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Preface

THE PRESENT MANUAL IS WRITTEN AS EDUCATIONAL MATERIAL FOR non-specialists in the field of fracture mechanics. The intention is to introduce a concept that can be understood and used by engineers who have had limited exposure to elastic-plastic fracture mechanics and/or advanced statistical methods. Such subjects are covered in detail in USNRC NUREG/CR-5504 [1].

Section 2 explains why the application of fracture mechanics to ordinary structural steels has been delayed for so long. Underlying the explanation is a problem with a technical subject matter that has become, to a degree, unnecessarily esoteric in nature. The Master Curve method, on the other hand, addresses the practical design related problem of defining the ductile to brittle fracture transition temperature of structural steels directly in terms of fracture mechanics data. Section 2 describes the evolution of the method from a discovery phase to the development of a technology that can be put to practical engineering use (see Note 1).

Note 1—Section 2 denotes stress intensity factors as K_{Ic} or K_{Jc}. The former implies linear elastic and the latter elastic-plastic stress intensity factor properties. K_{Ic} also implies that larger specimens had to be used.

Section 3 explains the data validity requirements imposed on test data and the number of data required to constitute a statistically useable data set for determining a reference temperature, T_o. The temperature, T_o, has a specific physical meaning with regard to the fracture mechanics properties of a material.

Section 4 describes the test specimens that can be used to develop valid K_{Jc} data. The recommended specimen designs optimize the conditions of constraint, while at the same time they require the least amount of test material to produce a valid K_{Jc} fracture toughness value. Care is taken to explain why certain other specimen types would be unsuitable for this type of work.

Section 5 presents, in simple terms, the fixturing and test equipment needs. Detailed descriptions are not necessary in the present manual, since *The Annual Book of ASTM Standards*, Volume 03.01, has several standard methods that present detailed information on fixtures that have been used successfully for the past 30 years. However, some of the lesser-known details relative to experience in the use of this equipment for transition temperature determination are presented herein.

Section 6 covers preparation of specimens for testing. The pre-cracking operation is an extremely important step, since, without sufficient care, it is possible to create false K_{Jc} data, influenced more by the pre-cracking operations than by accurately representing the material fracture toughness property.

Section 7 deals with test machines, their mode of operation, and recommended specimen loading rates. The usual practice of measuring slow stable crack growth during loading of test specimens is not a requirement when testing to determine K_{Jc} values. This greatly simplifies the procedure. Post-test visual measurement of the crack growth that has occurred up to the point of K_{Jc} instability is required, however.

Section 8 presents all of the information needed to calculate values of K_{Jc}. Some K_{Jc} data may have to be declared invalid due to failing the material performance requirements discussed in Section 3. Contrary to the implication in other ASTM Standards that invalid data are of no use, this method makes use of such data to contribute to the solution for the T_o reference temperature. The only data to be discarded as unusable are data from tests that have not been conducted properly.

Section 9 contains the statistical equations that produce the fracture toughness, "scale parameter," for the material tested. The only complexity involved is the determination of substitute (dummy) K_{Jc} values, which must replace invalid K_{Jc} values to be substituted into the calculations. The "scale parameter" is calculated and used in expressions given in Section 10 to calculate the reference temperature, T_o, which indexes the Master Curve.

Section 10 includes a second option for calculating the T_o temperature that is useable when the K_{Jc} data have been generated at varied test temperatures. In this case, test temperature becomes an added variable in the calculation.

Section 11 shows how the variability of K_{Jc} values is handled using the three-parameter Weibull model. Tolerance bounds that will bracket the data scatter can be calculated with associated confidence percentages attached to the bounds. Also included is reality-check information that sets limits, or truncation points, outside of which the ductile to brittle-transition (Master Curve) characterization of a material may not be represented by the test data.

Section 12 presents information on work in progress. The pre-cracked Charpy specimen, if proven to be viable for the production of fracture mechanics data, would greatly expand the applications for the Master Curve procedure. This specimen, because of its small size, taxes the limit of specimen size requirements, so that a classification of work in progress is warranted at the present time. Another subject introduced is a proposal for dealing with macroscopic metallurgical inhomogeneity of the steel being tested. Some steel products, such as heavy-section steel plate, can have fracture toughness property variations that are a significant function of the through-thickness position. The Master Curve concept, unmodified, is not well suited for dealing with such macroscale inhomogeneity. In this particular case, the recommended approach that is suggested herein is only a subject for future evaluation.

Section 13 contains a brief discussion of important considerations involved in directly applying Master Curve fracture toughness data to the fracture-safety analysis of actual structures.

Appendices taken directly from standard E 1921-03 [19] have been added to the present document, since they contain example problem solutions for Sections 10.1, 10.2, 11.1, and 11.3 of the present manual. These problems can be used as self educational material to familiarize the user of the manual with the computational steps involved with the determination of the Master Curve reference temperature, T_o.

1.1—Nomenclature

A_p	Area of plastic work done on test specimens; MJ, in.•lb
$A_{p(ff)}$	Plastic area determined from load-front face displacement test records; MJ, in.•lb

a or a_p	Physical crack size; meters, inches
B	Gross thickness of specimens; meters, inches
B_N	Net thickness of side-grooved specimens; meters, inches
B_x	Thickness variable, x, that represents the specimen thickness of prediction, meters, inches
B_1	The thickness of the specimens that were tested; meters, inches
B_4	Four-inch thick specimen; 0.1016 meters, 4-in., $B_x = 4$
B_e	Effective thickness of side grooved specimens used in normalized compliance, meters, inches
b	Weibull exponent; sometimes evaluated empirically, but in E 1921, used as a deterministic constant, 4, in all equations where fracture toughness is in units of K, and 2 for toughness in units of J
b_o	Initial remaining ligament length in specimens; meters, inches
C_n	Compliance, (V_{LL}/P) normalized by elastic modulus (E′) and effective thickness (B_e)
C	In Eq 21, a constant established by correlation between T_o and T_{CVN} transition temperature, °C
D_1	Coefficient in Eq 30 for establishing tolerance bounds, MPa$\sqrt{m}$
D_2	Coefficient in Eq 30 for establishing tolerance bounds, MPa$\sqrt{m}$
E'	Nominal elastic modulus established for ferritic steels; 206, 820 MPa, 30×10^6 psi
$f(\frac{a}{W})$	A dimensionless function that reflects the geometry and mode of loading of the specimen
H	Half height of a compact tension specimen, Fig. 7, meters, inches
i	Incremental order for test data, namely i increments from 1 to N
J	A path independent integral, J-integral; MJ/m^2, in.•lb/in.^{2}
J_e	Elastic component of J determined using K_e; MJ/m^2, in.•lb/in.^{2}
J_p	Plastic component of J determined using A_p; MJ/m^2, in.•lb/in.^{2}
J_c	J-integral measured at the point of onset of cleavage fracture, MJ/m^2, in.•lb/in.^{2}
J_{Ic}	J-integral measured at the point of 0.2 mm of slow-stable crack propagation, E 1820, MJ/m^2, in.•lb/in.^{2}
K_{Ic}	Plane strain stress intensity factor determined according to the requirements of E 399; MPa$\sqrt{m}$, ksi$\sqrt{in}$.
K_{Ia}	Stress intensity factor at crack arrest determined according to the requirements of E 1221; MPa$\sqrt{m}$, ksi$\sqrt{in}$.
K_{Jc}	Stress intensity factor determined by conversion from J_c;. MPa$\sqrt{m}$, ksi $\sqrt{in}$.
K_J	Final values of K (from J) where there was no cleavage instability involved; MPa$\sqrt{m}$, ksi$\sqrt{in}$.
$K_{Jc(limit)}$	The maximum value of K_{Jc} data where K_{Jc} can be considered valid, MPa$\sqrt{m}$, ksi$\sqrt{in}$.
K_{CENS}	A special type of K_{Jc} censored value used in the SINTAP data treatment procedure Section 12.2.1, MPa$\sqrt{m}$, ksi$\sqrt{in}$.
$K_{Jc(x)}$	The predicted K_{Jc} value for a specimen of size B_x, MPa$\sqrt{m}$, ksi$\sqrt{in}$.
$K_{Jc(med)}$	The median of a K_{Jc} data distribution for which $P_f = 0.5$, MPa$\sqrt{m}$, ksi$\sqrt{in}$.
K_o	A K_{Jc} value that represents the 63 percentile level of a K_{Jc} data distribution, MPa$\sqrt{m}$, ksi$\sqrt{in}$.

$K_o(T)$	K_o for a data distribution determined at test temperature, T, MPa$\sqrt{m}$, ksi$\sqrt{in}$.
K_{min}	A deterministic constant of the Weibull distribution, 20 MPa$\sqrt{m}$, 18 ksi$\sqrt{in}$, Eq 7
K_{max}	The peak K_e of the fatigue pre-cracking cycle, MPa$\sqrt{m}$, ksi$\sqrt{in}$.
K_e	A linear-elastic stress intensity factor, MPa$\sqrt{m}$, ksi$\sqrt{in}$.
R	In fatigue pre-cracking, the ratio $R = K_{min}/K_{max}$
N	Number of data, sum of valid plus invalid data
P_f	Probability of failure for a specimen, chosen at random from an infinite population of specimens, to fail at or before the K_{Jc} of interest
r	The number of valid K_{Jc} data, exclusive of all invalid data
P	Load; MN, pounds
T	Test temperature; °C
T_i	Test temperature of the i^{th} specimen in the incremental order, see Eq 26; °C
T_o	The Master Curve reference temperature, see Eqs 10 and 11; °C
T_Q	For testing with unrecommended specimens, a test temperature at which median K_{Jc} equals 100 MPa$\sqrt{m}$. T_Q is not used to establish the Master Curve
V_{LL}	Specimen displacement measured on the plane of loading; meters, inches
V_{ff}	Specimen displacement measured at the front face location, see Fig. 7; meters, inches
W	Specimen width denoted in Figs. 7 and 8, meters, inches
$Z_{(xx)}$	Standard normal deviate at cumulative probability level, P_f = xx

Greek Symbols

Δa_p	Slow-stable crack growth prior to the onset of cleavage fracture, mm, inches
ΔT_o	The increment to T_o that corresponds to one standard deviation; °C
σ_{To}	One standard deviation expected on multiple T_o determinations; °C
σ_{ys}	Material yield strength (temperature sensitive); MPa, ksi
θ	Scale parameter; units of J in Eq 3, units of $(K_o - K_{min})$ in Eq 27, MJ/m^2, in.•lb/in.^{2}
η_p	Plastic eta; a dimensionless coefficient that converts plastic work done on specimens into the plastic component of the J-integral
$\eta_{p(cmod)}$	Plastic eta modified to account for measuring displacement at the crack mouth position of SE(B) specimens, see Fig. 8
Γ	Gamma function, obtainable from handbooks of mathematical functions
δ_i	Kronecker delta; either one or zero: (1) used for valid K_{Jc} entries, and (0) for dummy value entries in Eq 26.

Specimen Size (nT) (see Figs. 7 and 8)

½ T,B = ½ in.
1T,B = 1 in.
4T,B = 4 in.