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INTERNATIONAL

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Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range[1]

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

1. Scope

1.1 This test method covers the determination of a reference temperature, T_0, 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 (3.2.2) covered are those with yield strengths ranging from 275 MPa to 825 MPa (40 ksi 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_0 values as a function of specimen type for the same material. T_0 values obtained from C(T) specimens are expected to be higher than T_0 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_0 values is approximately 10°C (**2**). C(T) and SE(B) T_0 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_0 results which fall between the T_0 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_0 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_0 is dependent on loading rate. T_0 is evaluated for a quasi-static loading rate range with 0.1< dK/dt < 2 MPa√m/s. Slowly loaded specimens (dK/dt < 0.1 MPa√m) can be analyzed if environmental effects are known to be negligible. Provision is also made for higher loading rates (dK/dt > 2 MPa√m/s) in Annex A1. Note that this threshold loading rate for application of Annex A1 is a much lower threshold than is required in other fracture toughness test methods such as E399 and E1820.

1.6 The statistical effects of specimen size on K_{Jc} in the transition range are treated using the weakest-link theory (**4**) applied to a three-parameter Weibull distribution of fracture toughness values. A limit on K_{Jc} values, relative to the specimen size, is specified to ensure high constraint conditions along the crack front at fracture. For some materials, particularly those with low strain hardening, this limit may not be sufficient to ensure that a single-parameter (K_{Jc}) adequately describes the crack-front deformation state (**5**).

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

1.8 The procedures described in this test method assume that the data set represents a macroscopically homogeneous material, such that the test material has uniform tensile and toughness properties. Application of this test method to an inhomogeneous material will result in an inaccurate estimate of the transition reference value T_0 and nonconservative confidence bounds. For example, multi-pass weldments can create heat-affected and brittle zones with localized properties that are

[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.

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quite different from either the bulk or weld materials. Thick-section steels also often exhibit some variation in properties near the surfaces. Metallography and initial screening may be necessary to verify the applicability of these and similarly graded materials. Section 10.6 provides a screening criterion to assess whether the data set may not be representative of a macroscopically homogeneous material, and therefore, may not be amenable to the statistical analysis procedures employed in this test method. If the data set fails the screening criterion in 10.6, the homogeneity of the material and its fracture toughness can be more accurately assessed using the analysis methods described in Appendix X5.

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

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

2. Referenced Documents

2.1 *ASTM Standards:*[3]

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

2.2 *ASME Standards:*[4]

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

3. Terminology

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

3.2 *Definitions:*

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

3.2.1.1 *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:

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

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

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

3.2.3 *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.

3.2.3.1 *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 7.8.1 to stipulate allowable precracking limits.

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

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

3.3.4 *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.

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

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

3.3.6.1 *Discussion*—In this test method, K_J also implies a

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

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

stress intensity factor determined at the test termination point under conditions that require censoring the data by 8.9.2.

3.3.7 *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.

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

3.3.9 *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**).

3.3.10 *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.

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

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

3.3.13 *pop-in*—a discontinuity in a force versus displacement test record (**8**).

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

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

3.3.15 *provisional reference temperature, (T_{0Q}) [°C]*—Interim T_0 value calculated using the standard test method described herein. T_{0Q} is validated as T_0 in 10.5.

3.3.16 *reference temperature, T_0 [°C]*—The test temperature at which the median of the K_{Jc} distribution from 1T size specimens will equal 100 MPa√m (91.0 ksi√in.).

3.3.17 *SE(B) specimen span, S [L]*—the distance between specimen supports (See Test Method E1820 Fig. 4).

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

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

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

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

3.3.20 *temperature, T_Q [°C]*—For K_{Jc} values that are developed using specimens or test practices, or both, that do not conform to the requirements of this test method, a temperature at which $K_{Jc\ (med)}$ = 100 MPa√m is defined as T_Q. T_Q is not a provisional value of T_0.

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

3.3.22 *Weibull fitting parameter, K_0*—a scale parameter located at the 63.2 % cumulative failure probability level (**9**). $K_{Jc} = K_0$ when $p_f = 0.632$.

3.3.23 *Weibull slope, b*—with p_f and K_{Jc} data pairs plotted in linearized Weibull coordinates obtainable by rearranging Eq 21, *b* is the slope of a line that defines the characteristics of the typical scatter of K_{Jc} data.

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

3.3.24 *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.

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

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

4. Summary of Test Method

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

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

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

4.5 For the definition of the toughness transition curve, a master curve concept is used (**11, 12**). The position of the curve on the temperature coordinate is established from the experimental determination of the temperature, designated T_0, at which the median K_{Jc} for 1T size specimens is 100 MPa√m (91.0 ksi√in.). Selection of a test temperature close to that at which the median K_{Jc} value will be 100 MPa√m is encouraged