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Standard Test Method for Measurement of Creep Crack Growth Times in Metals[1]

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1. Scope

1.1 This test method covers the determination of creep crack initiation (CCI) and creep crack growth (CCG) in metals at elevated temperatures using pre-cracked specimens subjected to static or quasi-static loading conditions. The solutions presented in this test method are validated for base material (that is, homogenous properties) and mixed base/weld material with inhomogeneous microstructures and creep properties. The CCI time, $t_{0.2}$, which is the time required to reach an initial crack extension of $\delta a_i = 0.2$ mm to occur from the onset of first applied force, and CCG rate, $\dot{a}$ or *da/dt* are expressed in terms of the magnitude of creep crack growth correlated by fracture mechanics parameters, C^* or K, with C^* defined as the steady state determination of the crack tip stresses derived in principal from $C^*(t)$ and C_t (**1-17**).[2] The crack growth derived in this manner is identified as a material property which can be used in modeling and life assessment methods (**17-28**).

1.1.1 The choice of the crack growth correlating parameter C^*, $C^*(t)$, C_t, or K depends on the material creep properties, geometry and size of the specimen. Two types of material behavior are generally observed during creep crack growth tests; creep-ductile (**1-17**) and creep-brittle (**29-44**). In creep ductile materials, where creep strains dominate and creep crack growth is accompanied by substantial time-dependent creep strains at the crack tip, the crack growth rate is correlated by the steady state definitions of C_t or $C^*(t)$, defined as C^* (see 1.1.4). In creep-brittle materials, creep crack growth occurs at low creep ductility. Consequently, the time-dependent creep strains are comparable to or dominated by accompanying elastic strains local to the crack tip. Under such steady state creep-brittle conditions, C_t or K could be chosen as the correlating parameter (**8-14**).

1.1.2 In any one test, two regions of crack growth behavior may be present (**12, 13**). The initial transient region where elastic strains dominate and creep damage develops and in the steady state region where crack grows proportionally to time. Steady-state creep crack growth rate behavior is covered by this standard. In addition, specific recommendations are made in 11.7 as to how the transient region should be treated in terms of an initial crack growth period. During steady state, a unique correlation exists between *da/dt* and the appropriate crack growth rate relating parameter.

1.1.3 In creep ductile materials, extensive creep occurs when the entire un-cracked ligament undergoes creep deformation. Such conditions are distinct from the conditions of small-scale creep and transition creep (**1-10**). In the case of extensive creep, the region dominated by creep deformation is significant in size in comparison to both the crack length and the uncracked ligament sizes. In small-scale-creep only a small region of the un-cracked ligament local to the crack tip experiences creep deformation.

1.1.4 The creep crack growth rate in the extensive creep region is correlated by the $C^*(t)$-integral. The C_t parameter correlates the creep crack growth rate in the small-scale creep and the transition creep regions and reduces, by definition, to $C^*(t)$ in the extensive creep region (**5**). Hence in this document the definition C^* is used as the relevant parameter in the steady state extensive creep regime whereas $C^*(t)$ and/or C_t are the parameters which describe the instantaneous stress state from the small scale creep, transient and the steady state regimes in creep. The recommended functions to derive C^* for the different geometries shown in Annex A1 is described in Annex A2.

1.1.5 An engineering definition of an initial crack extension size δa_i is used in order to quantify the initial period of crack development. This distance is given as 0.2 mm. It has been shown (**41-44**) that this initial period which exists at the start of the test could be a substantial period of the test time. During this early period the crack tip undergoes damage development as well as redistribution of stresses prior reaching steady state. Recommendation is made to correlate this initial crack growth period defined as $t_{0.2}$ at $\delta a_i = 0.2$ mm with the steady state C^* when the crack tip is under extensive creep and with K for creep brittle conditions. The values for C^* and K should be calculated at the final specified crack size defined as $a_o + \delta a_i$ where a_o is initial size of the starter crack.

1.1.6 The recommended specimens for CCI and CCG testing is the standard compact tension specimen C(T) (see Fig. A1.1) which is pin-loaded in tension under constant loading conditions. The clevis setup is shown in Fig. A1.2 (see 7.2.1 for

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

details). Additional geometries which are valid for testing in this procedure are shown in Fig. A1.3. These are the C-ring in tension CS(T), middle crack specimen in tension M(T), single edge notched tension SEN(T), single edge notched bend SEN(B), and double edge notched tension DEN(T). In Fig. A1.3, the specimens' side-grooving-position for measuring displacement at the force-line displacement (FLD) and crack mouth opening displacement (CMOD) and positions for the electric potential drop (EPD) input and output leads are shown. Recommended loading for the tension specimens is pin-loading. The configurations, size range are given in Table A1.1 of Annex A1, (**43-47**). Specimen selection will be discussed in 5.9.

1.1.7 The state-of-stress at the crack tip may have an influence on the creep crack growth behavior and can cause crack-front tunneling in plane-sided specimens. Specimen size, geometry, crack length, test duration and creep properties will affect the state-of-stress at the crack tip and are important factors in determining crack growth rate. A recommended size range of test specimens and their side-grooving are given in Table A1.1 in Annex A1. It has been shown that for this range the cracking rates do not vary for a range of materials and loading conditions (**43-47**). Suggesting that the level of constraint, for the relatively short term test durations (less than one year), does not vary within the range of normal data scatter observed in tests of these geometries. However, it is recommended that, within the limitations imposed on the laboratory, that tests are performed on different geometries, specimen size, dimensions and crack size starters. In all cases a comparison of the data from the above should be made by testing the standard *C(T)* specimen where possible. It is clear that increased confidence in the materials crack growth data can be produced by testing a wider range of specimen types and conditions as described above.

1.1.8 Material inhomogeneity, residual stresses and material degradation at temperature, specimen geometry and low-force long duration tests (mainly greater that one year) can influence the rate of crack initiation and growth properties (**42-50**). In cases where residual stresses exist, the effect can be significant when test specimens are taken from material that characteristically embodies residual stress fields or the damaged material, or both. For example, weldments, or thick cast, forged, extruded, components, plastically bent components and complex component shapes, or a combination thereof, where full stress relief is impractical. Specimens taken from such component that contain residual stresses may likewise contain residual stresses which may have altered in their extent and distribution due to specimen fabrication. Extraction of specimens in itself partially relieves and redistributes the residual stress pattern; however, the remaining magnitude could still cause significant effects in the ensuing test unless post-weld heat treatment (PWHT) is performed. Otherwise residual stresses are superimposed on applied stress and results in crack-tip stress intensity that is different from that based solely on externally applied forces or displacements. Not taking the tensile residual stress effect into account will produce C^* values lower than expected effectively producing a faster cracking rate with respect to a constant C^*. This would produce conservative estimates for life assessment and non-conservative calculations for design purposes. It should also be noted that distortion during specimen machining can also indicate the presence of residual stresses.

1.1.9 Stress relaxation of the residual stresses due to creep and crack extension should also be taken into consideration. No specific allowance is included in this standard for dealing with these variations. However the method of calculating C^* presented in this document which used the specimen's creep displacement rate to estimate C^* inherently takes into account the effects described above as reflected by the instantaneous creep strains that have been measured. However extra caution should still be observed with the analysis of these types of tests as the correlating parameters K and C^* shown in Annex A2 even though it is expected that stress relaxation at high temperatures could in part negate the effects due to residual stresses. Annex A4 presents the correct calculations needed to derive J and C^* for weldment tests where a mismatch factor needs to be taken into account.

1.1.10 Specimen configurations and sizes other than those listed in Table A1.1 which are tested under constant force will involve further validity requirements. This is done by comparing data from recommended test configurations. Nevertheless, use of other geometries are applicable by this method provided data are compared to data obtained from standard specimens (as identified in Table A1.1) and the appropriate correlating parameters have been validated.

1.2 The values stated in SI units are to be regarded as standard. The values given in parentheses after SI units are provided for information only and are not considered standard.

1.3 *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.*

1.4 *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. Scope of Material Properties Data Resulting from This Standard

2.1 This test method covers the determination of initial creep crack extension (CCI) times and growth (CCG) in metals at elevated temperature using pre-cracked specimens subjected to static or quasi-static loading conditions. The metallic materials investigated range from creep-ductile to creep-brittle conditions.

2.2 The crack growth rate $\dot{a}$ or da/dt is expressed in terms of the magnitude of CCG rate relating parameters, $C^*(t)$, C_t or K. The resulting output derived as $\dot{a}vC^*$ (as the steady state formulation of $C^*(t)$), or C_t for creep-ductile materials or as $\dot{a}vK$ (for creep-brittle materials) is deemed as material property for CCG.

2.3 In addition for CCI derivation of crack extension time $t_{0.2}\ v\ C^*$ (for creep-ductile materials) or $t_{0.2}vK$ (for creep-brittle materials) can also be used as a material property for the purpose of modeling and remaining life assessment.

2.4 The output from these results can be used as 'Benchmark' material properties data which can subsequently be used in crack growth numerical modeling, in component design and remaining life assessment methods.

3. Referenced Documents

3.1 *ASTM Standards:*[3]

E4 Practices for Force Calibration and Verification of Testing Machines

E74 Practices for Calibration and Verification for Force-Measuring Instruments

E83 Practice for Verification and Classification of Extensometer Systems

E139 Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials

E220 Test Method for Calibration of Thermocouples By Comparison Techniques

E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials

E647 Test Method for Measurement of Fatigue Crack Growth Rates

E1823 Terminology Relating to Fatigue and Fracture Testing

4. Terminology

4.1 Terminology related to fracture testing contained in Terminology E1823 is applicable to this test method. Additional terminology specific to this standard is detailed in 4.2 and 4.3. For clarity and easier access within this document some of the terminology in E1823 relevant to this standard is repeated below (see Terminology E1823, for further discussion and details).

4.2 *Definitions:*

4.2.1 *C*(t)-integral, C*(t)* $[FL^{-1}T^{-1}]$—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 rate fields at any instant around the crack front in a body subjected to extensive creep conditions

4.2.1.1 *Discussion*—The *C*(t)* expression for a two-dimensional crack, in the *x-z* plane with the crack front parallel to the *z*-axis, is the line integral:

$$C^*(t) = \int_{\Gamma} \left(W^*(t) dy - T \cdot \frac{\partial \dot{u}}{\partial x} ds \right) \quad (1)$$

where:

$W^*(t)$	=	instantaneous stress-power or energy rate per unit volume,
Γ	=	path of the integral, that encloses (that is, contains) the crack tip contour,
ds	=	increment in the contour path,
T	=	outward traction vector on ds,
$\dot{u}$	=	displacement rate vector at ds,
x, y, z	=	rectangular coordinate system, and
$T \cdot \frac{\partial \dot{u}}{\partial x} ds$	=	rate of stress-power input into the area enclosed by Γ across the elemental length ds.

4.2.1.2 *Discussion*—The value of *C*(t)* from this equation is path-independent for materials that deform according to constitutive law that may be separated into single-value time and stress functions or strain and stress functions of the forms:

$$\dot{\varepsilon} = f_1(t) f_2(\sigma) \quad (2)$$

or,

$$\dot{\varepsilon} = f_3(\varepsilon) f_4(\sigma) \quad (3)$$

where f_1-f_4 represent functions of elapsed time, t, strain, ε and applied stress, σ, respectively and $\dot{\varepsilon}$ is the strain rate.

4.2.1.3 *Discussion*—For materials exhibiting creep deformation for which the above equation is path-independent, the *C*(t)*-integral is equal to the value obtained from two, stressed, identical bodies with infinitesimally differing crack areas. This value is the difference in the stress-power per unit difference in crack area at a fixed value of time and displacement rate, or at a fixed value of time and applied force.

4.2.1.4 *Discussion*—The value of *C*(t)* corresponding to the steady-state conditions is called *C**. Steady-state is said to have been achieved when a fully developed creep stress distribution has been produced around the crack tip. This occurs when the secondary creep deformation characterized by the following equation dominates the behavior of the specimen.

$$\dot{\varepsilon}_{ss} = A\sigma^n \quad (4)$$

4.2.1.5 *Discussion*—This steady state in *C** does not necessarily mean steady state crack growth rate. The latter occurs when steady state damage develops at the crack tip. In this test method, this behavior is observed as 'tails' at the early stages of crack growth. This standard deals with this region as the initial crack extension period defined as time, $t_{0.2}$, measured for an initial crack growth of 0.2 mm after first loading (see 11.8.8 for further details).

4.2.2 C_t *parameter,* C_t $[FL^{-1}T^{-1}]$—a parameter equal to the value obtained from two identical bodies with infinitesimally differing crack areas, each subjected to stress, as the difference in stress-power per unit difference in crack area at a fixed value of time and displacement rate, or at a fixed value of time applied force for an arbitrary constitutive law.

4.2.2.1 *Discussion*—The value of C_t is path-independent and is identical to *C*(t)* for extensive creep conditions when the constitutive law described in 4.2.1 applies.

4.2.2.2 *Discussion*—Under small-scale creep conditions, *C*(t)* is not path-independent and is related to the crack tip stress and strain fields only for paths local to the crack tip and well within the creep zone boundary. Under these circumstances, C_t is related uniquely to the rate of expansion of the creep zone size (**13-15**). There is considerable experimental evidence that the C_t parameter (**5, 11, 13**) which extends the *C*(t)-integral* concept into small-scale creep and the transition creep regime, correlates uniquely with creep crack growth rate in the entire regime ranging from small-scale to extensive creep regime.

[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.