhomogeneity Effects in A533B Steel," *ECF 14—Fracture Mechanics Beyond 2000, Proceedings of the 14th European Conference on Fracture*, Cracow, September 2002.
- (4) Anderson, T. L., Steinstra, D., and Dodds, R. H., "A Theoretical Framework for Addressing Fracture in the Ductile-Brittle Transition Region," *Fracture Mechanics*, 24th Volume, *ASTM STP 1207*, ASTM, 1994, pp. 185-214.
- (5) Ruggeri, C., Dodds, R.H., and Wallin, K., "Constraint Effects on Reference Temperature, T_o , for Ferritic Steels in the Transition Region," *Engineering Fracture Mechanics*, 60(1), 1998, pp. 19-36.
- (6) Paris, P. C., "Fracture Mechanics in the Elastic-Plastic Regime," *Flaw Growth in Fracture*, *ASTM STP 631*, ASTM, August 1976, pp. 3-27.
- (7) Turner, C. E., "The Eta Factor," *Post Yield Fracture Mechanics*, Second Ed., Elsevier Applied Science Publishers, London and New York, 1984, pp. 451-459.
- (8) McCabe, D. E., *Evaluation of Crack Pop-ins and the Determination of their Relevance to Design Considerations*, NUREG/CR-5952 (ORNL/TM-12247), February 1993.
- (9) Wallin, K., "The Scatter in K_{Ic} Results," *Engineering Fracture Mechanics*, 19(6) (1984), pp. 1085-1093.
- (10) McCabe, D. E., Zerbst, U., and Heerens, J., "Development of Test Practice Requirements for a Standard Method of Fracture Toughness Testing in the Transition Range," *GKSS Report 93/E/81*, GKSS Forschungszentrum, Geesthacht, GmbH, Germany, 1993.
- (11) Steinstra, D. I. A., "Stochastic Micromechanical Modeling of Cleavage Fracture in the Ductile-Brittle Transition Region," MM6013-90-11, Ph.D. Thesis, Texas A & M University, College Station, TX, August 1990.
- (12) Wallin, K., "A Simple Theoretical Charpy V- K_{Ic} Correlation for Irradiation Embrittlement," *ASME Pressure Vessels and Piping Conference, Innovative Approaches to Irradiation Damage and Fracture Analysis*, PVP-Vol 170 , American Society of Mechanical Engineers, New York, July 1989.
- (13) Heerens, J., Read, D. T., Cornec, A., and Schwalbe, K.-H., "Interpretation of Fracture Toughness in the Ductile-to-Brittle Transition Region by Fractographical Observations," *Defect Assessment in Components - Fundamentals and Applications*, J. G. Blauel and K. H. Schwalbe, eds.,ESIS/EGF9, Mechanical Engineering Publications, London, 1991, pp. 659-78.
- (14) Landes, J. D., and McCabe, D. E., "Effect of Section Size on Transition Temperature Behavior of Structural Steels," *Fracture Mechanics: Fifteenth Symposium*, *ASTM STP 833*, ASTM, 1984, pp. 378-392.
- (15) Wallin, K., "Recommendations for the Application of Fracture Toughness Data for Structural Integrity Assessments," *Proceedings of the Joint IAEA/CSNI Specialists Meeting on Fracture Mechanics Verification by Large-Scale Testing*, NUREG/CP-0131 (ORNL/TM-12413), October 1993, pp. 465-494.
- (16) Petti, J.P., and Dodds, R.H., Jr., "Constraint Comparisons for Common Fracture Specimens: C(T)s and SE(B)s," *Engineering Fracture Mechanics*, Vol. 71, 2004, pp. 2677 – 2683.

- (17) Joyce, J. A., and Tregoning, R. L., "Determination of Constraint Limits for Cleavage Initiated Toughness Data," *Engineering Fracture Mechanics*, Vol. 72, Issue 10, July 2005, pp. 1559-1579.
- (18) Nanstad, R.K., et. al., "IAEA Coordinated Research Project on Master Curve Approach to Monitor Fracture Toughness of RPV Steels: Final Results of the Experiment Exercise to Support Constraint Effects," *Proceedings of PVP2009*, 2009 ASME Pressure Vessels and Piping Division Conference, July 26-30, 2009, Prague, Czech Republic.
- (19) Zhu, X. K., Leis, B.N., and Joyce, J.A., "Experimental Estimation of J-R Curves for Load-CMOD Records for SE(B) Specimens" *Journal of ASTM International*, Vol 5 No.5 March 2008.
- (20) Scibetta, M., "3-D Finite Element Simulation of the PCCv Specimen Statically Loaded in Three-Point Bending," (report R-3440) report BLG-860, SCK·CEN Mol, Belgium, March 2000.
- (21) Schwalbe, K. H., Hellmann, D., Heerens, J., Knaack, J., and Mueller-Roos, J., "Measurement of Stable Crack Growth Including Detection of Initiation of Growth Using Potential Drop and Partial Unloading Methods," *Elastic-Plastic Fracture Test Methods, Users Experience*, ASTM STP 856, ASTM, 1983, pp. 338-62
- (22) Landes, J. D., "J Calculation from Front Face Displacement Measurements of a Compact Specimen," *International Journal of Fracture*, Vol 16, 1980, pp. R183-86.
- (23) Sokolov, M. A., and Nanstad, R. K., "Comparison of Irradiation-Induced Shifts of K_{IC} and Charpy Impact Toughness for Reactor Pressure Vessel Steels," in *Effects of Radiation on Materials: 18th International Symposium*, ASTM STP 1325, R. K. Nanstad, M. L. Hamilton, F. A. Garner, and A. S. Kumar, Eds., American Society for Testing and Materials, West Conshohocken, PA, 1999, pp. 167-190.
- (24) Wallin, K., "Effect of Strain Rate on the Fracture Toughness Reference Temperature T_0 for Ferritic Steels", in *Recent Advances on Fracture*, R.K. Mahidhara, A.B. Geltmacher and K. Sadananda, eds., The Mineral, Metals, & Materials Society, 1997
- (25) Joyce, J. A., Tregoning, R.L., and Roe, C., "On Setting Testing Rate Limitations for the Master Curve Reference Temperature, T_0 , of ASTM E1921", *Journal of Testing and Evaluation*, Mar 2006, Vol. 34, No. 2.
- (26) Irwin, G.R., "Crack-Toughness Testing of Strain Rate Sensitive Materials", *Transactions of the ASME Journal of Engineering for Power*, Oct. 1964, pp. 444-450.
- (27) Shoemaker, A.K., "Factors Influencing the Plane-Strain Crack Toughness Values of a Structural Steel," *Transactions of the ASME, Journal of Basic Engineering*, Sept. 1969, pp. 506-511.
- (28) Pisarki, H.G., "Measurement of Heat Affected Zone Fracture Toughness," Paper TS31, *Steel in Marine Structures*, C. Noordhoek and J. De Back, eds., Proceedings of 3rd International ECSC Conference, Delft, June 15-18, 1987, Elsevier Science Publishers B.V., Amsterdam, pp. 647 - 656.
- (29) Wallin, K., "Validity of Small Specimen Fracture Toughness Estimates Neglecting Constraint Corrections," in *Constraint Effects in Fracture: Theory and Applications*, ASTM STP 1244, M. Kirk and A. Bakker, eds., ASTM, 1994, pp. 519-537.
- (30) ASME Boiler and Pressure Vessel Code. An American National Standard, Sect. XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," Article A-4000, American Society of Mechanical Engineers, New York, 1993.
- (31) Merkle, J. G., Wallin, K., and McCabe, D. E., *Technical Basis for an ASTM Standard on Determining the Reference Temperature, T_0 , for Ferritic Steels in the Transition Range*, NUREG/CR-5504 (ORNL/TM-13631), November 1998.
- (32) Van Der Sluys, W. A., Merkle, J. G., Young B. M., Yoon K. K., Hall B., Higuchi M., and Iida K., Indexing Fracture Toughness Data, Part 1: Results from the MPC Cooperative Test Program on the Use of Precracked Charpy Specimens for To Determination, WRC Bulletin 486, New York, Welding Research Council, Inc., Nov 2003 .
- (33) Van Der Sluys, W. A., Merkle, J. G., and Young B., Results from the MPC Cooperative Test Program on the Use of Precracked Charpy Specimens for To Determination, *Fatigue and Fracture Mechanics*: 33rd Volume, ASTM STP 1417, W. G. Reuter and R. S. Piascik, Eds., ASTM International, West Conshohocken, PA, 2002, pp. 689-714.
- (34) Mandel, J., Evaluation and Control of Measurements, *Quality and Reliability Series*, Marcel Dekker, New York, 1991 (Sections 4.4-4.5).
- (35) Efron, B., Bootstrap Methods: Another Look at the Jackknife, *The Annals of Statistics* 7 (1), pp. 1-26 (1979).
- (36) Efron, B., and Tibshirani, R., *An Introduction to the Bootstrap*, Chapman & Hall/CRC, Boca Raton, FL (1993).
- (37) Johnson, L. G., *The Statistical Treatment of Fatigue Experiments*, Elsevier, NY, 1957.
- (38) Lucon, E., Scibetta, M. and van Walle, E., "Assessment of the Master Curve approach on three reactor pressure vessel steels", *International Journal of Fracture* 119: 161-178, 2003.
- (39) Wallin, K., Master Curve Analysis of Ductile to Brittle Transition Region Fracture Toughness Round Robin Data (The Euro Fracture Toughness Curve), VTT Technical Document 367.58P, Espoo, Finland, 1998.

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