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.

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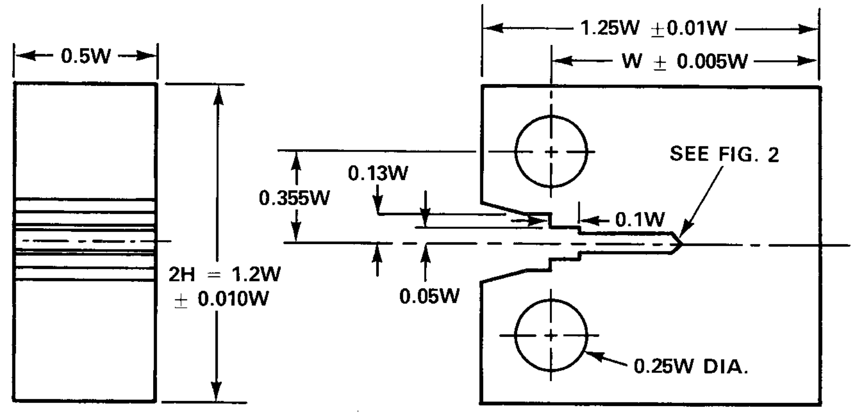
[1] This test method is under the jurisdiction of ASTM Committee E08 on Fracture Fatigue and is the direct responsibility of Subcommittee E08.06 on Crack Growth Behavior.

Current edition approved August 10, 2000. Published November 2000. Originally published as E 1457 – 92. Last previous edition E 1457 – 97.

[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

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 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.

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

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

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 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.

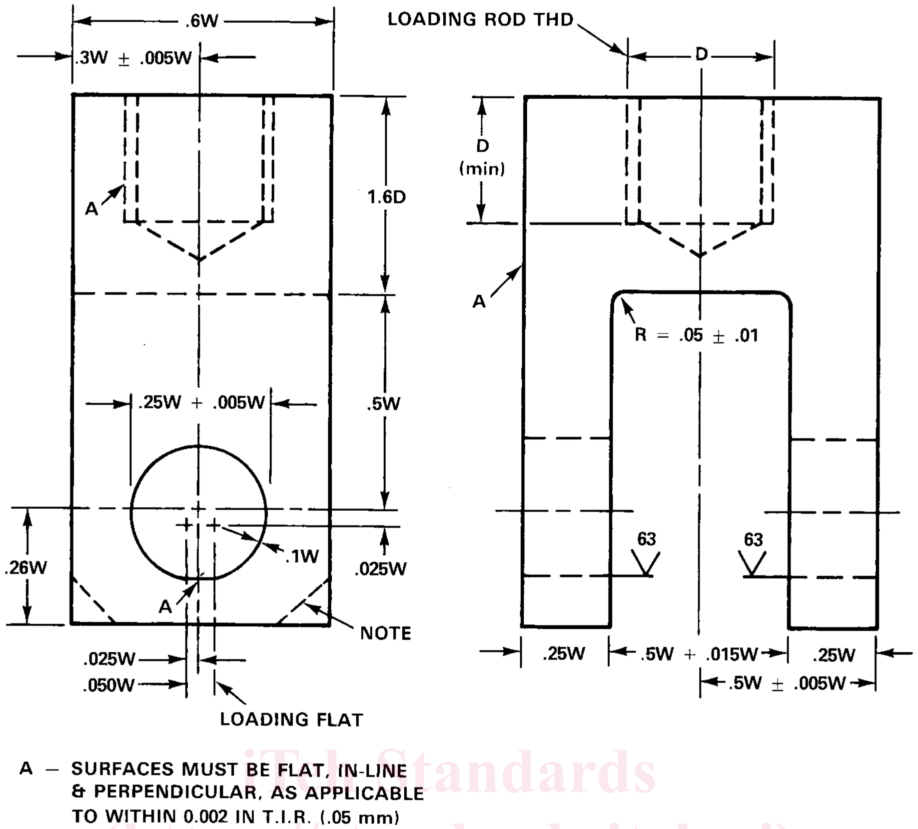
6.1.4 Precautions should be taken to ensure that the force on the specimen is applied as nearly axial as possible.

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 $C^*(t)$.



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

FIG. 2 Clevis Assembly

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 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.

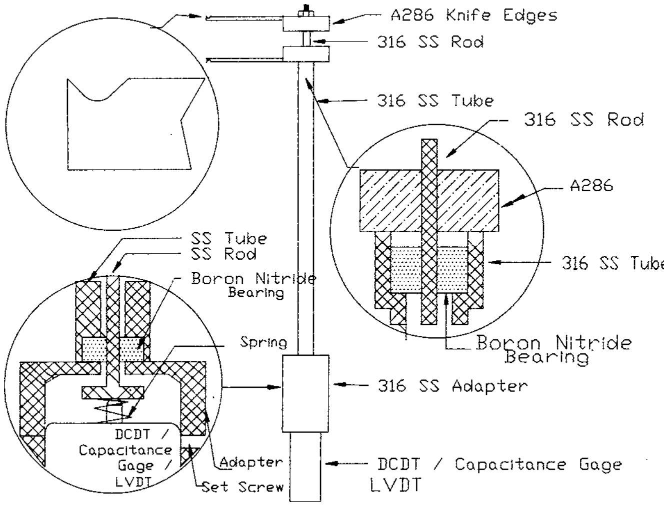
6.6 *Displacement Gage*:

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.

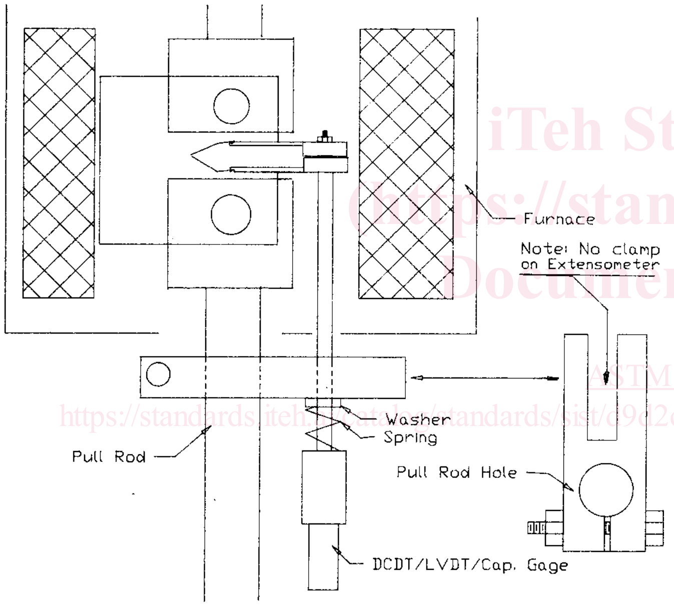
6.6.3 Knife edges are recommended for friction-free seating of the gage. Parallel alignment of the knife edges must be maintained to within ± 1°.

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



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

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 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 ≤ 0.4 ± 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 precracking 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.