Designation: E2714 – 13

Standard Test Method for Creep-Fatigue Testing[1]

This standard is issued under the fixed designation E2714; 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 mechanical properties pertaining to creep-fatigue deformation or crack formation in nominally homogeneous materials, or both by the use of test specimens subjected to uniaxial forces under isothermal conditions. It concerns fatigue testing at strain rates or with cycles involving sufficiently long hold times to be responsible for the cyclic deformation response and cycles to crack formation to be affected by creep (and oxidation). It is intended as a test method for fatigue testing performed in support of such activities as materials research and development, mechanical design, process and quality control, product performance, and failure analysis. The cyclic conditions responsible for creep-fatigue deformation and cracking vary with material and with temperature for a given material.

1.2 The use of this test method is limited to specimens and does not cover testing of full-scale components, structures, or consumer products.

1.3 This test method is primarily aimed at providing the material properties required for assessment of defect-free engineering structures containing features that are subject to cyclic loading at temperatures that are sufficiently high to cause creep deformation.

1.4 This test method is applicable to the determination of deformation and crack formation or nucleation properties as a consequence of either constant-amplitude strain-controlled tests or constant-amplitude force-controlled tests. It is primarily concerned with the testing of round bar test specimens subjected to uniaxial loading in either force or strain control. The focus of the procedure is on tests in which creep and fatigue deformation and damage is generated simultaneously within a given cycle. It does not cover block cycle testing in which creep and fatigue damage is generated sequentially. Data that may be determined from creep-fatigue tests performed under conditions in which creep-fatigue deformation and damage is generated simultaneously include *(a)* cyclic stress-strain deformation response *(b)* cyclic creep (or relaxation) deformation response *(c)* cyclic hardening, cyclic softening response *(d)* cycles to formation of a single crack or multiple cracks in test specimens.

NOTE 1—A crack is believed to have formed when it has nucleated and propagated in a specimen that was initially uncracked to a specific size that is detectable by a stated technique. For the purpose of this standard, the formation of a crack is evidenced by a measurable increase in compliance of the specimen or by a size detectable by potential drop technique. Specific details of how to measure cycles to crack formation are described in 9.5.1.

1.5 This test method is applicable to temperatures and strain rates for which the magnitudes of time-dependent inelastic strains (creep) are on the same order or larger than time-independent inelastic strain.

NOTE 2—The term *inelastic* is used herein to refer to all nonelastic strains. The term *plastic* is used herein to refer only to time independent (that is, non-creep) component of inelastic strain. A useful engineering estimate of time-independent strain can be obtained when the strain rate exceeds some value. For example, a strain rate of $1{\times}10^{-3}$ sec^{-1} is often used for this purpose. This value should increase with increasing test temperature.

1.6 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.7 *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:*[2]

E4 Practices for Force Verification of Testing Machines

E8/E8M Test Methods for Tension Testing of Metallic Materials

E83 Practice for Verification and Classification of Extensometer Systems

E111 Test Method for Young's Modulus, Tangent Modulus,

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[1] This test method is under the jurisdiction of ASTM Committee E08 on Fatigue and Fracture and is the direct responsibility of Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

and Chord Modulus

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

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E220 Test Method for Calibration of Thermocouples By Comparison Techniques

E230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples

E467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System

E606 Test Method for Strain-Controlled Fatigue Testing

E647 Test Method for Measurement of Fatigue Crack Growth Rates

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application

E1823 Terminology Relating to Fatigue and Fracture Testing

E2368 Practice for Strain Controlled Thermomechanical Fatigue Testing

2.2 *BSI Standards:*[3]

BS 7270: 2000 Method for Constant Amplitude Strain Controlled Fatigue Testing

BS 1041-4:1992 Temperature measurement – Part 4: Guide to the selection and use of thermocouples

2.3 *CEN Standards:*[4]

EN 60584-1–1996 Thermocouples – Reference tables (IEC 584-1)

EN 60584 -2– 1993 Thermocouples – Tolerances (IEC 584-2)

PrEN 3874–1998 Test methods for metallic materials – constant amplitude force-controlled low cycle fatigue testing

PrEN 3988–1998 Test methods for metallic materials – constant amplitude strain-controlled low cycle fatigue testing

2.4 *ISO Standards:*[5]

ISO 12106–2003 Metallic materials – Fatigue testing - Axial strain-controlled method

ISO 12111–2005 (Draft) Strain-controlled thermomechanical fatigue testing method

ISO 7500-1–2004 Metallic materials – Verification of static uniaxial testing machines – Part 1. Tension/compression testing machines – Verification and calibration of the force measuring system

ISO 9513–1999 Metallic materials – Calibration of extensometers used in axial testing

ISO 5725–1994 Accuracy (trueness and precision) of measurement methods

2.5 *JIS Standard:*[6]

JIS Z 2279–1992 Method of high temperature low cycle fatigue testing for metallic materials

3. Terminology

3.1 The definitions in this test method that are also included in Terminology E1823 are in accordance with Terminology E1823.

3.2 Symbols, standard definitions, and definitions specific to this standard are in 3.2.1, 3.3, and 3.4, respectively.

3.2.1 *Symbols:*

Symbol	Term
d [L]	Diameter of gage section of cylindrical test specimen
D_g, [L]	Diameter of grip ends
E, E_o, E_N , [FL^{-2}]	Elastic modulus, initial modulus of elasticity, modulus of elasticity at cycle
E_T, E_C [FL^{-2}]	Tensile modulus, compressive modulus
P [F]	Force
l, l_o [L]	Extensometer gage length, original extensometer gage length
L, L_o, [L]	Length of parallel section of gage length, original length of parallel section of gage length
N, N_f	Cycle number, cycle number to crack formation
r,[L}	Transition radius (from parallel section to grip end)
$\varepsilon_{min} / \varepsilon_{max}$, R_ε	Strain ratio
$\sigma_{min} / \sigma_{max}$, R_σ	Stress ratio
τ	Time
T [θ]	Specimen temperature
T_i [θ]	Indicated specimen temperature
N versus σ_{max}	Crack formation or end-of-life criterion is expressed as a percentage reduction in maximum stress from the cycles, N versus σ_{max} curve when the stress falls sharply (see Fig. 1), or a specific percentage decrease in the modulus of elasticity ratios in the tensile and compressive portions of the hysteresis diagrams, or as a specific increase in crack size as indicated by an electric potential drop monitoring instrumentation.
ε, ε_{max}, ε_{min}	Strain, maximum strain in the cycle, minimum strain in the cycle
ε_{ea}, ε_{pa}, ε_{ta}	Elastic strain amplitude, plastic strain amplitude, total strain amplitude
$\Delta\varepsilon_e$, $\Delta\varepsilon_p$, $\Delta\varepsilon_t$	Elastic strain range, plastic strain range, total strain range (see Fig. 2)
$\Delta\varepsilon_{in}$	Inelastic strain range, (see Fig. 2) is the sum of the plastic strain range and the creep strains during the cycle; it is the distance on the strain axis between points of intersections of the strain axis and the extrapolated linear regions of the hysteresis loops during tensile and compressive unloadings
σ, σ_{max}, σ_{min}	Stress, maximum stress in the cycle, minimum stress in the cycle
$\Delta\sigma$	Stress range

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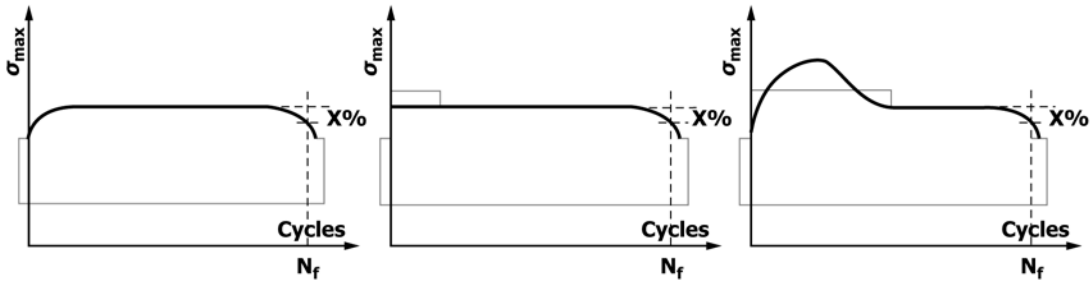
[3] Available from British Standards Institute (BSI), 389 Chiswick High Rd., London W4 4AL, U.K., http://www.bsi-global.com.

[4] Available from European Committee for Standardization (CEN), 36 rue de Stassart, B-1050, Brussels, Belgium, http://www.cenorm.be.

[5] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.ch.

[6] Available from Japanese Standards Organization (JSA), 4-1-24 Akasaka Minato-Ku, Tokyo, 107-8440, Japan, http://www.jsa.or.jp..

(a) For materials with stable or steady-state behavior after hardening



(b) For materials with continuous softening

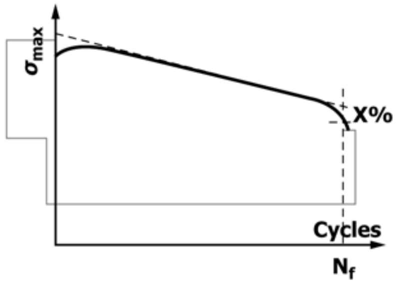


FIG. 1 Crack Formation and End-of-Test Criterion based on Reduction of Peak Stress for (a) Hardening and (b) Softening Materials

3.3 *Definitions:*

3.3.1 *cycle*—In fatigue, one complete sequence of values of force (strain) that is repeated under constant amplitude loading (straining)

3.3.2 *hold-time,* τ_h *[T]*—In fatigue testing, the amount of time in the cycle where the controlled test variable (force, strain, displacement) remains constant with time (Fig. 3).

3.3.2.1 *Discussion*—Hold- time(s) are typically placed at peak stress or strain in tension and/or compression, but can also be placed at other positions within the cycle.

3.3.3 *total cycle period,* τ_t *[T],*—The time for completion of one cycle. The parameter τ_t can be separated into hold (τ_h) and non-hold (τ_{nh}) (that is, steady and dynamic) components, where the total cycle time is the sum of the hold time and the non-hold time.

3.3.4 *hysteresis diagram*—The stress-strain path during one cycle (see Fig. 2).

3.3.5 *initial modulus of elasticity,* E_o *,* $[FL^{-2}]$ —The modulus of elasticity determined during the loading portion of the first cycle.

3.3.6 *modulus of elasticity at cycle N,* (E_N, $[FL^{-2}]$ —The average of the modulus of elasticity determined during increasing load portion (see E_c in Fig. 2) and the decreasing load portion (E_T in Fig. 2) of the hysteresis diagram for the N_{th} cycle.

3.3.7 *stress range,* $\Delta\sigma$ *,* $[FL^{-2}]$—The difference between the maximum and minimum stresses.

3.3.7.1 *Discussion*—For creep-fatigue tests, the difference between the maximum and minimum stresses is called the "peak stress range" and for tests conducted under strain control, the difference between the stresses at the points of reversal of the control parameter is called the "relaxed stress range" (see Fig. 2b).

3.4 *Definitions of Terms Specific to This Standard:*

3.4.1 *DCPD and ACPD*—Direct current and alternating current electrical potential drop crack monitoring instrumentation.

3.4.2 *homologous temperature*—The specimen temperature in °K divided by the melting point of the material also in °K.

3.4.3 *crack formation*—A crack is believed to have formed when it has nucleated and propagated in a specimen that was initially un-cracked to a size that is detectable by a stated technique.

4. Significance and Use

4.1 Creep-fatigue testing is typically performed at elevated temperatures and involves the sequential or simultaneous application of the loading conditions necessary to generate cyclic deformation/damage enhanced by creep deformation/damage or vice versa. Unless such tests are performed in vacuum or an inert environment, oxidation can also be responsible for important interaction effects relating to damage accumulation. The purpose of creep-fatigue tests can be to determine material property data for *(a)* assessment input data

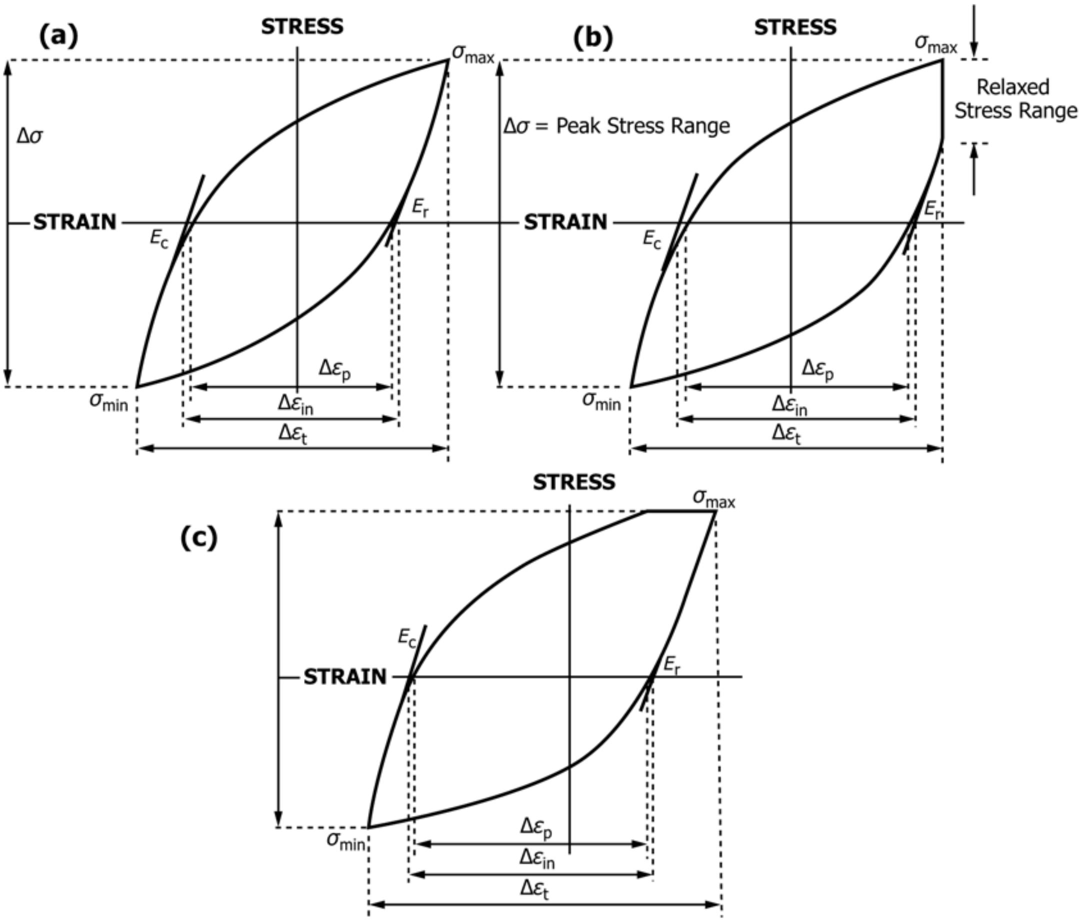


FIG. 2 Examples of Stress-Strain Hysteresis Diagrams (a) Without Hold Time, (b) With Hold Time (Strain Control), (c) With Hold Time (Force Control), see 3.2.1 for list of symbols.

for the deformation and damage condition analysis of engineering structures operating at elevated temperatures *(b)* the verification of constitutive deformation and damage model effectiveness *(c)* material characterization, or *(d)* development and verification of rules for new construction and life assessment of high-temperature components subject to cyclic service with low frequencies or with periods of steady operation, or both.

4.2 In every case, it is advisable to have complementary continuous cycling fatigue data (gathered at the same strain/loading rate) and creep data determined from test conducted as per Practice E139 for the same material and test temperature(s). The procedure is primarily concerned with the testing of round bar test specimens subjected (at least remotely) to uniaxial loading in either force or strain control. The focus of the procedure is on tests in which creep and fatigue deformation and damage is generated simultaneously within a given cycle. Data which may be determined from creep-fatigue tests performed under such conditions may characterize *(a)* cyclic stress-strain deformation response *(b)* cyclic creep (or relaxation) deformation response *(c)* cyclic hardening, cyclic softening response or (d) cycles to crack formation, or both.

4.3 While there are a number of testing Standards and Codes of Practice that cover the determination of low cycle fatigue deformation and cycles to crack initiation properties (See Practice E606, BS 7270: 2000, JIS Z 2279–1992, PrEN 3874, 1998, PrEN 3988–1998, ISO 12106–2003, ISO 12111–2005, and Practice E2368-04 and (**1, 2, 3**)[7], some of which provide guidance for testing at high temperature (for example, Practice E606, ISO 12106–2003, and Practice E2368-04, there is no single standard which specifically prescribes a procedure for creep-fatigue testing.

5. Functional Relationships

5.1 Empirical relationships that have been commonly used for description of creep-fatigue data are given in Appendix X1. These relationships typically have limitations with respect to material types such as high temperature ferritic and austenitic steels versus nickel base alloys. Therefore, original data should be reported to the greatest extent possible. Data reduction methods should be detailed along with assumptions. Sufficient information should be recorded and reported to permit analysis, interpretation, and comparison with results for other materials analyzed using currently popular methods.

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

(a) Low frequency triangular wave form

(b) Saw-tooth triangular wave form

(c) Cycle with hold time at control parameter peak in tension

(d) Cycle with hold time at intermedia position of control parameter

(e) Cycle with hold times at control parameters peaks in tension and compression

(f) Cycle with varying rates of the control parameter

FIG. 3 Example of Creep-Fatigue Cycle Shapes

6. Apparatus

6.1 *Test machines:*

6.1.1 Tests shall be conducted using a servo-controlled tension-compression fatigue machine that has been verified in accordance with ISO 7500-1–2004 or Practices E4-03 and E467-04. Hydraulic and electromechanical machines are acceptable. The testing machine shall have been designed for smooth start-up without any backlash when passing through zero force. It shall possess a high degree of lateral stiffness to maintain accurate alignment during compression loading suitable for meeting the requirements described in section 6.3.

6.1.2 The complete loading system comprising of the force transducer, loading grips and test specimen shall have great lateral rigidity to meet requirements specified in 6.3. Further, it must be capable of executing the prescribed cycle in either strain or force control. The control stability should be such that the maximum and minimum limits of the control variable are maintained within 1% of its range.

6.2 *Force transducer:*

6.2.1 The force transducer and its associated electronics shall comply with ISO 7500-1–2004. Alternatively, the force transducer calibration should be verified in accordance with Practices E4-03 and Practice E467-04.

6.2.2 The force transducer shall be designed for tension-compression fatigue testing and shall have high axial and lateral rigidity to meet the requirements specified in 6.3. Its capacity shall be sufficient to measure the axial forces applied during the test to accuracies better than 1% of the reading.

6.2.3 The force transducer shall be temperature compensated and not have zero drift nor sensitivity variation greater than 0.002% of the full scale per °C (See Practice E606–12). During test, the force transducer shall be maintained at a temperature within its temperature compensation range specified by the manufacturer.

6.3 *Loading Grips:*

6.3.1 To minimize bending strains or in other words to ensure uniform axial strain throughout the gage section of the specimen, test specimen fixtures should be aligned such that the major axis of the test specimen closely coincides with the force axis throughout each cycle. It is important that the accuracy of alignment be kept consistent from specimen to specimen. Alignment should be checked by means of a trial test diameter. The trial test specimen should be turned about its axis, installed, and checked for each of four orientations within the fixtures. The maximum bending strains so determined must not exceed 5% of the minimum axial strain range imposed during any test program for all four orientations.

NOTE 3—For specimens with uniform gage length, it is good practice to also place similar set of gages at one or two additional axial positions within the gage section. In such cases, one set of strain gages should be placed at the center of the gage length to detect misalignment that causes relative rotation of the specimen ends about axes perpendicular to the specimen axis. The additional set of gages should be placed away from the gage length center to detect relative lateral displacement of the specimen ends. The more uniform the axial strain and lower the bending strain, the more repeatable the test results will be from specimen to specimen.

6.3.2 The loading train should incorporate cooling arrangements to limit heat transfer from the hot zone to the testing machine and in particular the force transducer. The zero point and sensitivity of force transducers are subject to thermal drift and may be permanently damaged by temperatures in excess of 50°C. Suitable cooling arrangements include forced air cooling of fins at the outer ends of the loading bars or water cooling coils or jackets. Care should be taken to ensure that force transducer calibration and load train alignment are not affected by the presence of the cooling devices.

6.3.3 The loading bars incorporate grips to locate the test specimen and these should satisfy certain basic design requirements arising directly from the need for tension-compression loading without lost motion through zero force at the test specimen/grip interface(**4**, **5**, **6**) and Practice E1012-12. To achieve this, the design should provide the following basic features, *(a)* a loading surface through which the load in one direction will be transmitted *(b)* a surface ensuring alignment of the test specimen axis *(c)* a second loading surface through which the load in the reverse direction is transmitted *(d)* an arrangement maintaining the loading surfaces in contact with the specimen, whatever the state of loading, within the working range of the design. Common loading train misalignment problems that can lead to specimen bending are shown in Fig. 4 and must be avoided.

6.4 *Extensometer:*

6.4.1 The extensometer used shall be suitable for measuring dynamic displacements over long periods during which there shall be minimal drift, slippage and instrument hysteresis. Extensometers used for measurement and to control deformation in the test specimen gage section shall be suitable for dynamic measurements over periods of time, that is, should have a rapid response and with a low hysteresis (not greater than 0.1% of extensometer output). Strain gage or LVDT type transducers are generally used and should be calibrated according to Practice E83-02 and, ISO 9513–1999. Suitable extensometers that meet these requirements are those that are Grade B2 or better as specified by Practice E83-02 or Class 0.5 or better as specified by ISO 9513–1999.

6.4.2 Extensometers for parallel gage section test specimens shall measure longitudinal extension. A side-entry contacting extensometer with rounded contact edges is recommended for the purpose. These usually employ light spring pressure to maintain contact between the probes and the test specimen surface and in such circumstances, the extensometer body should be independently supported to minimize the forces between the probe tips and the test specimen surface (see Note 4).

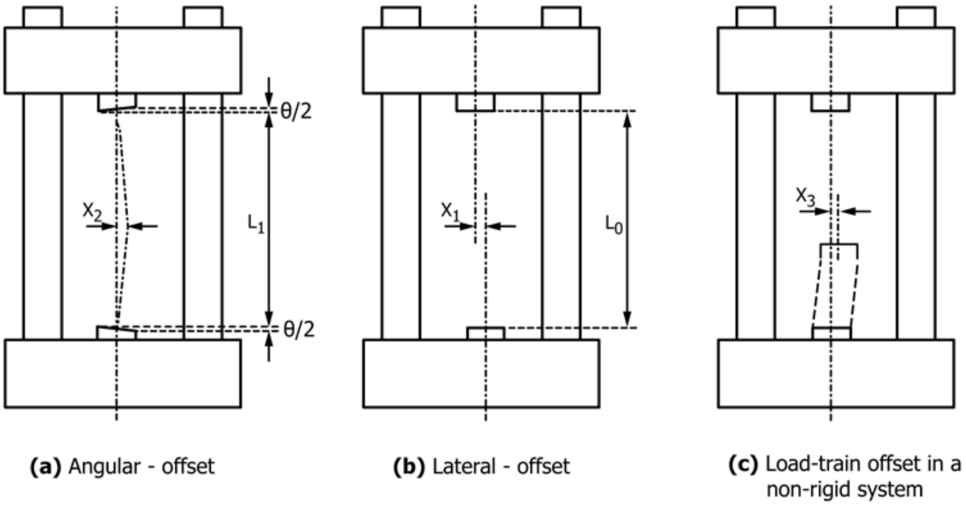
NOTE 4—If specimens with ridges are used for characterizing cycles to crack formation, the tests should be considered invalid if cracking is limited only to the regions near the ridges. This configuration is more desirable when the purpose of the test is only to determine cyclic deformation properties.

6.4.3 For hour-glass profiled test specimens, an extensometer measuring diametral deformation may be used such that the extensometer tips contact the test specimens across the minimum diameter. The extensometer should be supported and counterbalanced and should be adjusted to minimize the contact force imposed on the test specimen to prevent notching.

NOTE 5—The repeatability and sensitivity of diametral extensometers are significantly lower than those for axial extensometers and are not recommended as an alternative means of strain control in creep-fatigue tests when the use of an axial extensometer is feasible.

6.5 *Crack Monitoring:*

6.5.1 A direct current (DCPD) or alternating current (ACPD) electrical potential-drop crack monitoring system as per Practice E647 may be used in certain circumstances to



(a) Angular - offset

(b) Lateral - offset

(c) Load-train offset in a non-rigid system

FIG. 4 Bending Mechanisms Due to Misalignment in Fatigue Test Systems determine crack formation in parallel gage section test specimens, although this is not required.

NOTE 6—The test specimen (or loading grips) should be electrically insulated from the test machine loading frame and ancillary equipment in order to avoid unstable potential drop recordings associated with electrical ground loops.

6.5.2 The DCPD or ACPD system should be capable of reliably resolving crack extensions of at least ±0.1mm along the specimen surface as well as along the crack depth at the test temperature.

6.5.3 The use of multiple charged couple device (CCD) cameras placed around the test specimen is an alternative technique for observing crack development when induction heating is employed.

6.6 *Heating System:*

6.6.1 Heating methods used to achieve elevated temperature include *(a)* resistance furnace heating *(b)* radiant furnace heating *(c)* induction heating (see Note 7), or *(d)* inert gas or liquid heating. The heating device shall be such that the test specimen can be uniformly heated to the specified temperature, with an indicated temperature gradient across the gage section that is less than or equal to the greater of 2ºC or 1 percent of the nominal test temperature throughout the duration of the test. A resistance furnace with three individually controlled heating zones provides a good solution for isothermal creep-fatigue testing.

NOTE 7—For induction heating, the choice radio frequency (RF) generator frequency depends on the specimen diameter. It is advisable to select a RF generator with a sufficiently low frequency such as less than 10 kHz to prevent "skin heating effects" when testing large diameter specimens (greater than 20 mm). For majority of testing, suitable RF frequencies range between 70 kHz and 400 kHz. Caution should be exercised when using RF heating while testing ferritic steels. There is evidence that RF heating in ferromagnetic materials may yeild longer creep fatigue lives in comparison to resistance heating. **(7)**

6.6.2 The heating system shall be protected from draughts to avoid undesirable gradients and fluctuations in temperature and the controlled temperature must be maintained within ± 2°C throughout the duration of the test.

6.7 *Temperature Measurement:*

6.7.1 Test specimen temperature shall be measured using thermocouples in contact with the test specimen surface, or by means of other suitable sensors, for example, optical pyrometers that have been calibrated using a trial test specimen equipped with thermocouples and shown to be the same or better than thermocouples. In all cases involving the use of thermocouples, it is essential to ensure that intimate thermal contact is achieved between test specimen and thermocouple without scratching the gage portion of the test specimen. When using furnace heating, thermocouple beads shall be shielded from direct radiation.

NOTE 8—Optical pyrometers are not recommended for test specimen temperature measurement when the test material is prone to oxidation without the use of supportive observations from thermocouples attached to test specimen shoulders.

6.7.2 When using induction heating, each leg of the thermocouple should be spot-welded 180 degrees around the shoulder of the test specimen from the other leg so that the specimen itself becomes the thermocouple junction (bead). If stress-strain behavior only is to be measured then a thermocouple location on the gage section is acceptable. Calibration and use of methods of temperature measurement shall be carried out according to Test Method E220-02 and Specification E230-03, ISO 9513–1999 or EN 60584-1–1996, EN 60584-2–1993 and BS 1041-4:1992.

NOTE 9—The use of rare metal thermocouples, preferentially Type R or S is recommended for use at temperatures above 400ºC.

NOTE 10—The use of Type K thermocouples above 400ºC is recommended with the following caveat. They may be used only for short duration tests (<500h) at temperatures up to 600°C. Type N thermocouples may be used for short duration tests (<500h) at temperatures up to 800°C

6.8 *Cycle Counter:*

6.8.1 Standard practice should be to record all cycles in a data acquisition system. As a minimum, a digital device should be used to record the number of cycles applied to the test specimen. Five digits are required, thus, for tests lasting less than 10,000 cycles, individual cycles shall be counted. For longer tests, the device shall have a resolution better than 1% of the actual life.

6.9 *Data recording:*

6.9.1 An automatic digital recording system should be used which is capable of collecting and simultaneously processing the force, displacement and temperature data as a function of time and cycles. The sampling frequency of force-displacement-time data shall be sufficient to ensure correct definition of the hysteresis loop and hold time transient(s). In particular, it should be sufficient to identify values of force and extension at turning points in the hysteresis loop, for example, at cycle maxima and minima, and start and end of hold-time values.

NOTE 11—Adequate number of data points (50 to 200) should be collected to define the hysteresis loop, and additional points (50-200 data points should be collected to fully characterize hold-time transients. Obtaining reliable deformation data from the loading portion of the hysteresis loop generally requires approximately 200 data points.

NOTE 12—The simultaneous recording of stroke position is also recommended to assist in the retrospective diagnosis of disturbances during test, for example, extensometer slippage.

6.9.2 X-Y recordings may instead be used for the purpose of recording force-displacement hysteresis loops. A potentiometric X-Y recorder, or an oscilloscope equipped with a camera are acceptable alternatives. In addition, recorders should be used to monitor force, displacement and temperature as a function of time. This information is required particularly to determine initiation and to monitor changes to the dependent parameter during hold-times.

NOTE 13—X-Y and multi-channel X-t recorders should only be used when the test conditions result in a pen velocity that will not cause inaccurate results, for example, less than half of the recorders slewing speed.

6.9.3 When DCPD or ACPD electrical crack monitoring is used to measure crack formation reference voltages should be monitored by digital recording or using a multi-channel X-t recorder.

6.10 *Verification of Loading and Heating Systems:*

6.10.1 *Alignment*—Bending due to misalignment in rigid grip systems is generally caused by (Fig. 4) an angular offset of the specimen grips or a lateral offset of the loading bars in an ideally-rigid system or an offset in the load-train assembly with respect to a non-rigid system such as an actuator rod with side play in the bearings. The alignment shall be checked before each series of tests or anytime a change is made to the load train as described in 6.3. The bending strains shall be ≤5% of the minimum axial strain range imposed during the test program at all strains between the maximum and minimum applied strain. If the check is not satisfactory when the specimen is rotated in 90° intervals to one or more positions, the reproducibility of the measurements shall be verified by carrying out the process several times, and it shall be established if the results are attributable to the test assembly or the test-piece. Changes to the system or specimens will be made to meet the requirement that bending strains shall not exceed 5% of the minimum axial strain range imposed during the test program.

6.10.2 *Verification of Temperature Homogeneity*—The uniformity of temperature along the parallel length of the specimen shall be verified between every series of tests that involves a new geometry, or if the furnace position has changed. The verification should be made by means of a dummy specimen having the geometry that is to be tested and equipped with several thermocouples welded along its parallel length, or inserted into holes equally spaced over the specimen gage length. When induction heating is used, this verification should also be done every time the induction coil is knocked or when the temperatures measured on the specimen shoulders are not consistent with previous measurements. The distance between thermocouples on the dummy specimen be ≤ d and the results must meet the requirements of acceptable temperature gradients in the specimen specified in 6.6.

7. Test Specimens

7.1 *Geometry:*

7.1.1 *Uniform Gage Section Test Specimens*—Creep-fatigue tests are usually performed using uniform gage section test specimens shown in Fig. 5a. The following geometrical dimensions are recommended for parallel cylindrical gage test specimens.

Diameter of cylindrical gage section	$d \geq 5$ mm
Gage length	$l_o \geq 1.5d$ (see Note 15)
Transition radius (from parallel section to grip-end)	$r \geq 2d$
Diameter of grip-ends	$D_g \geq 2d$ (see Note 16)

NOTE 14—The parallel portion of the parallel gage section test

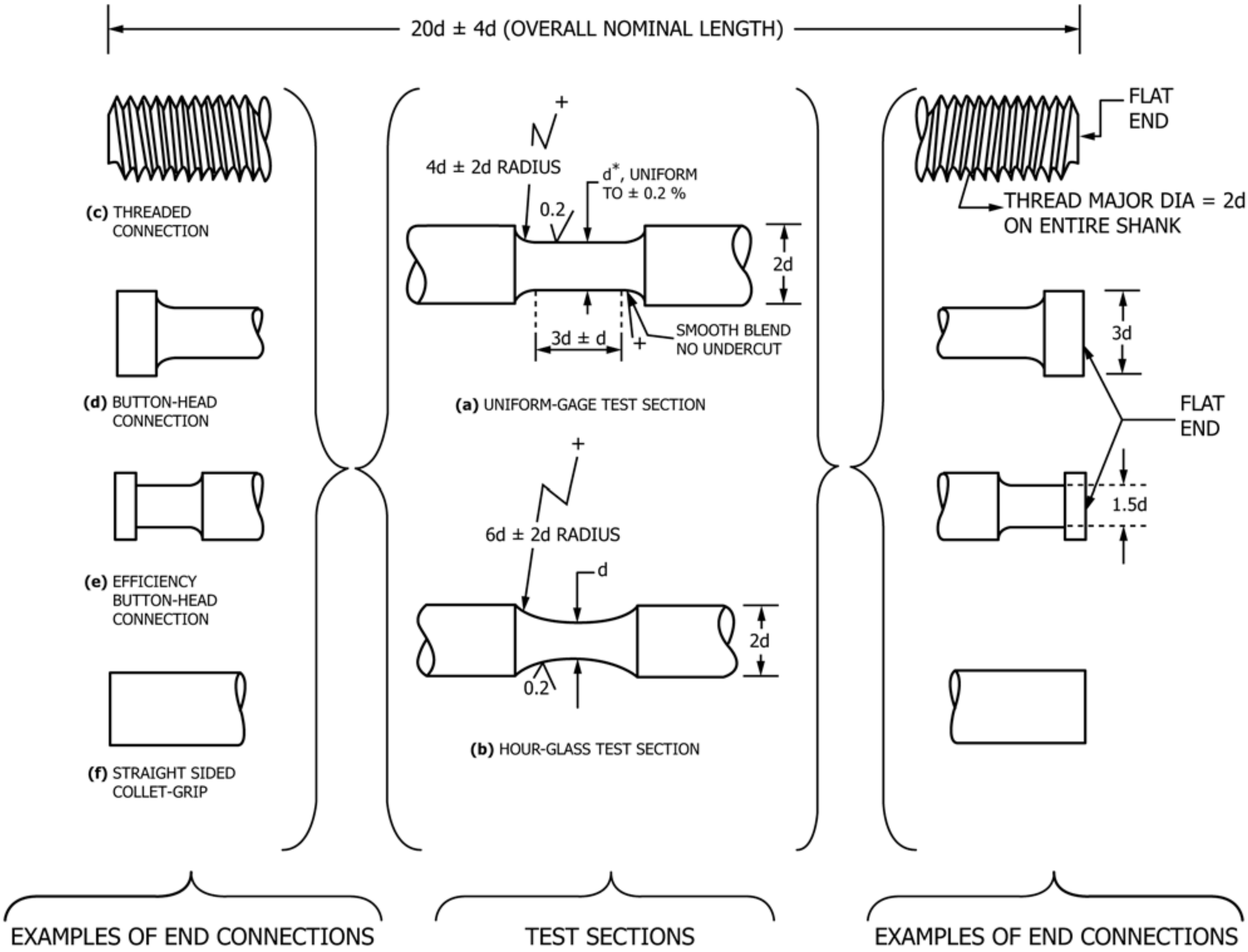


FIG. 5 Test Specimens Configurations

specimen, L_o, shall be longer than the extensometer gage length, l_o. However, L_o- l_0 must not be greater than *d* to reduce the chances of failure outside the extensometer gage length.

NOTE 15—For cycles involving a component of loading in compression, $l_o \leq 4d$ is recommended to avoid buckling.

NOTE 16—Notch sensitive materials and cyclic hardening materials may require a minimum grip-end diameter, D_g, of 3.5d to avoid failure in the threaded ends.

7.1.2 It is important that general tolerances of the test specimen respect the three following properties:

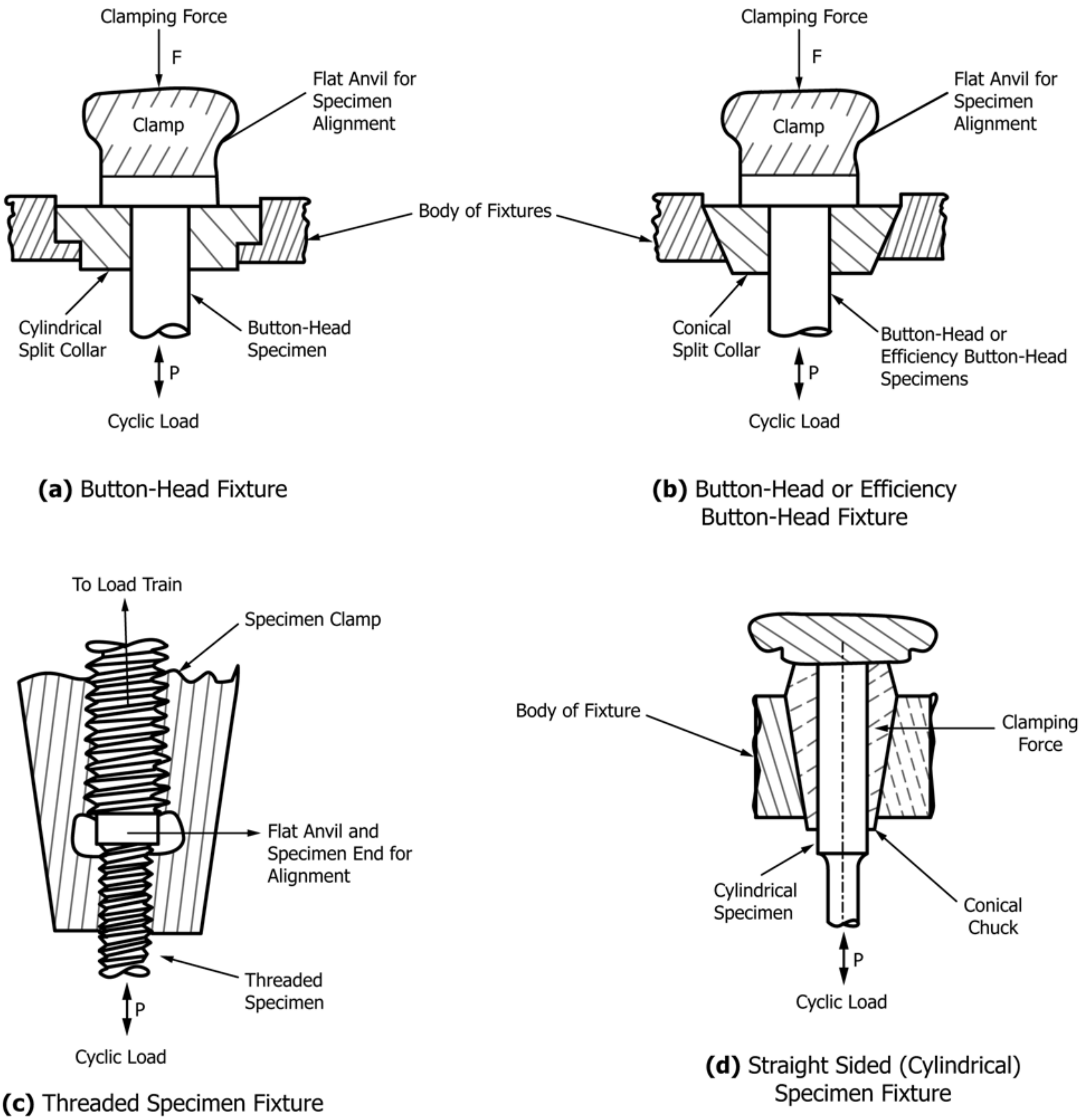
Parallelism:	// ≤ 0.01 mm
Concentricity:	O ≤ 0.01 mm
Perpendicularity:	⊥ ≤ 0.01 mm

(these values are expressed in relation to the axis or reference plane)

7.1.3 The dimensions of the end connections shall be defined as a function of the testing machine (see Note 17). The loading grip arrangement shall locate the test specimen and provide axial alignment. It shall not permit backlash. The design of the loading grip will depend on the test specimen end details. A number of solutions are given in (Fig. 6).

NOTE 17—For test specimen subject to through-zero loading, threaded and button-ended end-grip arrangements should incorporate features to ensure a smooth transition from tension into compression and vice-versa. This typically involves preloading of the test specimen during the gripping procedure (for example, Fig. 6). For threaded ended test specimen, a limited tolerance thread is also recommended.

NOTE 18—In general, designs for which test specimen alignment



(a) Button-Head Fixture

(b) Button-Head or Efficiency Button-Head Fixture

(c) Threaded Specimen Fixture

(d) Straight Sided (Cylindrical) Specimen Fixture

FIG. 6 Schematic Examples of Test Fixtures Suitable for Obtaining Good Alignment and Avoiding Back Lash for Various Test Specimen Designs

depends entirely on screw threads are not recommended.

NOTE 19—The clamping force should be greater than the cyclic load to avoid backlash within the test specimen fixture

7.1.4 *Tubular Test Specimens*—A variant to the parallel gage section test specimen is the tubular test specimen. As a generality, such test specimens are only used for creep-fatigue testing to minimize radial thermal gradients when heating is by induction. The use of such specimens is allowable provided all the conditions of 6.6 and 6.7 are met. In addition, all requirements of concentricity, parallelism, perpendicularity and surface finishing are met.

NOTE 20—The internal surface roughness of tubular test specimens must be equal to or better than that prescribed for the external surface. The opportunity for crack initiation to occur in such test specimens is approximately double because of twice as much exposed area available in comparison with a solid specimen of equivalent size. The machining marks on the internal and external surface must run parallel to the loading axis

7.1.5 *Hour-Glass Test Specimens*—The hour-glass test specimen is shown in Fig. 5b. These specimens are usually used only for high strain range tests when the risk of buckling a parallel gage section test specimen is high. The use of a diametral extensometer is required to control strain with this test specimen geometry. The details of conversion of diametral strain to axial strain are available in the Appendix X2 of Practice E606.

7.1.6 *Notched Test Specimens*—Circumferentially notched round bar test specimens may be used to determine the effect of triaxiality on creep-fatigue endurance (cycles to crack formation).

NOTE 21—Since notched specimen testing is performed to only determine application specific material properties, the geometrical detail of the notch will vary with the application and are therefore left to the user.

7.1.6.1 The use of electrical potential drop crack monitoring is recommended when using notched test specimens for creep-fatigue testing, as a means of detecting crack initiation.

7.2 *Preparation:*

7.2.1 *Sampling and Identification*—The specimen's unique identification number should be marked on the test specimen at each stage of its preparation. The test specimen identification may be written by any reliable method, in any region which will not be machined away during preparation and which will not interfere with test quality. In particular, it should remain visible at the end of test despite any oxidation of the test specimen. It is recommended to write the identification on both ends of the test specimen.

7.2.2 *Test Specimen Maching*—Unless the purpose of the test is to determine the influence of specific surface conditions on fatigue life, the final machining of the test specimens shall be performed in a way that will consistently produce a smooth surface with minimal stresses. The mean roughness shall be less than 0.2 µm R_a.

7.2.2.1 Final machining and polishing shall eliminate all circumferential scratches. Final grinding followed by longitudinal mechanical polishing is recommended. A low magnification inspection (approximately 20X) shall reveal no circumferential scratches

7.3 *Dimensional Check*—The dimensions should be measured on completion of the final machining stage using a metrology which does not leave scratches on the specimen surface.

7.4 *Sensor Attachment:*

7.4.1 The attachment of thermocouples to the test specimen by spot welding should be done prior to insertion into the loading grips.

NOTE 22—The attachment of thermocouples to the test specimen by means of heat resistant cord or soft wire (platinum) may be done after the test specimen has been mounted in the loading grips.

7.4.2 Similarly, current input and voltage monitoring leads associated with crack monitoring instrumentation should also be attached to the test specimen prior to insertion into the loading grips.

8. Procedure

8.1 *Test Specimen Mounting*—The test specimen shall be mounted into the loading grips in a way which will not jeopardize the alignment of the assembly, the surface condition of the test specimen or the properties of the material.

8.2 *Extensometer Attachement*—Locate the extensometer centrally along the test specimen gage length, with due regard to the manufacturer's recommendations.

NOTE 23—Where a contacting extensometer is used, too high a contact-pressure may lead to premature failure initiating from the position of probe contact and too low a contact-pressure may lead to extensometer slip.

8.3 *Cycle Shape*—The following cycle shapes may be used for creep-fatigue testing *(a)* low frequency triangular wave forms with low control parameter ramp rates *(b)* saw-tooth wave forms in which the ramp rate of the tensile-going transient is significantly different to that of the compression-going transient (either of which can be the lowest ramp rate transient) *(c)* Cyclic/hold forms comprising a series of ramps with hold-time(s) of the control variable (the ramp rates may not always be the same). Examples of common creep-fatigue cycle shapes are shown in Fig. 3. Other loading waveforms representative of the application for which the creep-fatigue data are being generated may be used; a complete description of the waveform used must be provided as part of the report.

8.4 *Preliminary Measurements*—In order to identify possible problems within the force, displacement and measuring systems, the following checks should be performed before starting a test *(a)* the elastic modulus should be measured at room temperature and at the test temperature. The values measured should not deviate by more than 10% of the expected values at each temperature. The procedure described in ISO 12106– 2003, Test Method E111-04, or in BS 1041-4:1992 is recommended for determining elastic modulus *(b)* the mean coefficient of thermal expansion should be determined after the temperature stabilizes at the test temperature (machine at zero force). The coefficient of thermal expansion can be calculated by dividing the thermal strain by the temperature change in going from room temperature to the test temperature. The coefficient should not deviate by more than 10% of the published values for those materials.

8.4.1 Usually, the extensometer will be mounted on the test specimen at room temperature and will not be readjusted to the original gage length after transition to the test temperature. In this case, the strain measurement at elevated temperature shall be corrected for the gage length extension due to thermal expansion. The gage length displacement between test and room temperature shall also be recorded for applying the correction after test completion. Automated systems should use the corrected gage length for on-line control and data acquisition.

NOTE 24—The extensometer may be mounted at room temperature and the output should be readjusted to zero on attainment of the test temperature.

8.5 *Heating the Test Specimen*—The test specimen shall be heated to the specified temperature and shall be maintained at that temperature for at least 30 min before loading. During heating, the temperature of the test specimen shall not exceed the specified temperature with its tolerances specified in 6.6 and repeated in 8.6.4. The test specimen shall not be stressed by more than 10% of the yield stress of the material (at the test temperature) throughout the heating process.

8.6 *Starting and Conducting the Test:*

8.6.1 The extensometer output should be brought to a null value with no force on the test specimen.

8.6.2 Unless the purpose of the test is to assess the effect of loading sequence, the direction of the first quarter of the first cycle shall be tensile.

8.6.3 The stability of the mechanical control parameter shall be such that the values of the limits of the controlled parameter are repeatable within 0.5% from cycle-to-cycle and within 2% over the entire duration of the test.

NOTE 25—In the event of test interruption, the test should be restarted only if can be determined that the specimen has not experienced any additional deformation due to the interruption. If the test is restarted, it must be reported and the effect of the test stoppage must be verified by analyzing the recordings after it is completed.

8.6.4 *Temperature Control:*

8.6.4.1 During the whole test, *i*) the total deviation of the indicated temperature from the specified test temperature (T_i-T), except that due to the thermoelastic effect (see Note 27) shall not be more than ± 2°C and *ii*) the temperature variation along the gage section (dT_i) shall not be more than ±max(2°C, 0.01.T_i) with due consideration to all combined sources of error, see ISO 5725–1994.

NOTE 26—Close temperature control is required in particular for strain controlled cyclic/hold time, creep-fatigue tests because changes in gage length due to expansion or contraction associated with fluctuations in temperature lead to variations in the measured stress (for example, see Practice E2368-04).

NOTE 27—Temperature changes during the fatigue cycle may arise due to the thermoelastic effect and are typically about ±2°C at high strain rates.

NOTE 28— In addition to performing the test in a laboratory with close control of ambient temperature and humidity, it is recommended that the region surrounding the test machine is protected from air currents. This is particularly important when recording data during hold-times since local changes in temperature due to draughts can cause significant variations in the control and response variables.

NOTE 29—When induction heating is employed, the temperature profile in test specimens manufactured from magnetic materials (those with relative permeability significantly greater than unity) may be changed due to the effect of varying stress on the eddy current distribution. For susceptible materials (for example, austenitic stainless steels), the most pronounced effect is in low frequency and cyclic-hold tests. The temperature profile in test specimens manufactured from magnetic materials should therefore be monitored throughout the straining cycle. If the temperature variations exceed the limits specified in 6.6, corrective action is required. It may be necessary to use a susceptor with the induction coil or to use an alternative heating method.

NOTE 30—The direction of induction coil winding at either end of the test specimen gage length can be influential in limiting the temperature gradient along the gage length. The best results for minimizing the temperature gradients in the test-piece are achieved when the coils at the two ends are wound in the opposite directions. This configuration is recommended for ferritic steels. However, in austenitic materials the magnetic permeability is low, so the power requirement for the RF generators increases dramatically. For these materials, it may be necessary to accept a slightly higher temperature gradient (up to approximately 5°C) to keep the power requirements within the capacity of the RF generators.

NOTE 31—The stress gradients around notches and cracks in test specimens of ferromagnetic materials heated by induction coil can cause unusual temperature variations. Prior to testing, it must be verified that all temperature control requirements of 6.6 are met. If necessary, corrective actions should be taken to meet the requirements.

9. Test Records

9.1 *Cycle Peaks*—During the course of test, the force, extension, temperature and crack condition (if PD instrumentation attached) shall be continuously recorded at critical turning points within the cycle, that is, at maximum and minimum force and extension and at the start and end of hold time(s).

9.2 *Load-Extension Hysteresis*—At the start of test, a continuous recording shall be made of the initial force-extension hysteresis loops. During the course of test, periodic recording is sufficient. The frequency of these recordings shall be in logarithmic increments of fatigue cycles (that is, 1, 2, 5, 10, 20 50 etc.) If data acquisition is automated, the acquisition of loops may be programmed either with a predefined interval or as a function of the progression of each of the two parameters (force and extension). In either case, the sampling frequency shall be sufficient to allow clear definition of the hysteresis loop (see 3.3.3)

NOTE 32—For longer term tests involving periods without personnel supervision for significant periods, it is recommended that a buffer file is continuously recorded. This will provide the means (albeit for a limited period) to monitor the conditions prior to, during and immediately after an incident within cycles which are not programmed for continuous recording.

9.3 *Time-Dependent Parameters*—Force, extension and temperature shall be monitored continuously with the aim of checking the control parameters and the development of the response variables. The time dependent records shall be collected for the same cycles for which hysteresis loop data is being gathered (see 9.1 and 6.9).

9.4 *Crack Formation*—As a minimum, the development of cracking when monitored by electrical potential drop instrumentation should be recorded, at least at the critical turning points (identified in 9.1). In certain circumstances, for example, for long hold time tests, it may be appropriate to record crack formation and propagation continuously throughout the hold time(s) of the cycles selected for hysteresis loop data collection.

9.5 *End of Test*—In particular for endurance tests, it is important that the crack formation and end-of-test criteria are clearly defined. The end-of-test is usually defined as the attainment of a specific percentage decrease in the maximum tensile stress in relation to the level determined during test (that is, 10%, that is, $x=10$ as in Fig. 1). It is good practice to stop the test prior to complete separation of the two test specimen halves, to avoid any damage a) to the extensometer and b) to the fracture surface. The containment of creep-fatigue damage within a single piece provides a good starting point for the effective metallographic assessment of physical damage during post test inspection.

NOTE 33—A specific percentage decrease in maximum tensile stress criterion can only be adopted in strain controlled tests as shown in Fig. 1.

9.5.1 *Crack Formation Criteria*—Selecting an appropriate crack initiation criterion is important for minimizing the scatter in endurance (cyclic life) within a single test series and for making reliable inter-laboratory comparisons of creep-fatigue endurance data. In practice, the number of cycles to crack formation is the number of cycles to the attainment of a specific crack size (or cracked area). This may be determined on the basis of *(a)* a specific percentage decrease in the maximum tensile stress in relation to the level during the test, that is, x% in Fig. 1, *(b)* a specific percentage decrease in the modulus of elasticity ratios in the tensile and compressive parts of the hysteresis diagrams *(c)* a specific percentage decrease in the maximum tensile stress in relation to the maximum compressive stress, or *(d)* a specific increase in crack size as indicated by an electrical potential drop crack monitoring instrumentation. The methods described in *(a)* thru *(d)* all apply to tests conducted under strain control but only methods described under *(b)* and *(d)* apply to tests conducted under force control.

NOTE 34—A specific percentage decrease (for example, 2%) in the maximum tensile stress is a commonly used criterion in strain controlled creep-fatigue testing for a number of materials but may not be suitable for all materials. It is noted that the crack sizes corresponding to 2% decrease in maximum tensile stress can be different for cyclic hardening and softening materials. Further, in some materials, the microstructures can continuously evolve with exposures to stress and temperature and cause changes in maximum stress not associated with crack formation. Maximum stress drop up to 10% may be used for defining crack formation in such cases. Metallographic analysis of the crack sizes in tested specimens and correlating it with percent decrease in maximum stress can provide additional useful information in choosing crack formation criterion and is therefore recommended whenever possible.

NOTE 35—The use of DCPD or ACPD instrumentation is not commonly used for the determination of crack formation in un-notched specimen creep-fatigue endurance tests but can be used when crack formation criteria of less than 0.5 mm are of interest, or for force controlled tests. As a caution it is noted that while the DCPD system can detect growth of internal cracks, the ACPD system is suitable only for detecting surface cracks.

NOTE 36—For load-controlled testing only methods described in *(b)* and *(d)* from 9.5.1 are applicable for choosing the number of cycles to crack formation.

9.5.2 *Shutdown*—The furnace shall be switched off as soon as the test is completed in order to limit the extent of oxidation to the test specimen and cracked surfaces prior to post-test examination. If a test terminates prior to total failure of the test specimen, every effort should be made to ensure that the test specimen is not over loaded during the cool down.

9.6 *Post-test Examination:*

9.6.1 The extent and location(s) of cracking shall be determined and shall be recorded in the test report. In particular, it should be noted if initiation is *(a)* between the extensometer probes *(b)* under an extensometer probe or at a thermocouple location *(c)* in the gage section, outside of the extensometer gage length *(d)* in the transition radius or *(e)* in the test specimen grips.

9.6.2 It should be confirmed by optical or scanning electron microscopy, or both, that crack initiation was not from surface scratches generated by bad machining practice or handling procedures.

9.6.3 Fatigue and creep damage fractions, and the mechanism(s) responsible for crack formation and crack development should be documented, to whatever extent possible, via metallographic examination and recorded.

NOTE 37—The scope of the metallographic examination will depend on the requirements of the test instigator. As a minimum it should comprise a qualitative recording of the mechanism(s) responsible for crack initiation and crack development. A more complete examination may include the qualitative determination of fatigue crack size distribution and creep cavity/cracking density distributions in the test specimen gage section.

10. Report

10.1 *Essential Information*—The test report on each test specimen shall contain:

10.1.1 Reference to this standard,

10.1.2 Material specification,

10.1.3 Modulus of elasticity and coefficient of thermal expansion,

10.1.4 Test specimen identity, type, dimension and reference to a documented method of preparation,

10.1.5 Test temperature,

10.1.6 Actual (and specified, if different) environment, cycle shape,

10.1.7 Strain (or force) ratio, including control parameter range applied,

10.1.8 Frequency or total strain (or loading) rate, and

10.1.9 If alignmentof the test rig is performed with a strain gaged specimen, then results of the alignment

10.1.10 Details of hold time(s) such as position(s), duration(s), control parameter(s).

10.1.11 Record for every cycle of stress, strain, temperature and crack condition (if PD instrumentation attached) at cycle turning points, that is, at cycle peaks, start and end of hold time(s).

10.1.12 *Characteristics of the First Cycle:*

10.1.12.1 Maximum and minimum strain,

10.1.12.2 Strains at start and end of hold time(s),

10.1.12.3 Maximum and minimum stress,

10.1.12.4 Stresses at start and end of hold time(s),

10.1.12.5 Moduli of elasticity (E_T and E_C), and

10.1.12.6 Inelastic strain range.

10.1.13 *Characteristics of the Half-life Cycle:*

10.1.13.1 Cycle number at mid-life,

10.1.13.2 Maximum and minimum strain

10.1.13.3 Strains at start and end of hold time(s),

10.1.13.4 Maximum and minimum stress,

10.1.13.5 Stresses at start and end of hold time(s), 10.1.13.6 Modulus of elasticity (E_T and E_C), and

10.1.13.7 Inelastic strain range.

10.1.14 Number of Cycles to crack formation,

10.1.14.1 Crack formation criterion.

10.1.15 Number of Cycles to Failure,

10.1.15.1 End-of-test criterion.

10.1.16 *Details of Post Test Examination:*

10.1.16.1 Fracture location(s) relative to the extensometer probes and transition radii,

10.1.16.2 Any evidence to indicate that cause of failure might invalidate the test result, and

10.1.16.3 Damage and fracture mechanisms observed in metallographic and SEM examinations.

10.2 Any deviation from this standard that might have an influence on the test result

10.3 *Additional Information:*

10.3.1 The following information is valuable and recommended for inclusion in the test report:

10.3.1.1 Material composition, heat treatment, microstructure, elastic modulus at room temperature and the test temperature, and coefficient of thermal expansion

10.3.1.2 Uniaxial tensile properties at room temperature and test temperature (including elongation and reduction of area at fracture, and the strain rates at which they were obtained as per PracticeE8/E8M.)

10.3.1.3 Complete identification of the part or product form from which the test-pieces are taken, or both,

10.3.1.4 Precise position and orientation of each test-piece,

10.3.1.5 Predominant material orientations due to the manufacturing process, such as rolling direction or casting direction,

10.3.1.6 Testing machine, heating device, extensometer,

10.3.1.7 Gage length of the extensometer,

10.3.1.8 Temperature distribution along gage length and variation with cycle number,

10.3.1.9 If alignment of the test rig is performed with a strain gaged specimen, then the results of the alignment test,

10.3.1.10 Details of PD instrumentation (if applicable), and

10.3.1.11 Position of PD instrumentation probes.

11. Precision and Bias

11.1 The precision of this test method is based on an inter-laboratory study specifically conducted to support this method (7). A total of 12 laboratories tested a single type of ASTM Grade P91 piping steel at strain amplitudes ranging from ±0.25% to ±0.75% under hold time conditions of up to 30 minutes. Every "test result" represented an individual determination. Each laboratory reported as many as four replicate test results for each material. Practice E691 was followed for the design and analysis of the data.

11.1.1 *Repeatability limit (r)*—Two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the "*r*" value for that material; "*r*" is the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment in the same laboratory.

11.1.1.1 Repeatability limits are listed in Table 1.

11.1.2 *Reproducibility limit (R)*—Two test results shall be judged not equivalent if they differ by more than the "*R*" value for that material; "*R*" is the interval representing the critical difference between two test results for the same material tested under nominally same conditions, obtained by different operators using different equipment in different laboratories.

11.1.2.1 Reproducibility limits are listed in Table 1.

11.1.3 The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E177.

11.1.4 Any judgment in accordance with statements 11.1.1 and 11.1.2 would normally have an approximate 95% probability of being correct, however the precision statistics obtained in this ILS must not be treated as exact mathematical quantities which are applicable to all circumstances and uses. The limited number of laboratories reporting replicate results under certain conditions guarantees that there will be times when differences greater than predicted by the ILS results will arise, sometimes with considerably greater or smaller frequency than the 95% probability limit would imply. Consider the repeatability limit and the reproducibility limit as general guides, and the associated probability of 95% as only a rough indicator of what can be expected.

11.2 *Bias*—This method is expected have no bias because creep-fatigue properties are defined in accordance with this method

12. Keywords

12.1 crack formation; creep; creep-fatigue damage; cyclic deformation; early crack growth; fatigue; metallic materials

TABLE 1 Analysis of the Round-Robin Results Conducted for the Verification Of The Standard to Establish Precision During Creep-Fatigue Testing (7).

Hold Time (minutes)/ strain amplitude)	Average Life (cycles)	Repeatability Standard Deviation (cycles)	Reproducibility Standard Deviation (cycles)	Repeatability Limit (cycles)	Reproducibility Limit (cycles)
	$\bar{x}$	s_r	s_R	r	R
0.0/ ±0.25%	3957.5	488.9	1902.8	1368.9	5328.0
0.0/±0.5%	869.8	105.8	207.0	296.3	579.5
0.0/±0.75%	491.5	82.3	84.0	230.5	235.3
10.0/±0.5%	740.8	143.7	266.3	402.3	745.8
10.0/±0.75%	456.7	47.1	102.9	131.9	288.2
30.0/±0.5%	696.6	163.8	247.3	458.5	692.4

APPENDIX

(Nonmandatory Information)

X1. FUNCTIONAL RELATIONSHIPS

X1.1 *Introduction*—This appendix provides examples of two empirical relationships that can be used to correlate isothermal creep-fatigue data. Several empirical techniques are available in the literature to correlate creep-fatigue cyclic life data with the testing variables. Only relationships that can be readily implemented using the control parameters and measurements, typically taken from hysteresis loops at half life, are given. These relationships result in good correlations when the hysteresis responses of all the test data exhibit measurable inelastic strain and there is no significant change in the time-dependent mechanism in the set of data being correlated. The wave form can affect the damage mechanism (i.e., the relative creep and/or environmental damage contribution). When the degradation mechanism in a set of data varies, relationships that account for these mechanisms must be considered to obtain a satisfactory correlation. These relationships are not considered here because further microscopic examination of the test specimens is needed to establish these mechanisms, which is beyond the scope of this test method.

X1.2 *Frequency-Modified Strain-Life*—The first relationship modifies the cycles to failure with frequency of the cycle (**8**),

$$\Delta\varepsilon_{in} = C\left(N_f \nu^{k-1}\right)^{-\beta} \quad (X1.1)$$

where :

$\Delta\varepsilon_{in}$ = inelastic strain range
ν = frequency of the cycle
N_f = cycles to failure

and the constants are C, β, and k. The constants are determined by a regression analysis. To verify the goodness of the regression analysis, it is convenient to plot the test data and correlation on the axes, $\Delta\varepsilon_{in}\ \nu^{\beta(k-1)}$ versus N_f. When k =1, this relationship reduces to the time-independent strain-life relationship (that is, fatigue life does not depend on frequency of the cycle).

X1.3 *Frequency Modified Tensile Hysteresis Energy*—The second relationship captures mean stress effects that are often significant for high strength, low ductility materials such as cast nickel-base superalloys (**9**),

$$\sigma_{max}\Delta\varepsilon_{in} = C_1\left(N_f \nu^{k_1-1}\right)^{-\beta_1} \quad (X1.2)$$

where:

σ_{max} = is the maximum stress in the cycle

and , C_1, k_1, and β_1 are regression constants and the remaining symbols have the same meaning as before. To verify the goodness of the regression analysis, it is convenient to plot the test data and correlation on the axes, versus .

X1.4 *Effective Frequency*—The wave form influence can be potentially captured using an effective frequency. The actual frequency ν is defined as the inverse of the total time for one cycle. However, different segments of the cycle may not be equally damaging. For example, in ductile materials, compressive holds may partially heal creep damage generated during tensile holds, resulting in a diminished influence of the frequency on life. Additional information on defining effective frequency in creep-fatigue correlations can be found in (**9**).

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