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

This standard is issued under the fixed designation E1457; 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—Section 4.2.1.1 was editorially corrected in July 2020.

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 (i.e. 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] This test method is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.06 on Crack Growth Behavior.

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

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 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 mis-match 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 the standard. The inch-pound units given in parentheses are for information only.

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 $\dot{a} \nu C^*$ (as the steady state formulation of $C^*(t)$), or C_t for creep-ductile materials or as $\dot{a} \nu K$ (for creep-brittle materials) is deemed as material property for CCG.

2.3 In addition for CCI derivation of crack extension time $t_{0.2}$ vC^* (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 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
E813 Test Method for JIc, A Measure of Fracture Toughness
E1152 Test Method for Determining-J-R-Curves
E1820 Test Method for Measurement of Fracture Toughness
E1823 Terminology Relating to Fatigue and Fracture Testing
E2818 Practice for Determination of Quasistatic Fracture Toughness of Welds

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:

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

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

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
~~$T \frac{\partial \dot{u}}{\partial x} d s$~~ = ~~rate of stress-power input into the area enclosed by Γ across the elemental length ds.~~
$T \cdot \frac{\partial \dot{u}}{\partial x} ds$ = 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:

[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.

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

or,

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

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.

$$\dot{\varepsilon}_{ss} = A\sigma^n \tag{4}$$

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.

4.2.2.3 *Discussion*—

For a specimen with a crack subject to constant force, P:

$$C_t = \frac{P\dot{V}_c}{BW}(f/f')$$

and

$$f' = \frac{df}{d(a/W)}$$

4.2.3 *crack-plane orientation*—an identification of the plane and direction of fracture or crack extension in relation to product configuration. This identification is designated by a hyphenated code with the first letter(s) representing the direction normal to the crack plane and the second letter(s) designating the expected direction of crack propagation.

4.2.4 *crack size, a [L]*—principal lineal dimension used in the calculation of fracture mechanics parameters for throughthickness cracks as defined in the applicable standard.

4.2.4.1 *Discussion*—

In practice, the value of a is obtained from procedures for measurement of physical crack size, a_p, original crack size, a_o, and effective crack size, a_e, as appropriate to the situation being considered.

4.2.4.2 *Discussion*—

In this test method, the physical crack size is represented as a_p. The subscript, p, is everywhere implied.

4.2.5 *creep crack growth (CCG) rate, da/dt, Δa/Δt [L/t]*—the rate of crack extension caused by creep damage and expressed in terms of average crack extension per unit time. **[E1823]**

4.2.6 *creep zone boundary*—the locus of points ahead of the crack front where the equivalent strain caused by the creep deformation equals 0.002 (0.2 %) (16).

4.2.6.1 *Discussion*—

Under small-scale creep conditions, the creep zone expansion with time occurs in a self-similar manner for planar bodies, (10) thus, the creep zone size, r_c, can be defined as the distance to the creep zone boundary from the crack tip at a fixed angle, θ, with respect to the crack plane. The rate of expansion of the creep zone size is designated as $_{(0)}\dot{r}_c(\theta)$.

4.2.7 *force-line displacement due to creep, elastic and plastic strain, V [L]*—the total displacement measured at the loading pins (V^{FLD}) due to the force placed on the specimen at any instant and the subsequent crack extension that is associated with the accumulation of creep, elastic and plastic strains in the specimen.

4.2.7.1 *Discussion*—

In creeping bodies, the total displacement at the force-line V^{FLD} can be partitioned into an instantaneous elastic part V_e, a plastic part, V_p, and a time-dependent creep part V_c where:

$$V \sim V_e + V_p + V_c \tag{5}$$

The corresponding symbols for the rates of force-line displacement components shown in Eq 5 are given respectively as $\dot{V}$, $\dot{V}_e$, $\dot{V}_p$, $\dot{V}_c$. This information is used to derive the parameter C^* and C_t. See Section 11.

4.2.7.2 *Discussion*—

For the set of specimens in Annex A1, Table A1.1 for creep ductile material where creep strains dominate and in which test times are longer (usually >1000 hours), the elastic and plastic displacement rate components are small compared to the creep and therefore it is recommended to use the total displacement rate, $\dot{V}$ assuming that, $\dot{V}_c \approx \dot{V}$ to derive the steady state C^*. See Section 11 for detailed discussion.

4.2.7.3 *Discussion*—

The force-line displacement associated with just the creep strains is expressed as V_c.

4.2.8 *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.

4.2.9 *net thickness, B_N [L]*—distance between the roots of the side grooves in side-grooved specimens.

4.2.10 *original crack size, a_o [L]* —the physical crack size at the start of testing.

4.2.11 *specimen thickness, B [L]*—distance between the parallel sides of a test specimen.

4.2.12 *specimen width, W [L]*—the distance from a reference position (for example, the front edge of a bend specimen or the force line of a compact specimen) to the rear surface of the specimen.

4.2.13 *stress intensity factor, K [FL$^{-3/2}$]*—the magnitude of the mathematically ideal crack-tip stress field (a stress-field singularity) for Mode 1 in a homogeneous, linear-elastic body.

4.2.14 *transition time, t_T [T]*—time required for extensive creep conditions to develop in a cracked body under sustained loading. For specimens, this is typically the time required for the creep deformation zone to spread through a substantial portion

of the uncracked ligament, or in the region that is under the influence of a crack in the case of a finite crack in a semi-infinite medium. This limit is employed to validate the steady state correlating parameter C^*. An estimate of transition time for materials that creep according to the power-law can be obtained from the following equation:

$$t_T = \frac{K^2(1 - \nu^2)}{E(n + 1)C^*}$$

where:

ν = Poisson's ratio, and
n = secondary creep exponent.

4.2.15 *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.

4.2.15.1 *Discussion*—

In this test method, yield strength is determined by the Offset Method (at a strain of 0.2 %).

4.3 *Definitions of Terms Specific to This Standard:*

4.3.1 *C*-integral, C* [FL-1T-1]*—The parameter relevant to correlating creep crack growth in this document is given as the C^*-integral which is defined as the steady state definition of $C^*(t)$. C^* is used to characterize the local steady state, stress-strain rate fields at any instant around the crack front in a body subject to extensive creep conditions.

4.3.1.1 *Discussion*—

See A2.4 for further discussion and equations to calculate C^*.

4.3.2 *initial crack extension increment (CCI) after full force-up, δa_i [L]*—the recommended time taken to crack extension of δa_i = 0.2 mm after first application of force for defining a crack growth period $t_{0.2}$ in hours as a function of $C^*(t)$, C_t, or K value taken at crack length $a_o + \delta a_i$ 0.2 mm.

4.3.3 *initial crack time to 0.2 mm, $t_{0.2}$ [T]*—the time to $\delta a_i = 0.2$ mm (0.008 in.) of crack extension δa by creep after full loading. This size is chosen as the limit of accuracy set for crack extension measurements in laboratory geometries.

5. Summary of Test Method

5.1 The main objective of creep crack growth testing is the determination of the relationship between the time and rate of crack growth, *da/dt*, due to creep and the applied value of the appropriate crack growth rate relating parameter. In addition results for time to crack extension of 0.2 mm at force-up (CCI) as defined in 1.1.5 are also correlated from the experimental data. This test method involves loading of sharply notched by means of EDM or fatigue pre-cracked specimens (see 8.8), using the recommended geometries, heated to the test temperature by means of a suitable furnace. The applied force is either held constant with time or is changed slowly enough to be considered quasi-static. The temperature must be constantly monitored to ensure that it remains at the specified level within allowable limits during the test. If servo-mechanical loading systems are used to maintain constant force, or if tests are conducted under conditions other than constant force, a record of force versus time also must be maintained.

5.2 Three different loading methods are available for creep crack growth testing. Dead weight loading is the recommended method and is the most commonly used method for loading specimens. In addition, constant displacement **(29)** and constant displacement rate **(1-4, 39)** loading may also be used but are only recommended when working with extremely brittle materials. For tests conducted under conditions other than dead-weight loading, the user must compare the results and verify the analysis from tests performed under dead-weight loading conditions.

5.3 It is recommended to carry out long term tests (at least >1000 h and usually, if possible, between 5000 to 10 000 h) in order to reduce crack tip plasticity which would occur at higher forces and allow for steady state creep cracking to take place. Large forces should be avoided since this will induce either fast fracture or extensive deformation due to creep or plastic collapse and/or rupture, thus rendering the crack growth test as void. Data from fast test are usually not appropriate for life assessment purposes as they may not reflect the stress state of the component at the crack-tip.

5.4 The crack size and force-line displacements are continuously recorded, digitally or autographically on strip-chart recorders, as a function of time. The force, force-line displacement and crack size data are numerically processed as discussed later to obtain the crack growth rate versus $C^*(t)$,C_t or K relationship.

5.5 Data scatter that is usually present in creep crack growth experiments **(43, 45, 51, 52)**. This will indicate that more than one test should be performed to gain confidence in the results. The number of specimens to be tested is dependent on a number of factors **(52)** such as the number of test variables (specimen type, size, dimension, crack size, force, CCI and CCG range and material batches) being considered. In general it is recommended for the range of conditions that a minimum of five tests at

different forces should be performed to produce overlapping crack growth data over the region of CCG rate of interest. Additional repeat tests would be preferable, but not compulsory, to improve confidence in the derived data range.

5.6 If the material exhibits such factors as irregular grain sizes and voids, weld (X-weld, HAZ) and other inhomogeneity the minimum number of tests should be increased (see 5.5). Also, more tests should be performed if the material creep crack growth behavior exhibits increased scatter regardless of the reason for the variability. If there is insufficient material available or if there are other reasons which would restrict multiple testing then the results should be considered with increased caution.

5.7 In some cases crack growth information is needed for the initial start of the test where steady state cracking has not been reached. Also this period coincides with the limit of accuracy in crack growth measurement (recommended as 0.2 mm see 1.1.2 (**35**). The data produced for (CCI) will therefore be one point per test (similar to uniaxial rupture tests). Hence more tests would be needed to accommodate the variability in the results. The minimum number of tests recommended will depend on the level of scatter, but should not be less than 5 tests which should also uniformly cover test times of interest.

5.8 *Specimen Selection*—For all cases attention must be given to the proper selection of specimen. The C(T) is always the primary choice as there is ample reference in the literature to the testing and analysis of this geometry.

5.9 The choice of specimen should reflect a number of factors. These priorities can be listed as follows:

5.9.1 Availability and the size of material prepared for testing indicates the number of specimens that can be tested.

5.9.2 Material creep ductility and stress sensitivity; for creep brittle specimens the C(T) is recommended.

5.9.3 Capacity of the test rig; the 3-point bend specimens and the C(T) specimens will typically take lower forces.

5.9.4 Type of loading (tension, bending, tension/bending) should be taken into consideration.

5.9.5 Compatibility with size and stress state of the specimen with the component under investigation.

5.9.6 Following a test if the crack front is substantially leading in the centre the indications are that constraint should be increased. If the crack front is substantially receding at the centre the opposite applies-This can be remedied by changing the size, thickness, side-grooving or the geometry of the specimen used for testing. See 8.3.

5.9.7 The length of time and temperature of testing; this will dictate the size, the applied force, initial crack size and side-grooving of the specimen.

5.9.8 *Discussion*—It is unlikely that all conditions for material selection can be satisfied at any one time. The main priority is to produce a test environment for stable crack growth to occur under steady state conditions. Therefore compromises may need to be made. This document goes part of the way to assist the user in this choice by identifying specific detail of a number of geometries. The appropriate decision may, however, need expert advice in the relevant field or industry.

6. Significance and Use

6.1 Creep crack growth rate expressed as a function of the steady state C^* or K characterizes the resistance of a material to crack growth under conditions of extensive creep deformation or under brittle creep conditions. Background information on the rationale for employing the fracture mechanics approach in the analyses of creep crack growth data is given in (**11**, **13**, **30-35**).

6.2 Aggressive environments at high temperatures can significantly affect the creep crack growth behavior. Attention must be given to the proper selection and control of temperature and environment in research studies and in generation of design data.

6.2.1 Expressing CCI time, $t_{0.2}$ and CCG rate, da/dt as a function of an appropriate fracture mechanics related parameter generally provides results that are independent of specimen size and planar geometry for the same stress state at the crack tip for the range of geometries and sizes presented in this document (see Annex A1). Thus, the appropriate correlation will enable exchange and comparison of data obtained from a variety of specimen configurations and loading conditions. Moreover, this feature enables creep crack growth data to be utilized in the design and evaluation of engineering structures operated at elevated temperatures where creep deformation is a concern. The concept of similitude is assumed, implying that cracks of differing sizes subjected to the same nominal $C^*(t)$,C_t, or K will advance by equal increments of crack extension per unit time, provided the conditions for the validity for the specific crack growth rate relating parameter are met. See 11.7 for details.

6.2.2 The effects of crack tip constraint arising from variations in specimen size, geometry and material ductility can influence $t_{0.2}$ and da/dt. For example, crack growth rates at the same value of $C^*(t)$,C_t in creep-ductile materials generally increases with increasing thickness. It is therefore necessary to keep the component dimensions in mind when selecting specimen thickness, geometry and size for laboratory testing.

6.2.3 Different geometries as mentioned in 1.1.6 may have different size requirements for obtaining geometry and size independent creep crack growth rate data. It is therefore necessary to account for these factors when comparing da/dt data for different geometries or when predicting component life using laboratory data. For these reasons, the scope of this standard is restricted to the use of specimens shown in Annex A1 and the validation criteria for these specimens are specified in 11.7. However if specimens other than the C(T) geometry are used for generating creep crack growth data, then the da/dt data obtained should, if possible, be compared against test data derived from the standard C(T) tests in order to validate the data.

6.2.4 Creep cracks have been observed to grow at different rates at the beginning of tests compared with the rates at equivalent $C^*(t)$,C_t or K values for cracks that have sustained previous creep crack extension (**12**, **13**). This region is identified as 'tail'. The duration of this transient condition, 'tail', varies with material and initially applied force level. These transients are due to rapid changes in the crack tip stress fields after initial elastic loading and/or due to an initial period during which a creep damage zone

evolves at the crack tip and propagates in a self-similar fashion with further crack extension (**12, 13**). This region is separated from the steady-state crack extension which follows this period and is characterized by a unique *da/dt* versus $C^*(t)$,C_t or K relationship. This transient region, especially in creep-brittle materials, can be present for a substantial fraction of the overall life (**35**). Criteria are provided in this standard to quantify this region as an initial crack growth period (see 1.1.5) and to use it in parallel with the steady state crack growth rate data. See 11.8.8 for further details.

6.3 Results from this test method can be used as follows:

6.3.1 Establish predictive models for crack incubation periods and growth using analytical and numerical techniques (**18-21**).

6.3.2 Establish the influence of creep crack development and growth on remaining component life under conditions of sustained loading at elevated temperatures wherein creeps deformation might occur (**23-28**).

NOTE 1—For such cases, the experimental data must be generated under representative loading and stress-state conditions and combined with appropriate fracture or plastic collapse criterion, defect characterization data, and stress analysis information.

6.3.3 Establish material selection criteria and inspection requirements for damage tolerant applications.

6.3.4 Establish, in quantitative terms, the individual and combined effects of metallurgical, fabrication, operating temperature, and loading variables on creep crack growth life.

6.4 The results obtained from this test method are designed for crack dominant regimes of creep failure and should not be applied to cracks in structures with wide-spread creep damage which effectively reduces the crack extension to a collective damage region. Localized damage in a small zone around the crack tip is permissible, but not in a zone that is comparable in size to the crack size or the remaining ligament size. Creep damage for the purposes here is defined by the presence of grain boundary cavitation. Creep crack growth is defined primarily by the growth of intergranular time-dependent cracks. Crack tip branching and deviation of the crack growth directions can occur if the wrong choice of specimen size, side-grooving and geometry is made (see 8.3). The criteria for geometry selection are discussed in 5.8.

7. Apparatus

7.1 *Testing Machine*—This standard does not recommend a specific type of testing equipment. It does however specify accuracy limits for the test equipment and suggestions for the types of equipment that could be used to achieve the accuracy limits specified.

7.1.1 Dead-weight or servo-mechanical loading machines capable of maintaining a constant force or maintaining constant displacement rates in the range of 10^{-5} to 1 mm/h can be used for creep crack growth testing. If servo-hydraulic machines are used under constant force conditions, the force must be monitored continuously and the variations in the indicated force must not exceed ±1.0 % of the nominal value at any time during the test. If either constant displacement rate or constant displacement is used, the indicated displacement must be within 1 % of the nominal value at any given time during the test.

7.1.2 The accuracy of the testing machine shall be within the permissible variation specified in Practice E4.

7.1.3 If lever-type, dead-weight creep machines are used, it is preferable that they automatically maintain the lever arm in a horizontal position. If such a device is not available, the lever arm should be manually adjusted at such intervals so that the arm position at any time does not deviate from the horizontal by an amount leading to 1 %, variation of force on the specimen.

7.1.4 Precautions should be taken to ensure that the force on the specimen is applied as nearly axial as possible.

7.2 *Grips and Fixtures* for specimens listed in Annex A1: It is allowed to deviate from the recommended testing apparatus as long as the relevant accuracies and loading conditions are adhered to.

7.2.1 Clevis assemblies shall be incorporated in the force train at both the top and bottom of the specimen to allow in-plane rotation as the specimen is loaded. Fig. A1.2 shows an example for the clevis setup for the tension specimens shown in Fig. A1.3. The bend specimen will be simply a 3-point bend loading assembly.

7.2.2 Suggested proportions and critical tolerances of the fixtures shall be within the specified variation shown in Fig. A1.2. Note that surface finish does not have a major effect on creep crack growth and therefore a normal smooth finish to the specimen is sufficient.

7.2.3 The pin-to-hole clearances are designed to minimize friction thereby eliminating unacceptable end-movements that would invalidate the specimen calibrations for determining K,J, and $C^*(t)$.

7.2.4 The material for the grips and pull rods should be chosen with due regard to test temperature and force level to be employed. Some elevated temperature materials currently being used include American Iron and Steel Institute (AISI) Grade 304 and 316 stainless steel, Grade A286 steel, nickel-based superalloys like alloy 718 or alloy X750. The loading pins are machined from A286 steel (or equivalent or better temperature resistant steel) and are heat treated such that they develop a high resistance to creep deformation and rupture.

7.3 *Alignment of Grips*—It is important that attention be given to achieving good alignment in the force-line through careful machining of all gripping fixtures. The length of the force train should be chosen with proper attention to the height of the furnace for heating the test specimen.

7.4 *Heating Apparatus:*

7.4.1 The apparatus for, and method of, heating the specimens should provide the temperature control necessary to satisfy the requirements in 10.3, without manual adjustments more frequent than once in each 24-h period after force application.

7.4.2 Heating shall be by an electric resistance or radiation furnace with the specimen in air at atmospheric pressure unless other media are specifically agreed upon in advance.

NOTE 2—The test conditions in which tests are performed may have a considerable effect on the results. This is particularly true when properties are influenced by plasticity, environmental effects, oxidation or other types of corrosion.

7.5 *Temperature-Measurement Apparatus*—The method of temperature measurement must be sufficiently sensitive and reliable to ensure that the specimen temperature is within the limits specified in 10.3. For details of types of apparatus used see Specification E139.

7.6 *Displacement Gage*—For the measurement of the *FLD* or *CMOD* displacement during the test.

7.6.1 Continuous displacement measurement is needed to evaluate the magnitude of $C^*(t)$ and C_t at any time during the test. Displacement measurements must be made on the force-line.

7.6.2 As a guide, the displacement gage should have a working range no more than twice the displacement expected during the test. Accuracy of the gage should be within ±1 % of the full working range of the gage. In calibration, the maximum deviation of the individual data points from the fit to the data shall not exceed ±1 % of the working range.

7.6.3 Knife edges are recommended for friction-free seating of the gage. Parallel alignment of the knife edges must be maintained to within ±1°.

7.6.4 The displacement along the force-line may be directly measured by attaching the entire clip gage assembly to the specimen and placing the whole assembly in the furnace. Alternatively, the displacements can be transferred outside the furnace with a rod and tube assembly such as that shown in Figs. A1.4 and A1.5.

7.6.5 In the latter procedure, the transducer is placed outside the furnace. It is important to make the tube and rod from materials that are thermally stable and are from the same material to avoid erroneous readings caused by differences in thermal expansion coefficients. Other designs that can measure displacements to the same levels of accuracy may also be used.

7.7 *Apparatus for Crack Size Measurement*—A crack size monitoring technique capable of reliably resolving crack extensions of at least ±0.1 mm at test temperature is recommended for creep crack growth measurements. Since crack extension across the thickness of the specimen is not always uniform, surface crack size measurements by optical means are not considered reliable as a primary method. Optical observation may be used as an auxiliary measurement method. The selected crack size measurement technique must be capable of measuring the average crack size across the thickness. The most commonly used technique for crack size measurement during creep crack growth testing is the electric potential technique that is described in Annex A4.

NOTE 3—The crack size measurement precision is herein defined as the standard deviation of the mean value of crack size determined for a set of replicate measurements.

7.8 *Room Temperature Control*—The ambient temperature in the room should be sufficiently constant so that the specimen temperature variations do not exceed the limits stated in 10.3.5.

7.9 *Timing Apparatus*—Suitable means for recording and measuring elapsed time to within 1 % of the elapsed time should be provided.

8. Specimen Configuration

8.1 The schematic and dimension of the standard C(T) specimen and the additional specimens are shown in Fig. A1.3.

8.2 The configurations and size range of all the geometries are given in Table A1.1.

8.2.1 Crack opening slot is the machined crack width. For C(T) specimens it can be as much as 0.1 *a/W*. For the rest of the geometries, which have shorter crack starters it is recommended to have an opening of 0.05 *a/W*.

8.2.2 The self consistency of the starter notch is important for repeatability and test comparison. The user should use an internally reproducible starter notch process to give comparable results within a specific test program. This is especially important for the CCI calculations.

8.2.3 The width-to-thickness ratio *W/B* for the C(T) specimen is recommended to be 2, nominally. Other *W/B* ratios, up to 8, may be used for thickness effect characterization; it is however important to note that the stress state may vary with thickness (see 1.1.7 and 5.9).

8.2.4 The initial crack size, a_o (including a sharp starter notch or pre-crack), shall be at least 0.45 times the width, *W*, but no greater than 0.55*W*. This may be varied within the stated interval depending on the selected force level for testing and the desired test duration.

8.3 *Side-Grooving*—In most cases 20 % side-grooving is sufficient to meet crack front straightness requirements (see 5.9, 6.2.2, and 8.4). However more or less side-grooving in specimens may be required depending on the ductility and crack growth behavior of the material. The depth of required side-grooves for a particular material might only be found by trial and error but a total reduction of 20 % has been found to work well for many materials. However, for extremely creep-ductile materials, a total side-groove reduction of up to 40 % may be needed to produce straight crack fronts. Any included angle of side groove less than 90° is allowed. Root radius shall be ≤ 0.4 ± 0.2 mm in order to produce nearly-straight pre-crack fronts; it is desirable, but not a requirement, to have the pre-cracking done prior to side-groove machining operation.

8.4 *Specimen Size*—There are no specific size requirements imposed in this method but considerations due to constraint effects should be taken into account. Also specimen size must be chosen with consideration to the material availability, capacity of the loading system, being able to fit the specimen into the heating furnace with sufficient room for attaching the necessary extensometers, and providing sufficient ligament size for growing the crack in a stable fashion to permit collection of crack growth data (see also 1.1.7, 1.1.10, 5.9).

8.5 *Specimen Measurements*—The specimen dimensions are given in Fig. A1.3 and Table A1.1. They shall be machined within the machining tolerances given in Fig. A1.1 and the dimensions should be measured before and after the test.

8.6 *Notch Preparation*—The machined notch for the test specimens (see 8.2.1) may be made by electrical-discharge machining (EDM), milling, broaching, or saw cutting. It is recommended that the last 0.1 *a/W* of the crack be machined using electro discharge machining (EDM) of a width of 0.1 mm. This will allow easier pre-cracking or further crack tip sharpening by EDM to the final crack starter size prior testing. See Note in Fig. A1.3.

8.7 Associated pre-cracking requirements are discussed in 8.8.

8.8 *Pre-Cracking*—EDM or Fatigue pre-cracking are two methods used to introduce a sharp crack tip starter. It is recommended, using electro-discharge machine (EDM) method, that a narrow slit (of 0.1 mm width) should be introduced to produce a sharp and even crack starter. Fatigue pre-cracking could be performed as long as it can be ascertained that the final crack front will be straight and flat and does not deviate from the crack plane. EDM is preferable for some creep-brittle materials such as inter-metallics **(29)** and certain geometries due to difficulties in growing cracks with straight fronts. There may be indications that the mode of pre-cracking could affect the initial slow CCG period (see 1.1.5) and that the use of EDM may give longer times for the initial crack growth period compared with fatigue pre-crack. However this has not been fully established **(43)**.

8.8.1 Care must be exercised during pre-cracking by either method to avoid excessive damage at the notch root. Hereafter, the two methods for pre-cracking are described.

8.8.2 *EDM Pre-Crack*—This is the preferred mode of inducing a sharp straight-fronted pre-crack. The width of the EDM pre-crack shall not exceed 0.1 mm. Precautions must be taken to avoid any localized over-heating which may alter the microstructure of the material near the crack tip. A minimum EDM length of 0.05 *a/W* from a blunt notch is recommended.

8.8.3 *Fatigue Pre-Cracking*—Specimens may also be pre-cracked at room temperature or at a temperature between ambient and test temperature under fatigue forces with a R-Ratio preferably of 0.1.

$$P_f = \frac{0.4B_N (W - a_o)^2 \sigma_{ys}}{(2W - a_o)} \tag{6}$$

8.8.3.1 For the final 0.64 mm (0.025 in.) of fatigue pre-crack extension, the maximum force shall be no larger than P_f or a value such that the ratio of stress intensity factor range to Young's Modulus ($\Delta K/E$) is equal to or less than 0.0025 $mm^{1/2}$ (0.0005 $in.^{1/2}$), whichever is less. The accuracy of the fatigue force value shall be within ±5 %. The force range shall be no less than 90 % of the maximum force. The stress intensity factor range, ΔK, may be calculated using equations provided in A2.2.

8.8.4 The maximum force during the last 0.5 mm (0.02 in.) of pre-fatigue crack extension must not exceed the force used during creep crack growth testing.

8.8.5 To facilitate fatigue pre-cracking at low stress ratios, the machined notch root radius can be approximately 0.075 mm (0.003 in.). It may at times be expedient to have an EDM notch of 0.1 mm width to enhance the fatigue crack growth. A chevron form of machined notch as described in Test Method E399 or pre-compression of the straight through notch as described in Test Method E399 may be helpful when control of crack shape is a problem.

8.8.6 Pre-cracking is to be done with the material in the same heat-treated condition as that in which it will be tested for creep crack growth behavior. No intermediate heat treatments between pre-cracking and testing are allowed.

8.8.7 The size of the pre-crack extension from the machined notch shall be no less than 0.05 *a/W*.

8.9 *Specimen Preparation for Electric Potential Measurement:*

8.9.1 The stability of the EPD system both due to the electronics and environmental changes is very important in CCG testing as the period of some tests are measured in months or possibly years. It is possible to determine the stability by placing a second EPD probe remote from the crack to check the reference signal change which is independent of any crack growth. In this way if there is found to be a difference the main EPD crack signal can be subtracted from the reference signal.

8.9.2 The procedure for using EPD to measure crack length is presented in Annex A4 and detailed in reference **(53, 54)**. It should be noted that for all the geometries in Fig. A1.1 it is recommended to follow the procedures set out here.

8.9.3 For gripping fixtures and wire selection and attachment also refer to the Annex in Test Method E647.

8.10 *Attachment of Thermocouples and Input Leads:*

8.10.1 The potential drop could be AC or DC powered. The input should be remote from the crack either welded or screw threaded. See Fig. A1.3 for C(T) specimen geometry.

8.10.2 A thermocouple must be attached to the specimen for measuring the specimen temperature. The thermocouple should be located in the un-cracked ligament region of the specimen 2 to 5 mm (0.08 to 0.2 in.) above or below the crack plane. Multiple

thermocouples are recommended for specimens wider than 50 mm (2 in.). These thermocouples must be evenly spaced over the un-cracked ligament region above or below the crack plane as stated above.

8.10.3 In attaching thermocouples to a specimen, the junction must be kept in intimate contact with the specimen and shielded from radiation, if necessary. Shielding is not necessary if the difference in indicated temperature from an unshielded bead and a bead inserted in a hole in the specimen has been shown to be less than one half the permitted variations in 10.3.2. The bead should be as small as possible and there should be no shorting of the circuit (such as could occur from twisted wires behind the bead). Ceramic insulators should be used in the hot zone to prevent such shorting.

8.10.4 Specifications in Test Methods E139 identify the type of thermocouples that may be used in different temperature regimes. It is important to note that creep crack growth test durations are invariably long. Thus, a stable temperature measurement method should be used to reduce experimental error.

9. Calibration and Standardization

9.1 Performance of the electric potential system, the force measuring system, the temperature measurement systems and the displacement gage must be verified. Calibration of these devices should be as frequent as necessary to ensure that the errors for each test are less than the permissible indicated variations cited in this standard. The testing machine should be calibrated at least annually or, for tests that last for more than a year, after each test. Instruments in constant (or nearly constant) use should be calibrated more frequently; those used occasionally must be calibrated before each use.

9.1.1 Calibrate the force measuring system according to Practices E4 and E74.

9.1.2 Calibrate the displacement gage according to Method E83.

9.1.3 Verify electric potential system according to guidelines in Annex A4 and recommendation in Section 11.

9.1.4 Calibrate the thermocouples according to Test Method E220.

10. Test Procedure

10.1 *Plans for a Test Matrix*—A test matrix should be setup identifying, as far as possible, the goals for the tests such as the planned test times, available specimens, number of tests and the force levels that may be needed for the tests. Availability of spare specimens is essential as repeat tests may be required in some instances.

10.2 *Number of Tests*—Creep crack growth rate data exhibit scatter. The *da/dt* values at a given value of $C^*(t)$ and C_t can vary by as much as a factor of 2 **(45, 52)** for creep-ductile materials if all other variables such as geometry, specimen size, crack size, loading method and temperature are kept constant. For creep-brittle materials, the scatter in *da/dt* versus *K* relationship can be up to a factor of 4 **(35)**. This scatter may be increased further by variables such as micro-structural differences, force precision, environmental control, and data processing techniques. Therefore, it is good practice to conduct replicate tests; when this is impractical, multiple specimens (at least 4) should be planned such that regions of overlapping *da/dt* versus $C^*(t)$,C_t or *K* data are obtained. Confidence in the inferences drawn from the data will increase with the number of tests and the number of tests will depend on the end use of the data.

10.3 *Specimen Installation:*

10.3.1 Install the specimen on the machine by inserting both pins, then apply a small force (approximately 10 % of the intended test force) to remove slack from the loading train. Connect the current input and voltage leads to the current source and potentiometer, respectively. Attach the displacement gage to the specimen and the thermocouple to the appropriate potentiometer. Bring furnace into position and start heating the specimen.

10.3.2 Choose the appropriate force that will give the required specimen failure times. This can be calculated using previous tests of the same batch if available or estimated from available data in the literature on similar materials. If none is available the first test should be tested with incremental force increases to identify the failure force levels.

10.3.3 As an example the initial *K* (to compare to fracture toughness levels) and references stress (to compare to creep rupture times of uniaxial specimens) at force-up would give a good indication of the test lifetimes for most alloys **(12, 13)**.

10.3.4 Before the test force is applied and for the duration of the test, do not permit the difference between the indicated temperature and the nominal test temperature to exceed the following limits: *(a)* Up to and including 1000°C (1800°F) ±2°C (±3°F) above 1000°C (1800°F) ±3°C (±5°F). *(b)* The term "indicated temperature" means the temperature indicated by the temperature measuring device using good quality pyro-metric practice.

NOTE 4—It is recognized that the true temperature may vary more than the indicated temperature. Permissible indicated temperature variations in 10.3.5 are not to be construed as minimizing the importance of good pyro-metric practice and precise temperature control. All laboratories should keep indicated and true temperature variations as small as practical. It is well recognized, in view of the extreme dependency of material properties to temperature, that close temperature control is necessary. The limits prescribed represent ranges that reflect common practice.

10.3.5 Temperature overshoots during heating should not exceed the limits above. It may be desirable to stabilize the furnace at a temperature from 5 to 30°C (10 to 50°F) below the nominal test temperature before making final adjustments. Report any temperature overshoot with regard to magnitude and duration.

10.3.6 The time for holding at temperature prior to start of test should be governed by the time necessary to ensure that the temperature can be maintained within the limits specified in 10.3.4. This time will not be less than one hour per 25 mm (1 in.) of specimen thickness. Report the time to attain test temperature and the time at temperature before loading.