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

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

ε^1 NOTE—Editorial changes were made throughout in October 2008.

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.

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, multipass weldments can create heat-affected and brittle zones with localized properties that are quite different from either the bulk material or weld. Thick section steel also often exhibits some variation in properties near the surfaces. 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]

E 4 Practices for Force Verification of Testing Machines

E 8/E 8M Test Methods for Tension Testing of Metallic Materials

E 23 Test Methods for Notched Bar Impact Testing of Metallic Materials

E 74 Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines

E 208 Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels

E 399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials

E 436 Test Method for Drop-Weight Tear Tests of Ferritic Steels

E 561 Test Method for ***K-R*** Curve Determination

E 1820 Test Method for Measurement of Fracture Toughness

E 1823 Terminology Relating to Fatigue and Fracture Testing

3. Terminology

3.1 Terminology given in Terminology E 1823 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 E 23, E 208 and E 436.

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

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

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

3.2.4 *J-integral, $J[FL^{-1}]$*—a mathematical expression; a line or surface integral that encloses the crack front from one crack surface to the other; used to characterize the local stress-strain field around the crack front (**6**). See Terminology E 1823 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 E 1820, 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, $E_e[FL^{-2}]$*—an elastic modulus that can be used with experimentally determined elastic compliance to effect an exact match to theoretical (modulus-normalized) compliance for the actual initial crack size, a_o.

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

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

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

3.3.5 *elastic modulus, $E'[FL^{-2}]$*—a linear-elastic factor relating stress to strain, the value of which is dependent on the degree of constraint. For plane stress, $E' = E$ is used, and for plane strain, $E/(1 - \nu^2)$ is used, with E being Young's modulus and ν being Poisson's ratio.

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

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

3.3.7.1 *Discussion*—In this test method, K_J also implies a stress intensity factor determined at the test termination point under conditions 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, $K^{eq}_{Jc(med)}$* $[FL^{-3/2}]$—an equivalent value of the median toughness for a multi-temperature data set.

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

3.3.13 *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] 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.

3.3.14.1 *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 specimen*—SE(B) specimen with $W = B = 10$ mm (0.394 in.).

3.3.16 *provisional reference temperature,* (T_{oQ}) [°C]—Interim T_o value calculated using the standard test method described herein. If all validity criteria are met then $T_o = T_{oQ}$

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

3.3.18 *SE(B) specimen span, S[L]*—the distance between specimen supports (See Test Method E 1820 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 *stress intensity factor rate* $\dot{K}$[$FL^{-3/2}T^{-1}$]—rate of increase of applied stress intensity factor.

3.3.22 *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$\sqrt{m}$ is defined as T_Q. T_Q is not a provisional value of T_o.

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

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

3.3.25 *Weibull slope, b*—with p_f and K_{Jc} data pairs plotted in linearized Weibull coordinates obtainable by rearranging Eq. 15, *b* is the slope of a line that defines the characteristics of the typical scatter of K_{Jc} data.

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

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

4. Summary of Test Method

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

4.2 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$\sqrt{m}$ (91.0 ksi$\sqrt{in.}$). Selection of a test temperature close to that at which the median K_{Jc} value will be 100 MPa$\sqrt{m}$ is encouraged and a means of estimating this temperature is suggested. Small specimens such as precracked Charpy's may have to be tested at temperatures below T_o where $K_{Jc(med)}$ is well below 100 MPa$\sqrt{m}$. In such cases, additional specimens may be required as stipulated in 8.5.

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

5. Significance and Use

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

5.2 Ferritic steels are inhomogeneous with respect to the orientation of individual grains. Also, grain boundaries have properties distinct from those of the grains. Both contain carbides or nonmetallic inclusions 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