Designation: E 1457 – 00

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

This standard is issued under the fixed designation E 1457; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of creep crack growth rates in metals at elevated temperature using compact type, *C(T)*, (see Fig. 1) specimens subjected to static or quasi-static loading conditions. The time rate of crack growth, $\dot{a}$ (*t*) or *da/dt* is expressed in terms of the magnitude of crack growth rate relating parameters, $C^*(t)$, C_t or *K*.

1.1.1 The choice of the crack growth rate relating parameter, $C^*(t)$, C_t, or *K* depends on the material behavior. Two types of material behavior are generally observed during creep crack growth tests; creep-ductile and creep-brittle. In creep ductile materials, creep crack growth is accompanied by substantial time-dependent creep strains at the crack tip and the crack growth rate is correlated by $C^*(t)$ and/or C_t **(1-4)**.[2] 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, *K* is chosen as the correlating parameter **(5)**.

1.1.2 In creep ductile materials, extensive creep occurs when the entire uncracked ligament undergoes creep deformation. Such conditions are distinct from the conditions of small-scale creep and transition creep **(4, 6)**. In the case of extensive creep, the region dominated by creep deformation is significant in size in comparison to the crack size and to the uncracked ligament size. In small-scale-creep only a small region of the uncracked ligament near the crack tip experiences creep deformation. 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 **(4)**.

1.1.3 Only steady-state creep crack growth rate behavior is covered by this method. During steady state, a unique correlation exists between $\dot{a}$ and the appropriate crack growth rate relating parameter. Transient crack growth conditions occur in the early stages of crack growth tests for the whole range of creep brittle/ductile behavior which is excluded by this method.

1.1.4 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 and geometry also will affect the state-of-stress at the crack tip and are important factors in determining crack growth rate.

1.1.5 The recommended specimen is the standard compact tension specimen *C(T)* with $B/W = 0.5$ and pin loaded in tension under constant loading conditions, Fig. 1. The specimen configuration has fixed planar dimensional proportionality with an initial normalized crack size, a_o/W, of 0.45 to 0.55. Side-grooved specimens are recommended to promote uniform crack extension across the thickness of the specimen **(7)**.

1.1.6 Residual stresses can influence the measurement of crack growth properties **(8)**. The effect can be significant when test coupons are taken from material that characteristically embodies residual stress fields; for example weldments, and/or thick cast, forged, extruded, products and product shapes where full stress relief is impractical. Specimens taken from such products that contain residual stresses will likewise themselves contain residual stresses. Extraction of specimens in itself partially relieves and redistributes the residual stress pattern, however, the remaining magnitude can still cause significant effects in the ensuing test. Residual stress is superimposed on applied stress and results in crack-tip stress intensity that is different from that based solely on externally applied forces or displacements. Distortion during specimen machining often indicates the presence of residual stresses. No allowance is included in this standard for dealing with residual stresses.

1.1.7 Specimen configurations other than the *C(T)* specimen tested under constant load may involve validity requirements different from those presently specified in this test method. Nevertheless, use of geometries other than *C(T)* are permitted by this method provided data are compared to data obtained from *C(T)* specimens. Other specimens used in creep crack growth testing include the Single Edge Notch Bend *(SENB)* specimen, Single Edge Notch Tension *(SENT)* specimen, Middle Cracked Tension *M(T)* specimen.

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*

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

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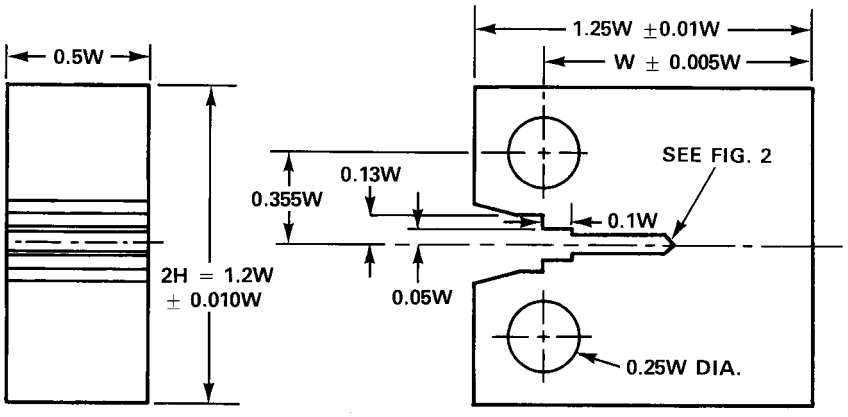
[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.



COMPACT TEST SPECIMEN FOR PIN OF 0.24W (+0.000W/−0.005W) DIAMETER

FIG. 1 Drawing of a Standard *C(T)* Specimen

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:*

E 4 Practices for Force Verification of Testing Machines[3]

E 74 Practice for Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines[3]

E 83 Practice for Verification and Classification of Extensometers[3]

E 139 Practice for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials[3]

E 220 Method for Calibration of Thermocouples by Comparison Techniques[4]

E 399 Test Method for Plane-Strain Fracture Toughness of Metallic Materials[3]

E 647 Test Method for Measurement of Fatigue Crack Growth Rates[3]

E 1820 Standard Test Method for Measurement of Fracture Toughness

E 1823 Terminology Relating to Fracture Testing[3]

3. Terminology

3.1 *Definitions*:

3.1.1 Terminology related to fracture testing contained in Terminology E 1823 is applicable to this test method.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *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.

3.2.1.1 *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:

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

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,

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 (see Fig. 2 of Terminology E 616), and

$T \cdot \frac{\partial \dot{u}}{\partial x}\, ds$ = the rate of stress-power input into the area enclosed by Γ.

The value of $C^*(t)$ from this equation is path-independent for materials that deform according to the following constitutive law that is separable into single-value time and stress functions of the form:

$$\dot{\epsilon} = f_1(t)\, f_2(\sigma),$$

f_1 and f_2 represent functions of elapsed time, t, and applied stress, σ, respectively; $\dot{\epsilon}$ is the strain rate.

3.2.1.2 *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.

3.2.1.3 *Discussion*—The value of $C^*(t)$ corresponding to the steady-state conditions is called C_s^*. Steady-state is said to have been achieved when a fully developed creep stress distribution has been produced around the crack tip.

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

3.2.2.1 *Discussion*—The value of C_t is path-independent

[3] *Annual Book of ASTM Standards*, Vol 03.01.

[4] *Annual Book of ASTM Standards*, Vol 14.03.

and is identical to $C^*(t)$ for extensive creep conditions when the constitutive law described in 3.2.1 applies.

3.2.2.2 *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 (see section 3.2.3 for definition). Under these circumstances, C_t is related uniquely to the rate of expansion of the creep zone size **(9, 10)**. There is considerable experimental evidence that the C_t parameter **(4, 7, 10)** which extends the $C^*(t)$-integral concept into the small-scale creep and the transition creep regimes and is equal to $C^*(t)$ in the extensive creep regime, correlates uniquely with creep crack growth rate in the entire regime ranging from small-scale to extensive creep regime.

3.2.3 *creep zone boundary*—the creep zone boundary is defined as the locus of points ahead of the crack front where the equivalent strain caused by the creep deformation equals 0.002 (0.2%) **(11)**.

3.2.3.1 *Discussion*—Under small-scale creep conditions, the creep zone expansion with time occurs in a self-similar manner **(6)** 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.

3.2.4 *crack size*—a [L]-in this test method, the physical crack size is represented as a_p. The subscript, p, is everywhere implied (see Terminology E 1823).

3.2.5 *crack-plane orientation*—an identification of the plane and direction of a crack growth test specimen 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 (see Terminology E 1823 for further discussion).

3.2.6 *creep crack growth behavior*—a plot of the time rate of crack growth, *da/dt*, as a function of $C^*(t)$, C_t, or K.

3.2.7 *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 (see Terminology E 1823, for further discussion).

3.2.8 *load-line displacement due to creep, V_c*[L]—additional displacement at the loading pins due to the crack that is directly associated with the accumulation of creep strains.

3.2.8.1 *Discussion*—In creeping bodies, additional load-point displacement caused by crack, V, can be partitioned into an instantaneous part, V_i, and a time-dependent creep part, V_c.

$$V = V_i + V_c \tag{1}$$

3.2.8.2 *Discussion*—the symbol for the rate of load-line displacement related to creep is called $\dot{V}_c$.

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

3.2.10 *original crack size a_o (L)*—the physical crack size at the start of testing.

3.2.11 *specimen thickness, B[L]*—distance between sides of the specimen.

3.2.12 *specimen width, W[L]*—distance from the reference plane to the back surface of the specimen. The reference plane in *C(T)* specimens is the plane normal to the sides containing the load-line.

3.2.13 *stress intensity factor, K[FL$^{-3/2}$]*—the magnitude of the ideal crack tip stress field (a stress-field singularity) for Mode 1 in a homogeneous, linear-elastic body (see Terminology E 1823, for further discussion).

3.2.14 *transition time, t_T[T]*—time required for extensive creep conditions to develop in a cracked body. For test specimens, this is typically the time required for the zone of creep deformation to spread through a substantial portion of the uncracked ligament, or in the region which is under the influence of a crack in the case of a finite crack in a semi-infinite medium.

3.2.15 *yield strength, σ_{YS}[FL^{-2}]*—the stress at which the material exhibits a deviation equal to a strain of .002 from the proportionality of stress to strain.

3.2.16 *crack initiation period, t_o[T]*—the time prior to first 0.2 mm (.008 in) of crack extension by creep.

4. Summary of Test Method

4.1 The objective of creep crack growth testing is the determination of the relationship between the time rate of crack growth, *da/dt*, due to creep and the applied value of the appropriate crack growth rate relating parameter as stated in 1.1.1. This test method involves loading of sharply notched specimens or fatigue pre-cracked specimens 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 crack size and load-line displacements are continuously recorded, digitally or autographically on strip-chart recorders, as a function of time. The temperature must be monitored to ensure that it remains constant within allowable limits during the test. If servomechanical 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.

4.2 The force, load-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.

4.3 Three different loading methods are available for creep crack growth testing. Dead weight loading is highly recommended and is the most commonly used method for loading specimens. In addition, constant displacement **(12)** and constant displacement rate **(1, 3)** 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 to data and analysis from tests performed under dead-weight loading conditions.

5. Significance and Use

5.1 Creep crack growth rate expressed as a function of $C^*(t)$-integral, $C^*(t)$, or K characterizes the resistance of a material to crack growth under conditions of extensive creep deformation. Background information on the rationale for employing the fracture mechanics approach in the analyses of creep crack growth data is given in **(7, 9, 13, 14)**.

5.1.1 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.

5.1.2 Expressing *da/dt* as a function of an appropriate crack growth rate relating parameter, as discussed in section 1.1.1, generally provides results that are independent of specimen size and planar geometry for the same stress state at the crack tip. 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 rate 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(s) crack growth rate relating parameter(s) are met.

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

5.1.4 Different geometries as mentioned in 1.1.7 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 *C(T)* specimens and a full set of validation conditions for this specimen is specified. If other specimen geometries such as the ones mentioned in 1.1.7 are used for generating creep crack growth data, then the *da/dt* data obtained must be compared against test data derived from the standard *C(T)* tests.

5.1.5 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 **(15)**. The duration of this transient condition 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 **(16)**. The steady-state crack extension which follows this period is characterized by a unique *da/dt* versus $C^*(t)$, C_t or K relationship. The transient region, especially in creep-brittle materials, can be present for a substantial fraction of the overall life **(17)**. Criteria are provided in this standard to separate the transient and steady-state portions of creep crack growth.

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

5.2.1 Establish the influence of creep crack growth on component life under conditions of sustained loading at elevated temperature wherein creep deformation may occur provided that the experimental data are generated under representative loading and stress-state conditions and combined with appropriate fracture or plastic collapse criterion, defect characterization data, and stress analysis information **(18)**.

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

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

5.3 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 around the crack. 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.

6. Apparatus

6.1 *Testing Machine*:

6.1.1 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.

6.1.2 The accuracy of the testing machine shall be within the permissible variation specified in Practice E 4.

6.1.3 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.

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

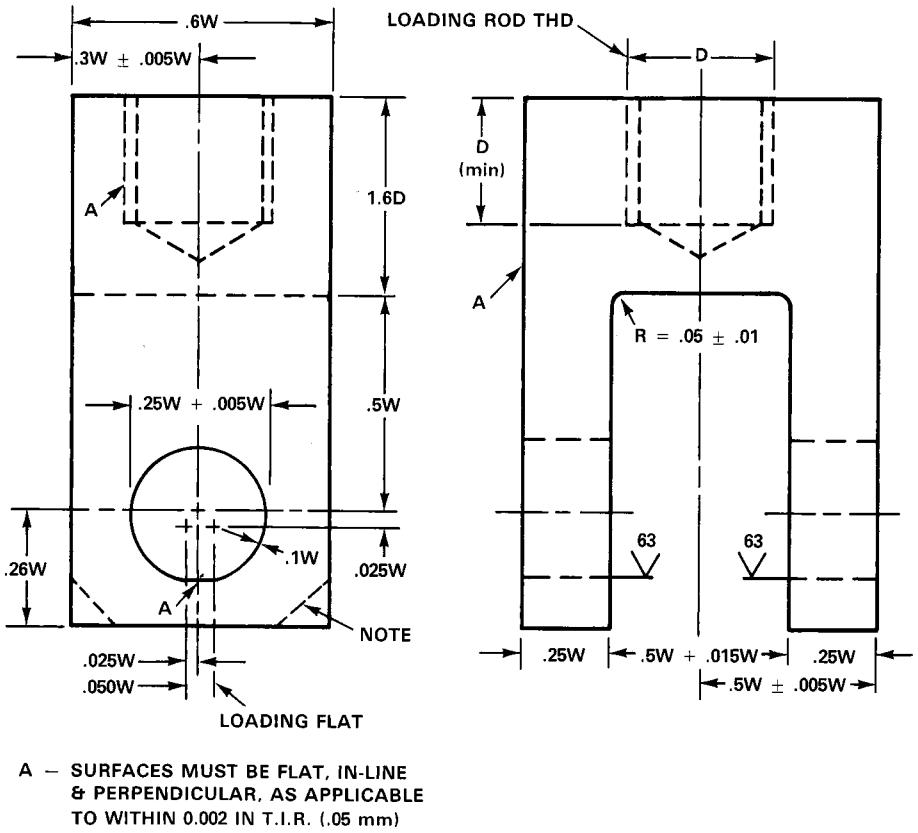
6.2 *Grips and Fixtures for C(T) Specimens*:

6.2.1 Clevis assemblies (see Fig. 2) shall be incorporated in the load train at both the top and bottom of the specimen to allow in-plane rotation as the specimen is loaded.

6.2.2 Suggested proportions and critical tolerances of the clevis are given (see Fig. 2) in terms of the specimen width, *W*.

6.2.3 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 $C^*(t)$.

6.2.4 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-base superalloys like alloy 718 or alloy X750. The loading pins are machined from A286 steel (or equivalent temperature



NOTE 1—Corners of the clevis may be removed as necessary to accommodate the clip gage.

FIG. 2 Clevis Assembly

resistant steel) and are heat treated such that they develop a high resistance to creep deformation and rupture.

6.3 *Alignment of Grips*—It is important that attention be given to achieving good alignment in the load train through careful machining of all gripping fixtures (see Fig. 2 for machine tolerances). The length of the load train should be chosen with proper attention to the height of the furnace for heating the test specimen.

6.4 *Heating Apparatus*:

6.4.1 The apparatus for, and method of, heating the specimens should provide the temperature control necessary to satisfy the requirements of 9.2.2 without manual adjustments more frequent than once in each 24-h period after load application.

6.4.2 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 1—The test conditions in which the tests are performed may have a considerable effect on the results of the tests. This is particularly true when properties are influenced by oxidation or other types of corrosion.

6.5 *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 9.2.2. For details of types of apparatus used see Specification E 139.

6.6 *Displacement Gage*:

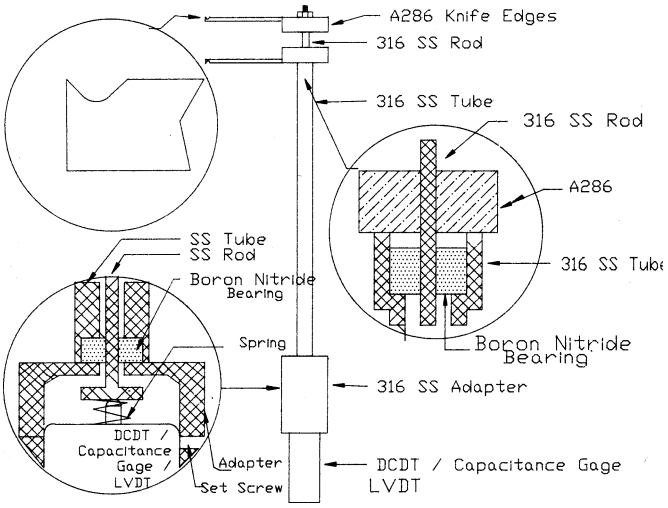
6.6.1 Continuous displacement measurement is needed to evaluate the magnitude of $C^*(t)$ and C_t at any time during the test. Displacement measurements must be made on the load-line.

6.6.2 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.

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

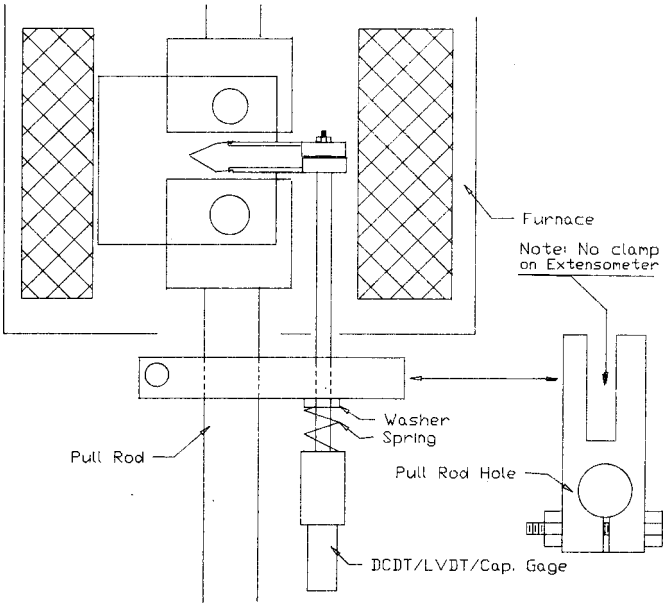
6.6.4 The displacement along the load-line may be directly measured by attaching the entire clip gage assembly to the specimen and placing the whole assembly in the furnace. Alternatively, the displacements can be transferred outside the furnace with a rod and tube assembly such as that shown in Figs. 3 and 4. 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.

6.7 *Apparatus for Crack Size Measurement*—A crack size monitoring technique capable of reliably resolving crack extensions of at least ± 0.1 mm (0.004 in.) 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



NOTE 1—The rod and tube must be made from the same material.

FIG. 3 Schematic of a Clip Gage Assembly for Measuring Load-Line Deflection



NOTE 1—The materials used must be adequate for the test temperature.

FIG. 4 Schematic of an Overall Test Set-Up Showing the Clip Gage As Attached to the Specimen

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 A1.

NOTE 2—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.

6.8 *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 9.2.2.

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

7. Specimen Configuration, Dimensions, and Preparation

7.1 *Specimen Configuration*:

7.1.1 The configuration of the standard *C(T)* specimen is shown in Fig. 1.

7.1.2 The crack starter slot width for the compact specimens shall lie within the envelope shown in Fig. 5.

7.1.3 The width-to-thicknes ratio, *W/B*, recommended is 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.

7.1.4 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 times the width. This may be varied within the above interval depending on the selected load level for testing and the desired test duration.

7.2 To meet crack front straightness requirements imposed in 10.2.2, side-grooved specimens may be required. 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 $\leq 0.4 \pm 0.2$ mm (0.016 ± 0.008 in.). 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.

7.3 *Specimen Size*— There are no specific size requirements imposed in this method. However, specimen size must be chosen with consideration to the 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.

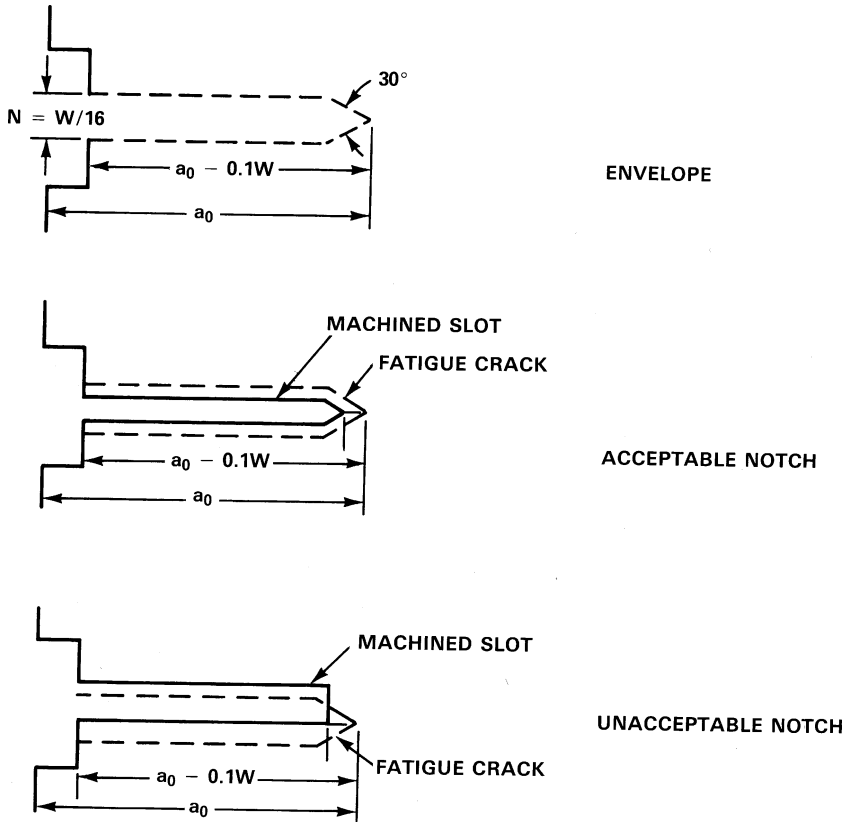
7.4 *Notch Preparation*—The machined notch for the test specimens may be made by electrical-discharge machining (EDM), milling, broaching, or saw cutting. Associated pre-cracking requirements are shown in Fig. 5.

7.5 *Specimen Measurements*—The specimen dimensions shall be within the tolerances given in Fig. 1.

7.6 *Precracking*—Fatigue pre-cracking is recommended for most situations. However a narrow slit induced by an electro-discharge machine (EDM) can also be used as a crack starter. For example EDM is preferable for some creep-brittle materials such as intermetallics **(19)** due to difficulties in growing cracks with straight fronts. Both methods of pre-cracking are described.

7.6.1 *EDM pre-crack*—The width of the EDM pre-crack shall not exceed 0.1 mm. Precautions must be taken to avoid any over-heating, however localized, which may alter the microstructure of the material near the crack tip.

7.6.2 *Fatigue pre-cracking*—Specimens may also be pre-cracked at room temperature or at a temperature between ambient and test temperature under fatigue forces not to exceed the maximum value, P_f as given by:



NOTE 1—*N*, need not be less than 1.6 mm (1/16 in.) but must not exceed *W*/16.

NOTE 2—The intersection of the crack starter surfaces with the two specimen faces shall be equidistant from the top and bottom edges of the specimen within 0.005.

FIG. 5 Starter Crack Envelope

$$P_f = \frac{0.4\, B_N (W - a_o)^2 \sigma_{ys}}{(2W + a_o)} \quad (2)$$

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 10.4.3.

7.6.2.1 The maximum force during the last 0.5 mm (0.02 in.) of crack extension must not exceed the load used during creep crack growth testing.

7.6.2.2 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 0.25 mm (0.01 in.) size to enhance the fatigue crack initiation. A chevron form of machined notch as described in Test Method E 399 or pre-compression of the straight through notch as described in Test Method E 399 may be helpful when control of crack shape is a problem.

7.6.3 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.

7.6.4 The size of the pre-crack extension from the machined notch shall be no less than 5 % of the total crack size, a_o, and not less than 1.3 mm (0.05 in.).

7.6.5 Care must be exercised during pre-cracking by either method to avoid excessive damage at the notch root.

7.7 *Specimen Preparation for Electric Potential Measurement*—For gripping fixtures and wire selection and attachment refer to the annex in Test Method E 647.

7.8 *Attachment of Thermocouples*:

7.8.1 A thermocouple must be attached to the specimen for measuring the specimen temperature. The thermocouple should be located in the uncracked 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 uncracked ligament region above or below the crack plane as stated above.

7.8.2 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 variation in 9.2.2. 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.

7.8.3 Specifications in E 139 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.

8. Calibration and Standardization

8.1 Performance of the electric potential system, the force measuring system 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 practice. 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.

8.1.1 Calibrate the load measuring system according to Practices E 4 and E 74.

8.1.2 Calibrate the displacement gage according to Method E 83.

8.1.3 Verify electric potential system according to guidelines in Annex A1.

8.1.4 Calibrate the thermocouples according to Method E 220.

9. Procedure

9.1 *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 a factor of two **(7, 20)** 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 **(17)**. This scatter may be increased further by variables such as microstructural differences, force precision, environmental control, and data processing techniques. Therefore, it is good practice to conduct replicate tests; when this is impractical, multiple specimens 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.

9.2 *Specimen Installation*:

9.2.1 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.

9.2.2 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:

9.2.2.1 Up to and including 1000°C (1800°F) ± 2°C (± 3°F) above 1000°C (1800°F) ± 3°C (± 5°F).

9.2.2.2 The term "indicated temperature" means the temperature indicated by the temperature measuring device using good quality pyrometric practice.

NOTE 3—It is recognized that the true temperature may vary more than the indicated temperature. Permissible indicated temperature variations in 9.2.2 are not to be construed as minimizing the importance of good pyrometric 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.

9.2.3 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.

9.2.4 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 9.2.2. 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.

9.2.5 Any positive temperature excursion beyond the limits specified in 9.2.2 is cause for rejection of the test. Negative temperature excursions wherein temperature falls below the specified limits should not be cause for rejection. Low temperatures do not induce the potentially adverse material changes associated with elevated temperatures. It is recommended that the crack growth data obtained during the low temperature excursion and during the period corresponding to 0.5 mm (0.02 in.) of crack extension following stabilization of the temperature be considered invalid and excluded.

9.2.6 The current for the electric potential system should be turned on at the same time as the furnace. This is necessary to ensure that resistance heating of the specimen caused by the applied current also stabilizes as the specimen is brought up to the test temperature.

9.3 *Loading Procedures*:

9.3.1 For constant force testing, a small fraction of the test force (not exceeding 10 %) may be applied before and during heating of the specimen. This procedure usually improves the axiality of loading by reducing the displacement caused by lateral forces.

9.3.2 Apply the test carefully so that shock forces or inertial overloads are avoided. The force should be applied in increments and the displacement should be monitored to ensure that the extensometer is properly seated. The time for application of the force should be as short as possible within these limitations.

9.4 *Measurements During the Test*—The electric potential voltage, force, load-line displacement, and test temperature should be recorded continuously during the test if autographic strip chart recorders are used. If digital data acquisition systems are used, the frequency of sampling should be no less than a full set of readings every fifteen minutes.

NOTE 4—If dead-weight creep machines are used for conducting the tests, it is not necessary to make load measurements.

NOTE 5—If dc current potential technique is used, the no current voltage (see Annex A1) should be measured. These measurements should

be made at least once every 24 h.

9.5 *Post-Test Measurements*:

9.5.1 When the test is complete, remove the force and turn off the furnace. After the specimen has cooled down, remove the specimen from the machine.

9.5.2 If the specimen did not fracture at the end of the test, it should be broken open taking care to minimize additional permanent deformation. The use of cyclic loading to break open the specimen works well. Also, ferritic steels may be cooled to a temperature below the ductile-brittle transition and fractured.

NOTE 6—It is highly recommended to terminate a test prior to fracture because the final crack front is delineated more clearly and can be accurately measured for verifying the potential drop measurement.

9.5.3 Along the front of the pre-crack and the front of the marked region of creep crack growth, measure the crack size at nine equally spaced points centered on the specimen mid-thickness line and extending to 0.005 *W* from the roots of the side-grooves. Calculate the original crack size, a_o, and the final crack size, a_f, as follows: average the two near-surface measurements, combine the result with the remaining seven crack length measurements and determine the average. The measuring instrument shall have an accuracy of 0.025 mm (0.001 in.).

10. Calculation

10.1 *Determination of Crack Size*—Following the procedure described in Annex A1, determining the crack size during the test as a function of time.

10.1.1 The test should be stopped as soon as both the potential drop and the displacement measurement indicate that the tertiary stage of crack growth has begun and that final failure of the specimen is imminent. Determine the crack size from the electric potential reading using the linear interpolation method described in A1.1. Then calculate the crack extension, Δa_f, by subtracting the initial crack size, a_o, from the value of the final crack size, a_f. The final crack size shall be determined from surface fractography measurements where possible. If $\Delta a_f / a_o > 0.2$, use the procedure in section 10.1.2 to estimate crack size versus time behavior.

10.1.2 If failure of the specimen occurs prior to the stoppage of the test then fractography measurements of the final crack size may not be possible. In this case or when $\Delta a_f / a_o > 0.2$, determine the crack size following the procedure described in A1.2, using a predictive formula. The crack size from the electric potential reading can be used to calculate the predicted crack extension, Δa_{pf}, by subtracting the initial crack size, a_o, from the predicted value of the final crack size, a_{pf}.

10.2 *Validation of Test*—The crack size data, using this method, are valid for further processing if it is ensured that the crack size measurements are within the required limits as follows:

10.2.1 If method 10.1.2 is used to determine crack size then the data are valid for further processing if:

$$0.85 \le \left(\frac{\Delta a_{pf}}{(a_f - a_o)} \right) \le 1.15 \tag{3}$$

NOTE 7—If a_f is unknown, a check using this equation is not possible. It is recommended that measurements from tests in question be compared with other valid data under similar conditions prior to inclusion in the data set.

10.2.2 *Original Crack Size*—If any of the nine physical measurements of original pre-crack size differ by more than 5 % from the original crack size, as defined in 9.5.3, the test is not valid.

10.2.3 *Final Crack Size*— If any of the nine physical measurements of the final pre-crack size differ by more than 5 % from the final crack size a_f defined in 9.5.3, the test is not valid. For subsequent specimens, the side groove configuration can be modified to facilitate meeting this requirement.

10.2.4 Any and all temperature excursions must be within the allowable levels in 9.2.2, otherwise the test is not valid.

10.3 *Determination of Crack Growth Rate and Load-Line Displacement Rate*:

10.3.1 From the recorded crack size and load-line deflection versus time results, choose the following data for further processing. The first data point consists of the pre-crack size with the corresponding time and accumulated deflection set at zero. Choose subsequent data points consisting of crack size and the corresponding load-line displacement and time, such that the minimum crack extension between successive data points is 0.25 mm (0.01 in.) and the minimum increment in deflection is 0.1 % of the full range of the extensometer. The maximum allowed Δa between successive readings is 0.02 *W*.

10.3.2 The creep crack growth rate and the load-line displacement rate can be determined from the crack size versus time (a versus t) and the load-line displacement versus time (V versus t) data. Recommended approaches that utilize the secant or incremental polynomial methods are given in Appendix X1.

NOTE 8—Both recommended methods for processing a versus t and V versus t data are known to give similar da/dt and dV/dt response. However, the secant method often results in increased scatter in da/dt and dV/dt relative to the incremental polynomial method, since the latter numerically smooths the data **(21)**. This apparent inconsistency introduced by the two methods needs to be considered, especially in utilizing creep crack growth data in design and remaining life prediction analyses.

10.4 *Calculation of Creep Displacement Rate*:

10.4.1 The dV/dt data must be processed further to calculate dV_c / dt (or $\dot{V}_c$) at the various times during the test.

10.4.2 $\dot{V}_c$ is calculated as follows **(22, 23)**:

$$\dot{V}_c = \dot{V} - \frac{\dot{a} B_N}{P} \left[\frac{2K^2}{E'} \right] \tag{4}$$

where:

$\dot{a}$ = crack growth rate, da/dt,
P = applied force,
E' = $E/(1–\nu^2)$ for plane strain and E for plane stress where, E = elastic modulus and ν = Poisson's ratio.
B_N = net section thickness
K = stress intensity factor

NOTE 9—When working with highly ductile materials such as austenitic stainless steels, it may be necessary to include additional terms in the equation in section 10.4.2 to account for plasticity. Guidelines for including plasticity in calculating creep deflection rate are provided in Appendix X2.

10.4.3 The expression for calculating K is given below **(24)**:

$$K = \frac{P}{(BB_N)^{\frac{1}{2}} W^{\frac{1}{2}} (1 - a/W)^{\frac{3}{2}}} \frac{2 + a/W}{} f\,(a/W) \quad (5)$$

where:

$$f(a/W) = 0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4 \quad (6)$$

10.5 The crack growth rate relating parameters $C^*(t)$, C_t and K for the *C(T)* are calculated using the following expressions.

10.5.1 *Determination of C*(t)-Integral*—The magnitude of the $C^*(t)$-integral for the *C(T)* specimen at each point can be determined as follows **(3, 14)**:

$$C^*(t) = \frac{P\dot{V}_c}{B_N(W - a)} \frac{n}{n + 1} \left(2 + 0.522 \frac{W - a}{W}\right) \quad (7)$$

where:

n = creep exponent in the relationship between minimum creep rate and applied stress. The value of n may be obtained from creep test data in accordance with Practice E 139. If creep tests cannot be performed, the accepted value of n from the literature may be used. The n value used and its source must be reported.

10.5.2 *Determination of* C_t— The magnitude of C_t should be estimated as follows **(4)**:

$$C_t = \frac{P\dot{V}_c}{(BB_N)^{\frac{1}{2}} W} (F'/F) \quad (8)$$

where,

$$F'/F = \left[\frac{1}{2(1 + a/W)} + \frac{3}{2(1 - a/W)}\right] + \frac{f'\,(a/W)}{f\,(a/W)} \quad (9)$$

f (a/W) is defined in section 10.4.3, and

$$f'(a/W) = 4.64 - 26.64(a/W) + 44.16(a/W)^2 - 22.4(a/W)^3 \quad (10)$$

10.6 *Validity Criteria*—Choosing the appropriate crack growth rate relating parameter: The choice of the most appropriate crack growth rate relating parameter depends on whether the material exhibits creep-ductile or creep-brittle behavior **(5, 10, 25)**. Steady-state creep crack growth rates in creep-ductile materials are correlated by C_t or $C^*(t)$. C_t is used for data in the small scale creep region to the extensive creep region and $C^*(t)$ for data in the extensive creep region. The steady-state creep crack growth rate in creep-brittle materials are correlated by K in this method.

10.6.1 Calculate the ratio of the $\dot{V}_c / \dot{V}$ for each data point. If $\dot{V}_c / \dot{V} \geq 0.5$, the data are classified as being creep-ductile and the candidate crack growth rate relating parameters are C_t or $C^*(t)$. Section 10.6.2 shows steps to determine whether the parameter should be C_t or $C^*(t)$. If $\dot{V}_c / \dot{V} \leq 0.25$ for which the data are classified as being creep-brittle the candidate parameter is K and the user must go to section 10.6.3 for further evaluation of the data.

NOTE 10—For $0.25 < \dot{V}_c / \dot{V} < 0.5$, the method does not provide specific recommendations for a crack growth rate relating parameter. The users are advised to correlate *da/dt* with C_t and also with K and report their findings. Some guidelines for treating such data are reported in reference **(26)**.

10.6.2 Data for which the time exceeds transition time, t_T, are correlated by $C^*(t)$ as calculated by equation in 10.5.1. The data for which time is $\leq t_T$, data are correlated only by C_t as calculated by equation in 10.5.2. The transition time t_T is estimated as follows:

$$t_T = \frac{K^2(1 - \nu^2)}{E(n + 1)C^*(t_T)} \quad (11)$$

The calculation of t_T depends on the value of $C^*(t_T)$. Thus, the following procedure must be used for its estimation. For time, t, corresponding to each data point, calculate t'_T using the above equation but substituting $C^*(t)$ for $C^*(t_T)$. t_T is then the largest value of t'_T in the entire data set.

10.6.3 For crack growth rate data in creep-brittle materials to correlate with K, the following requirements must be met:

initial crack extension of 0.2 mm must be disregarded **(13)** and $\dot{V}_c / \dot{V} \leq 0.25$

Data that do not meet the above requirements are not uniquely dependent on the magnitude of K and are not considered valid by this method. The scope of this standard does not cover creep brittle behavior where there is no steady state crack growth. However under these circumstances the initial value of stress intensity factor K, time to 0.2 mm initial crack extension and final failure time should be recorded. There are a number of methods being developed **(13)** for dealing with this situation.

10.7 *Further Validity Requirements*

10.7.1 The time required to achieve the first 0.2 mm (0.008 in.) of crack extension during a constant force test is referred to as the crack initiation period, t_o. It may constitute all or part of the transient region, as discussed in section 5.1.5. The crack growth behavior during the transient region is affected by creep damage development and in some creep-brittle materials can represent a substantial portion (up to as high as 80 %) of the test time **(17)**. It is recommended that a record of the time taken to obtain a crack extension of 0.2 mm be made as the crack initiation period, t_o and included as a part of the report. Any data gathered prior to 0.2 mm of crack extension must not be included in data used to calculate *da/dt*.

10.7.2 As stated in 10.7.1, t_o may include only a portion of the transient region in creep-brittle materials.

10.7.3 If, during the test, the crack deviates outside an envelope that encompasses the material between the planes that are oriented at ± 5° from the idealized plane of crack growth and that intersect the axis of loading, the data are invalid by this test method.

10.7.4 Data acquired after the accumulated load-line deflection, exceeds 0.05W, which could be due to either creep or plasticity, are considered invalid by this test method.

11. Report

11.1 Report the following information:

11.1.1 Specimen type and dimensions including thickness, B, net thickness, B_N (if side-grooved) and width, W,

11.1.2 Description of the test machine and equipment used to measure crack size and the precision with which crack size measurements were made,

11.1.3 Test material characterization in terms of the heat treatment, chemical composition, tensile properties at room temperature and test temperature, the pre-exponent A and the creep exponent n used in calculations, including how it was

derived. Also identify product size and form (for example, sheet, plate, and forging),

11.1.4 *Crack Plane Orientation*—In addition, if the specimen is removed from a large product form, give its location with respect to the parent,

11.1.5 The terminal value of K, P_{max}, P_{min}, the pre-cracking temperature, and the frequency of loading and the number of cycles used for fatigue pre-cracking. If pre-crack loads were stepped-down, state the procedure employed for the loading method and give the amount of crack extension at the final force level. If an EDM notch is used in-lieu of a fatigue pre-crack, report the root radius and the length of the notch,

11.1.6 State test force and experimental variables such as test temperature and environment. For environments other than laboratory air, report the chemical composition of the gas,

11.1.7 Report data analysis methods, including the technique used to convert crack size and deflection data into rates and the specific procedure used to correct for discrepancies between measured crack extension on the fracture surface with that predicted from the electric potential method,

11.1.8 Plot *da/dt*, versus $C^*(t)$, C_t or K. It is recommended that $C^*(t)$ be the abscissa and *da/dt*, be the ordinate. Log-Log co-ordinates are normally used. Report all data that violate the validity criteria of 10.6 and 10.7 and identify.

11.1.9 Report the time for the crack to extend by 0.2 mm,

11.1.10 Description of any occurrences that appear to be related to anomalous data (for example, transient behavior following test interruptions or changes in load-levels), and

11.1.11 It is desirable, but not required, to tabulate test results. When using this test method for presentation of results, the following information should be tabulated for each test: a, t, da/dt, V, $\dot{V}_c/\dot{V}$, $C^*(t)$, C_t, K, R, t_T, t_o.

12. Precision and Bias

12.1 *Precision*—The precision of *da/dt*, versus $C^*(t)$ or K is a function of inherent material variability as well as errors in measuring crack size, temperature, creep displacement rates and applied force levels. The required loading precision of 8.1.1 is readily attained by modern creep machines and by servo-mechanical test machines. The ± 1 % variation in force that is permitted can lead to ± 4 to ± 12 % variation in the value of $C^*(t)$ and C_t and 1 % variation in K; this translates to ± 3 to ± 10 % variation in *da/dt*, at a given $C^*(t)$, C_t or K value. However, in general the crack size and displacement measurement errors cause a more significant contribution to the variability in *da/dt* although this contribution is difficult to isolate since it is coupled to the analytic procedure for converting a versus t and V versus t to *da/dt* and *dV/dt*, and to the inherent variability in the material. Nevertheless, it is clear that the overall variation in *da/dt* is dependent on the ratio of crack size and displacement measurement interval to measurement error **(20)**. Furthermore, an optimum crack size measurement interval exists because of the fact that the interval should be large compared to the measurement error (or precision), but small in comparison to the $C^*(t)$ C_t or K gradient of the test specimens. These considerations form the basis for the recommended intervals of 10.3.1.

12.1.1 Although it is often impossible to separate the contributions from each of the above mentioned sources of variability, an overall measure of variability in *da/dt*, versus $C^*(t)$, C_t or K is available from the results of an interlaboratory test programs **(16, 17, 20)**. Some of these data, for example, obtained on highly homogeneous 1 Cr-1 Mo-0.25 V steel at 594°C (1100°F), showed the reproducibility in *da/dt* versus $C^*(t)$ or C_t to be ± 25 % **(20)**. Values cited are residual errors based on ± 2 residual standard deviations about the mean response determined from regression analysis. The *da/dt* data correlated with K exhibit much higher variability, up to a factor of 4 **(16, 27)**.

12.1.2 It is important to recognize that for the purposes of design or remaining life assessment, inherent material variability often becomes the primary source of variability in *da/dt*. The variability associated with a given lot of material is caused by inhomogeneities in chemical composition, microstructure, or both. These same factors coupled with varying processing conditions give rise to further lot-to-lot variabilities **(7, 28)**. An assessment of inherent material variability, either within or between heats or lots, can be determined only by conducting a statistically planned test program on the material of interest. Thus, the results cited above from the inter-laboratory test programs utilizing materials selected to minimize material variability allow assessment of measurement precision, but are generally not applicable to questions regarding inherent variability in other materials.

12.2 *Bias*—There is no accepted "standard" value for *da/dt* versus $C^*(t)$, C_t, K for any material. In the absence of such true value, no meaningful statement can be made concerning bias of data.

ANNEX

(Mandatory Information)

A1. GUIDELINES FOR USE OF ELECTRIC POTENTIAL DIFFERENCE (PD) FOR CRACK SIZE DETERMINATION

A1.1 *Voltage Versus Crack Size Relationships for C(T) Specimens*— The initial and final potential difference (PD) readings correspond to the initial and final crack sizes, respectively, during the test. For the intermediate points, crack size at any instant may be determined by a direct linear interpolation of the PD data corresponding to the measured initial crack size, a_o, and final measured crack size, a_f, provided both a_o and a_f can be precisely measured on the fracture surface of the specimen at the end of the test. Thus, the crack size at any instant, a is given by

$$a = \left[(a_f - a_o) \frac{(V - V_o)}{(V_f - V_o)} \right] + a_o \qquad \text{(A1.1)}$$

where, V_o and V_f are the initial and final potential difference readings, respectively and V is the instantaneous potential difference corresponding to the crack size, a. This method is not recommended when $\Delta a_f / a_o > 0.2$.

A1.2 If $\Delta a_f / a_o > 0.2$, a predetermined relationship between measured voltage and crack size suitable for the chosen specimen geometry and input and output lead locations may be used to determine crack size as a function of time. For example, for an input current and voltage lead locations shown in Fig. A1.1, the following closed form equation can be used to compute crack size from measured V/V_o values **(29, 30)**:

$$a/W = \frac{2}{\pi} \cos^{-1} \left[\frac{\cosh(\pi Y_o / 2W)}{\cosh\left[\frac{V}{V_o} \cosh^{-1} \left\{ \frac{\cosh \pi\, Y_o/2W}{\cos \pi\, a_o/2W} \right\} \right]} \right] \qquad \text{(A1.2)}$$

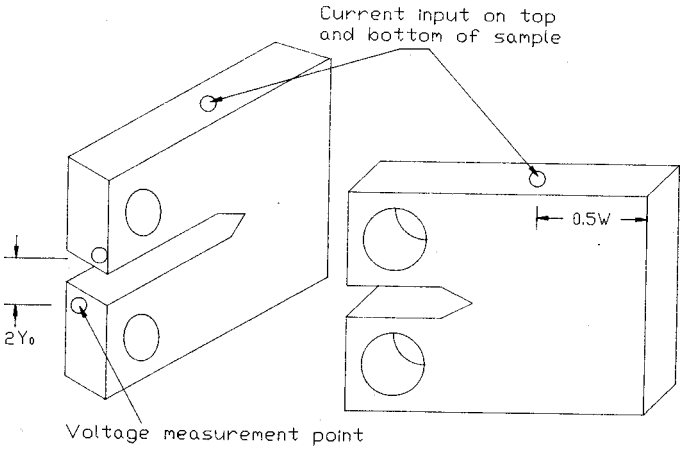


FIG. A1.1 Input Current and Voltage Lead Locations for Which the Eq A1.1 Applies

where:

a_o = reference crack size with respect to the reference voltage, V_o. Usually, a_o will be initial crack size, a_o and V_o is the initial voltage,
Y_o = half distance between the output voltage leads, and
V = output voltage.

NOTE A1.1—Equation A1.2 may also be used to estimate crack size as a function of time if the measured value of a_f is not available. In this instant, additional tests as recommended in Note 7 in section 10.2.1 must be performed to validate the data obtained on this specimen.

If the validity criterion in section 10.2.1 is met and a final crack size, a_f, is available, a correction of all data between a_o and a_f is recommended by linear interpolation as given by:

$$a = \left[\frac{(a_f - a_o)}{(a_{pf} - a_o)} (a_p - a_o) \right] + (a_o) \qquad \text{(A1.3)}$$

where:

a_{pf} = the final predicted crack size
a_f = the actual crack size
a_o = the initial crack size

A1.3 *Measurement of Thermal Voltage for Direct Current Technique*—The voltages V and V_o used for determining crack size in the equation in A1.1 may be different from their respective indicated readings when using a direct current technique. This difference is caused by the thermal voltage, V_{th}, caused by the minor differences in the junction properties or the resistances of the two output leads. An initial measurement of V_{th} is necessary. This can be accomplished by shutting off the current and recording the output voltage. In addition to the initial measurement, a periodic measurement of V_{th} also should be made by shutting off the current for short periods of time during testing. The values of V_{th} must be subtracted from the indicated values of V and V_o before substituting them in the equation given in A1.2.

NOTE A1.2—The guidelines for use of electric potential difference for crack size determination outlined in the annex of Test Method E 647 are applicable in their entirety for creep crack growth measurements also. The readers should consult this test method for recommendations on how to use this technique.

A1.4 *Discussion*—It should be noted that in some cases the initial PD readings at the beginning of the tests could drop before stabilization and eventually increase with crack extension. Conditions of initial loading, plasticity, excessive creep and damage and crack tip oxidation could effect the extent of this drop in the PD. In such cases, it is recommended that the minimum value of PD attained should be extrapolated back to zero time before crack size determinations are made. There is likelihood of increased scatter in crack size measurements during initial periods of testing.

APPENDIXES

(Nonmandatory Information)

X1. RECOMMENDED DATA REDUCTION TECHNIQUES

X1.1 *Secant Method:*

X1.1.1 The secant or point-to-point technique for computing crack growth rate and deflection rate simply involves calculating the slope of a straight line connecting two adjacent data points on the *a* versus *t* and the *V* versus *t* curve. It is formally expressed as follows:

$$\left(\frac{da}{dt}\right)_{\bar{a}} = (a_{i+1} - a_i)/(t_{i+1} - t_i) \tag{X1.1}$$

$$\left(\frac{dV}{dt}\right)_{\bar{a}} = (V_{i+1} - V_i)/(t_{i+1} - t_i) \tag{X1.2}$$

X1.1.2 Since the computed *da/dt* and *dV/dt* are average rate over the ($a_{i+1} - a_i$) increment, the average crack length, $\bar{a} = ½ (a_{i+1} + a_i)$, is normally used to calculate *K, J, C*(t)* and C_t.

X1.2 *Incremental Polynomial Method:*

X1.2.1 This method for computing *da/dt*, and *dV/dt* involves fitting a second order polynomial (parabola) to sets of (2 *n* + 1) successive data points, where *n* is commonly 3.

X1.2.2 The form of the equation for the local fits is as follows:

$$\hat{a}_i = b_{01} + b_{11}\left(\frac{t_i - C_1}{C_2}\right) + b_{21}\left(\frac{t_i - C_1}{C_2}\right)^2 \tag{X1.3}$$

$$\hat{V}_i = b_{02} + b_{12}\left(\frac{t_i - C_1}{C_2}\right) + b_{22}\left(\frac{t_i - C_1}{C_2}\right)^2 \tag{X1.4}$$

where:

$$-1 \le \left(\frac{t_i - C_1}{C_2}\right) \le +1 \tag{X1.5}$$

b_{01}, b_{11}, b_{21}, b_{02}, b_{12}, and b_{22} are regression parameters that are determined by the least squares method (that is minimization of the square of the deviations between observed and fitted values of crack length and deflection) over the range respectively. The values a_i and V_i are the fitted values of crack length and deflection at t_i. The parameters $C_1 = 0.5\ (t_{i-n} + t_{i+n})$ and $C_2 = 0.5\ (t_{i-n} - t_{i+n})$ are used to scale input data, thus avoiding numerical difficulties in determining the regression parameters. The rates of crack growth and increase in deflection at t_i are obtained from the derivatives of the Eq X1.3 and X1.4 and are given by the following expressions:

$$(da/dt)\hat{a}_i = b_{11}/C_2 + 2b_{21}(t_i - C_1)/C_2^2 \tag{X1.6}$$

and:

$$(dV/dt)\hat{V}_i = b_{12}/C_2 + 2b_{22}(t_i - C_1)/C_2^2 \tag{X1.7}$$

The values of *K, J, C *(t)* and C_t associated with the above rates are computed using the fitted crack length, $\hat{a}_i$, corresponding to t_i.

X2. RECOMMENDED METHOD FOR INCLUDING PLASTICITY IN ESTIMATION OF CREEP DEFLECTION RATE

In the presence of significant plastic deformation, the deflection rate due to creep may be estimated using the following equations **(22)**:

$$\dot{V}_c = \dot{V} - \frac{\dot{a}B_N}{P}\left(\frac{2K^2}{E'} + (m+1)J_p\right) \tag{X2.1}$$

J_p = fully-plastic contributions to J-integral
m = stress exponent in the Ramberg-Osgood stress versus strain relationship ($\epsilon_p = D_1(\sigma/\sigma_{ys})^m$), where, D_1 = constant

X2.1 Calculate the plastic contribution to *J*, J_p as follows for C_t specimens **(31)**:

$$J_p = \frac{D_1 h_1(a/W, m)}{(\sigma_{ys}(W-a))^m}\left(\frac{P}{1.455\,B_N\alpha}\right)^{m+1} \tag{X2.2}$$

where:

$\alpha = (\phi^2 + 2\phi + 2)^{1/2} - (\phi + 1)$

$\phi = \dfrac{2a}{(W-a)}$

D_1 and m are constants that relate to the material's stress-strain behavior and h_1 is a function of *a/W* and *m* and is given in Table X2.1 **(31)**.

TABLE X2.1 h_1 (*a/W, m*) Values for *C(T)* Specimens Under Plane Strain Conditions (31)

a/W	h_1								
	m = 1	2	3	5	7	10	13	16	20
0.25	2.23	2.05	1.78	1.48	1.33	1.26	1.25	1.32	1.57
0.375	2.15	1.72	1.39	0.970	0.693	0.443	0.276	0.176	0.098
0.50	1.94	1.51	1.24	0.919	0.685	0.461	0.314	0.216	0.132
0.625	1.76	1.45	1.24	0.974	0.752	0.602	0.459	0.347	0.248
0.75	1.71	1.42	1.26	1.033	0.864	0.717	0.575	0.448	0.345
1	1.57	1.45	1.35	1.18	1.08	0.950	0.850	0.730	0.630

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