Designation: E2207 − 15

Standard Practice for
Strain-Controlled Axial-Torsional Fatigue Testing with Thin-Walled Tubular Specimens[1]

This standard is issued under the fixed designation E2207; 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 The standard deals with strain-controlled, axial, torsional, and combined in- and out-of-phase axial torsional fatigue testing with thin-walled, circular cross-section, tubular specimens at isothermal, ambient and elevated temperatures. This standard is limited to symmetric, completely-reversed strains (zero mean strains) and axial and torsional waveforms with the same frequency in combined axial-torsional fatigue testing. This standard is also limited to characterization of homogeneous materials with thin-walled tubular specimens and does not cover testing of either large-scale components or structural elements.

1.2 *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]

E3 Guide for Preparation of Metallographic Specimens
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E8/E8M Test Methods for Tension Testing of Metallic Materials
E9 Test Methods of Compression Testing of Metallic Materials at Room Temperature
E83 Practice for Verification and Classification of Extensometer Systems
E111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
E112 Test Methods for Determining Average Grain Size
E143 Test Method for Shear Modulus at Room Temperature
E209 Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates
E467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System
E606/E606M Test Method for Strain-Controlled Fatigue Testing
E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
E1417/E1417M Practice for Liquid Penetrant Testing
E1444/E1444M Practice for Magnetic Particle Testing
E1823 Terminology Relating to Fatigue and Fracture Testing
E2624 Practice for Torque Calibration of Testing Machines and Devices

3. Terminology

3.1 *Definitions*—The terms specific to this practice are defined in this section. All other terms used in this practice are in accordance with Terminologies E6 and E1823.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *axial strain*—refers to engineering axial strain, ε, and is defined as change in length divided by the original length ($\Delta L_g/L_g$).

3.2.2 *shear strain*—refers to engineering shear strain, γ, resulting from the application of a torsional moment to a cylindrical specimen. Such a torsional shear strain is simple shear and is defined similar to axial strain with the exception that the shearing displacement, ΔL_s is perpendicular to rather than parallel to the gage length, L_g, that is, $\gamma = \Delta L_s / L_g$ (see Fig. 1).

3.2.2.1 *Discussion*—γ= is related to the angles of twist, θ and Ψ as follows:

$\gamma = \tan \Psi$, where Ψ is the angle of twist along the gage length of the cylindrical specimen. For small angles expressed in radians, $\tan \Psi$ approaches Ψ and γ approaches Ψ.

$\gamma = (d/2)\theta/L_g$, where θ expressed in radians is the angle of twist between the planes defining the gage length of the cylindrical specimen and d is the diameter of the cylindrical specimen.

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[1] This practice 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.

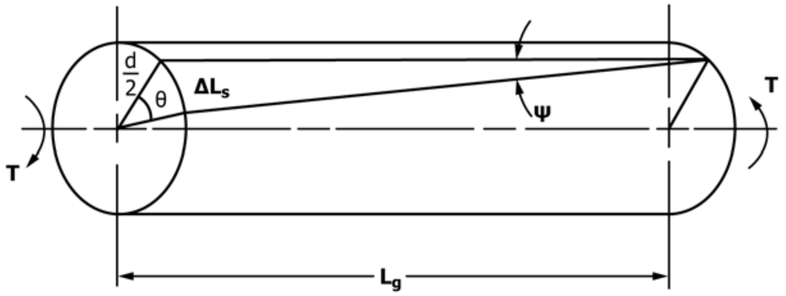

FIG. 1 Twisted Gage Section of a Cylindrical Specimen Due to a Torsional Moment

3.2.2.2 *Discussion*—ΔL_s is measurable directly as displacement using specially calibrated torsional extensometers or as the arc length $\Delta L_s = (d/2)\theta$, where θ is measured directly with a rotary variable differential transformer.

3.2.2.3 *Discussion*—The shear strain varies linearly through the thin wall of the specimen, with the smallest and largest values occurring at the inner and outer diameters of the specimen, respectively. The value of shear strain on the outer surface, inner surface, and mean diameter of the specimen shall be reported. The shear strain determined at the outer diameter of the tubular specimen is recommended for strain-controlled torsional tests, since cracks typically initiate at the outer surfaces.

3.2.3 *biaxial strain amplitude ratio*—in an axial-torsional fatigue test, the biaxial strain amplitude ratio, λ is defined as the ratio of the shear strain amplitude (γ_a) to the axial strain amplitude (ε_a), that is, γ_a/ε_a.

3.2.4 *phasing between axial and shear strains*— in an axial-torsional fatigue test, phasing is defined as the phase angle, φ, between the axial strain waveform and the shear strain waveform. The two waveforms must be of the same type, for example, both must either be triangular or both must be sinusoidal.

3.2.4.1 *in-phase axial-torsional fatigue test*— for completely-reversed axial and shear strain waveforms, if the maximum value of the axial strain waveform occurs at the same time as that of the shear strain waveform, then the phase angle, φ = 0° and the test is defined as an "in-phase" axial-torsional fatigue test (Fig. 2(a)). At every instant in time, the shear strain is proportional to the axial strain.

NOTE 1—Proportional loading is the commonly used terminology in plasticity literature for the in-phase axial-torsional loading described in this practice.

3.2.4.2 *out-of-phase axial-torsional fatigue test*— for completely-reversed axial and shear strain waveforms, if the maximum value of the axial strain waveform leads or lags the maximum value of the shear strain waveform by a phase angle φ ≠ 0° then the test is defined as an "out-of-phase" axial-torsional fatigue test. Unlike in the in-phase loading, the shear strain is not proportional to the axial strain at every instant in

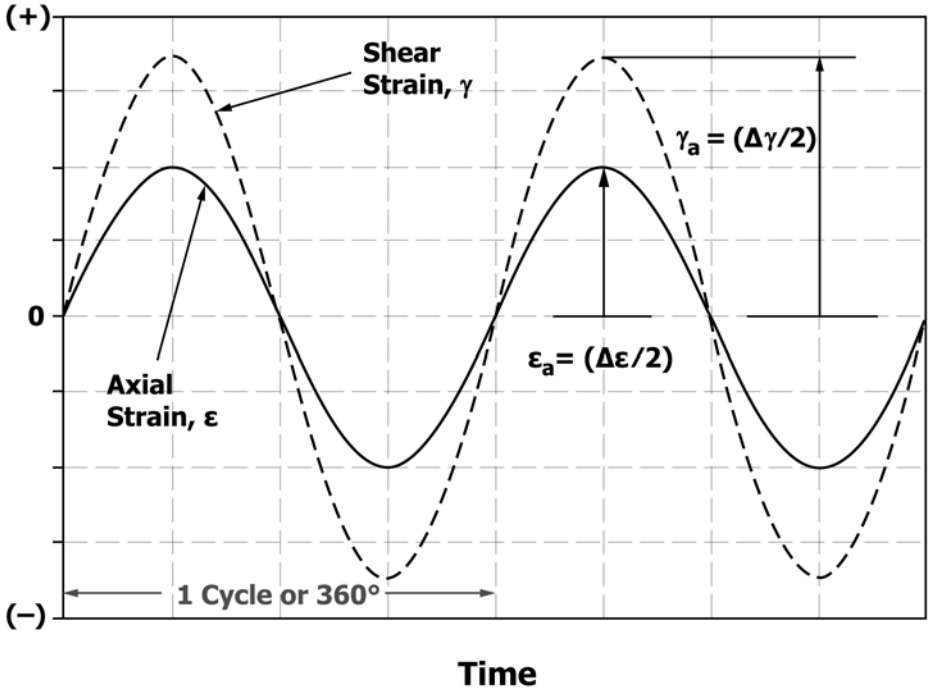

FIG. 2 Schematics of Axial and Shear Strain Waveforms for In- and Out-of-Phase Axial-Torsional Tests

time. An example of out-of-phase axial-torsional fatigue test with φ = 75° is shown in Fig. 2(b). Typically, for an out-of-phase axial-torsional fatigue test, the range of φ (≠ 0°) is from -90° (axial waveform lagging the shear waveform) to + 90° (axial waveform leading the shear waveform).

NOTE 2—In plasticity literature, nonproportional loading is the generic terminology for the out-of-phase loading described in this practice.

3.2.5 *shear stress*—refers to engineering shear stress, τ, acting in the orthogonal tangential and axial directions of the gage section and is a result of the applied torsional moment, (Torque) *T*, to the thin-walled tubular specimen. The shear stress, like the shear strain, is always the greatest at the outer diameter. Under elastic loading conditions, shear stress also varies linearly through the thin wall of the tubular specimen. However, under elasto-plastic loading conditions, shear stress tends to vary in a nonlinear fashion. Most strain-controlled axial-torsional fatigue tests are conducted under elasto-plastic loading conditions. Therefore, assumption of a uniformly distributed shear stress is recommended. The relationship between such a shear stress applied at the mean diameter of the gage section and the torsional moment, *T*, is

$$\tau = \frac{16T}{(\pi(d_o^2 - d_i^2)(d_o+d_i))} \qquad (1)$$

Where, τ is the shear stress, d_o and d_i are the outer and inner diameters of the tubular test specimen, respectively. However, if necessary, shear stresses in specimens not meeting the criteria for thin-walled tubes can also be evaluated (see Ref (**1**)).[3]

Under elastic loading conditions, shear stress, τ(*d*) at a diameter, *d* in the gage section of the tubular specimen can be calculated as follows:

$$\tau(d) = \frac{16Td}{(\pi(d_o^4 - d_i^4))} \qquad (2)$$

In order to establish the cyclic shear stress-strain curve for a material, both the shear strain and shear stress shall be determined at the same location within the thin wall of the tubular test specimen.

4. Significance and Use

4.1 Multiaxial forces often tend to introduce deformation and damage mechanisms that are unique and quite different from those induced under a simple uniaxial loading condition. Since most engineering components are subjected to cyclic multiaxial forces it is necessary to characterize the deformation and fatigue behaviors of materials in this mode. Such a characterization enables reliable prediction of the fatigue lives of many engineering components. Axial-torsional loading is one of several possible types of multiaxial force systems and is essentially a biaxial type of loading. Thin-walled tubular specimens subjected to axial-torsional loading can be used to explore behavior of materials in two of the four quadrants in principal stress or strain spaces. Axial-torsional loading is more convenient than in-plane biaxial loading because the stress state in the thin-walled tubular specimens is constant over the entire test section and is well-known. This practice is useful for generating fatigue life and cyclic deformation data on homogeneous materials under axial, torsional, and combined in- and out-of-phase axial-torsional loading conditions.

5. Empirical Relationships

5.1 *Axial and Shear Cyclic Stress-Strain Curves*—Under elasto-plastic loading conditions, axial and shear strains are

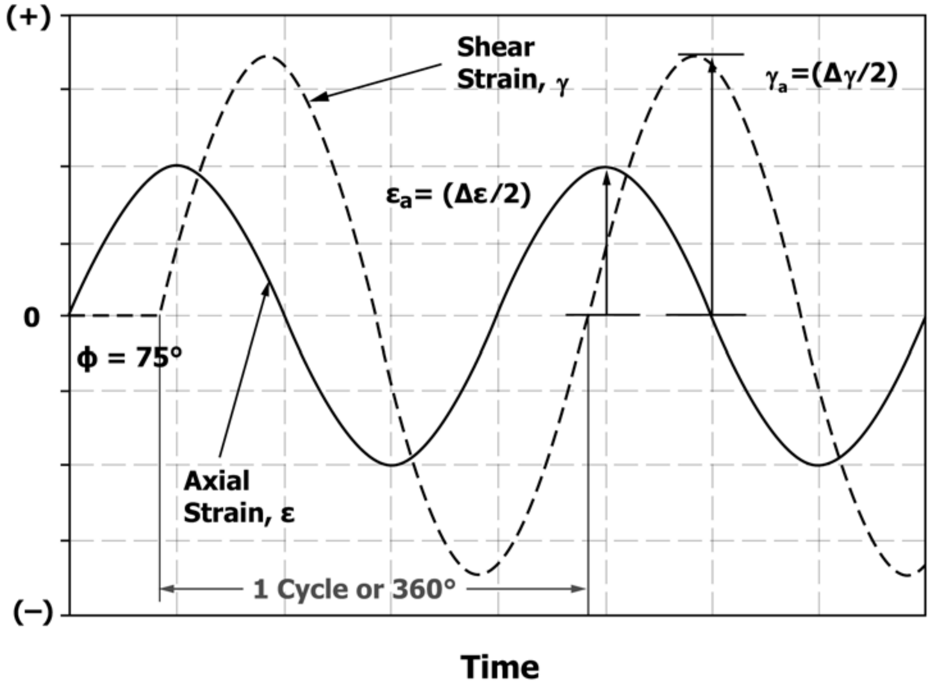

FIG. 2 Schematics of Axial and Shear Strain Waveforms for In- and Out-of-Phase Axial-Torsional Tests *(continued)*

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

composed of both elastic and plastic components. The mathematical functions commonly used to characterize the cyclic axial and shear stress-strain curves are shown in Appendix X1. Note that constants in these empirical relationships are dependent on the phasing between the axial and shear strain waveforms.

NOTE 3—For combined axial-torsional loading conditions, analysis and interpretation of cyclic deformation behavior can be performed by using the techniques described in Ref (**2**).

5.2 *Axial and Shear Strain Range-Fatigue Life Relationships*—The total axial and shear strain ranges can be separated into their elastic and plastic parts by using the respective stress ranges and elastic moduli. The fatigue life relationships to characterize cyclic lives under axial (no torsion) and torsional (no axial loading) conditions are also shown in Appendix X1. These axial and torsional fatigue life relationships can be used either separately or together to estimate fatigue life under combined axial-torsional loading conditions.

NOTE 4—Details on some fatigue life estimation procedures under combined in- and out-of-phase axial-torsional loading conditions are given in Refs (**3-5**). Currently, no single life prediction method has been shown to be either effective or superior to other methods for estimating the fatigue lives of materials under combined axial-torsional loading conditions.

6. Test Apparatus

6.1 *Testing Machine*—All tests should be performed in a test system with tension-compression and clockwise-counter clockwise torsional loading capability. The test system (test frame and associated fixtures) must shall be in compliance with the bending strain criteria specified in Test Method E606/E606M and Practice E1012. The test system shall possess sufficient lateral stiffness and torsional stiffness to minimize distortions of the test frame at the rated maximum axial force and torque capacities, respectively.

6.2 *Gripping Fixtures*—Fixtures used for gripping the thin-walled tubular specimen shall be made from a material that can withstand prolonged usage, particularly at high temperatures. The design of the fixtures largely depends upon the design of the specimen. Typically, a combination of hydraulically clamped collet fixtures and smooth shank specimens provide good alignment and high lateral stiffness. However, other types of fixtures, such as those specified in Test Method E606/E606M (for example, specimens with threaded ends) are also acceptable provided they meet the alignment criteria. Typically specimens with threaded ends tend to require significantly more effort than the smooth shank specimens to meet the alignment criteria specified in Test Method E606/E606M. For this reason, smooth shank specimens are preferred over the specimens with threaded ends.

6.3 *Force and Torque Transducers*—Axial force and torque must be measured with either separate transducers or a combined transducer. The transducer(s) must be placed in series with the force train and must comply with the specifications in Practices E4, E467 and E2624. The cross-talk between the axial force and the torque shall not exceed 1 % of full scale reading, whether a single transducer or multiple transducers are used for these measurements. Specifically, application of the rated axial force (alone) shall not produce a torque output greater than 1% of the rated torque and application of the rated torque (alone) shall not produce an axial force output greater than 1% of the rated axial force. In other words, the cross-talk between the axial force and the torque shall not exceed 1%, whether a single transducer or multiple transducers are used for these measurements.

6.4 *Extensometers*—Axial deformation in the gage section of the tubular specimen shall be measured with an extensometer such as, a strain-gaged extensometer, a Linear Variable Differential Transformer (LVDT), or a non-contacting (optical or capacitance type) extensometer. Procedures for verification and classification of extensometers are available in Practice E83. Twist in the gage section of the tubular specimen shall be measured with a troptometer such as, a strain-gaged external extensometer, internal Rotary Variable Differential Transformer (RVDT), or a non-contacting (optical or capacitance type) troptometer (Refs (**6, 7**)). Strain-gaged axial-torsional extensometers that measure both the axial deformation and twist in the gage section of the specimen may also be used provided the cross-talk is less than 1 % of full scale reading (Ref (**8**)). Specifically, application of the rated extensometer axial strain (alone) shall not produce a torsional output greater than 1 % the rated total torsional strain and application of the rated extensometer torsional strain (alone) shall not produce an axial output greater than 1 % of the rated total axial strain. In other words, the cross-talk between the axial displacement and the torsional twist shall not exceed 1 %, whether a single transducer or multiple transducers are used for these measurements.

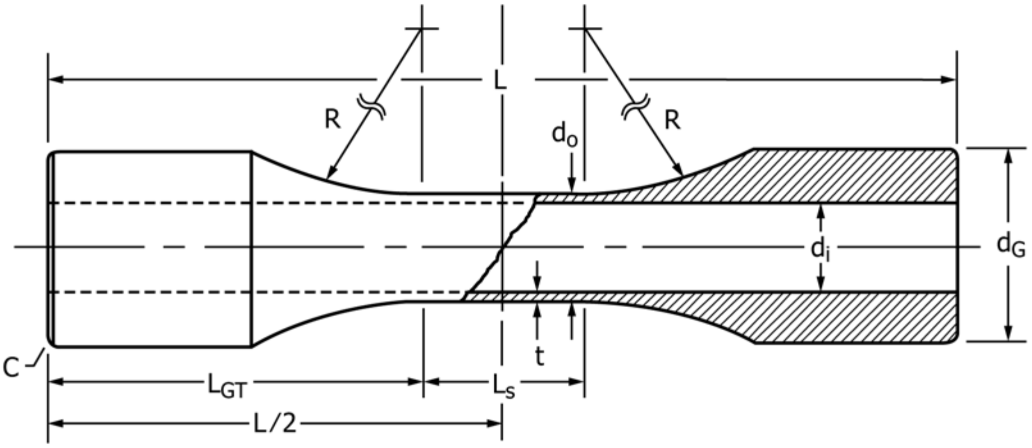
6.5 *Transducer Calibration*—All the transducers shall be calibrated in accordance with the recommendations of the respective manufacturers. Calibration of each transducer shall be traceable to the National Institute of Standards and Technology (NIST).

6.6 *Data Acquisition System*—Digital acquisition of cyclic test data is recommended or analog X-Y and strip chart recorders shall be employed to document axial and torsional hysteresis loops and variation of axial force/strain and torque/shear strain with time.

7. Thin-Walled Tubular Test Specimens

7.1 *Test Specimen Design*—The specimen's wall thickness shall be large enough to avoid instabilities during cyclic loading without violating the thin-walled tube criterion, that is, a mean diameter to wall thickness ratio of 10:1 or greater. For polycrystalline materials, at least 10 grains should be present through the thickness of the wall to preserve isotropy. In order to determine the grain size of the material, metallographic samples should be prepared in accordance with Practice E3 and the average grain size should be measured according to Test Method E112. If required for the test specimen's design, tensile and compressive properties of the material can be determined with Test Methods E8/E8M, E9, and E209. Suggested dimensions for the thin-walled tubular specimen are shown in Fig. 3. The test specimen design should minimize the bending stresses within the transition region under uniaxial tension.

NOTE 5—For tubular test specimens with mean diameter to wall



Legend:
t = wall thickness of the thin-walled tube in the gage section = $0.5(d_o - d_i)$,
d_o = outer diameter of the tube in the gage section = $14t \pm 3t$,
d_i = inner diameter of the tube = $0.85\ d_o \pm 0.04\ d_o$
d_G = outer diameter of the tube in the grip end = $1.6\ d_o \pm 0.4\ d_o$,
c = chamfer at 45°,
R = transition radius = $3.2\ d_o \pm 0.4\ d_o$
L = total length of the specimen = $8.5\ d_o \pm 1.5 d_o$
L_G = length of the grip end = $2\ d_o \pm 0.3 d_o$
L_{GT} = length of the grip end and transition region = $3.5 d_o \pm 0.5$
L_s = length of the straight section in the middle of the specimen = $1.5 d_o \pm 0.5 d_o$, and
L_g = length of the gage section in the middle of the specimen = $0.9\ d_o \pm 0.3 d_o$.
d_o and d_i shall be concentric within $\pm\ 0.015\ t$
Typical range for the wall thickness, t is 2.0±0.5mm.

FIG. 3 Schematic of Thin-Walled Tubular Specimen for Axial-Torsional Fatigue Testing

thickness ratios of less than 10, the thin-walled tube assumption may not be appropriate. As a result, shear stress may vary significantly through the thick wall of the specimen. Shear stresses in such test specimens can be evaluated with the method described in Ref (**1**).

NOTE 6—For nonpolycrystalline materials (for example, single-crystal (SC) and directionally-solidified (DS) materials) wall thickness of the tubular test specimen should be large enough to adequately capture the representative microstructure of the material being tested.

NOTE 7—In general, fatigue life under cyclic loading conditions involving torsion can be dependent on the ratio of the inner diameter to the outer diameter, d_i/d_o of the tubular test specimen (Ref (**9**)). Therefore, caution should be exercised in comparing fatigue lives obtained on the same material from specimens with substantially different d_i/d_o ratios. Under combined axial-torsional loading conditions, differences in fatigue lives are not expected to be significant for the range of d_i/d_o ratios allowed in the standard (Ref (**8**)).

7.2 *Specimen Fabrication*—Bore of the tubular specimen shall be honed to inhibit fatigue crack initiation from the inner surface of the specimen (Ref (**8**)). The gage section portion of the tubular test specimen should be machined in a single-pass from one end of the specimen to the other end. The inner and outer diameters of the tubular specimen shall have surface roughness, R_a values that are less than 0.2 µm in gage section. In addition, the procedure employed for machining thin-walled tubular specimens shall meet all the specifications documented in Appendix X3 of Test Method E606/E606M.

8. Test Procedure

8.1 *Measurement of Test Specimen Dimensions*—The outer and inner diameters of the thin-walled tubular test specimen shall be measured at least at three different locations (at each end and the center) within the gage section. To verify concentricity of the tubular specimen an additional set of three measurements should be made perpendicular to the first set of measurements. Average values computed from these measurements shall be used to calculate the test specimen dimensions for test control and post test data processing purposes.

NOTE 8—For elevated temperature tests, average values computed from the room temperature measurements may be corrected with the coefficient of thermal expansion to calculate the specimen dimensions at the test temperature. The calculated high temperature dimensions may also be used to estimate the test control parameters and for post-test data processing. Thermal coefficient of expansion can be measured for each test specimen before starting the fatigue test or alternatively, handbook value for the material, if available, can be used.

8.2 *Specimen Loading*—The specimen shall be mounted on the test machine without subjecting it to any axial or torsional preloads. Care should be exercised not to scratch the external or internal surfaces of the gage section while mounting contact-type external and internal extensometers or other instrumentation.

8.3 *Test Environment*—For elevated temperature tests, specimen heating can be accomplished with any of the techniques specified in Test Method E606/E606M. The temperature of the test specimen may be monitored with either contact type (for example, thermocouples) or with a non-contact type (for example, optical) temperature measurement device. The temperature variation within the gage section of the specimen should be less than 5K or within 1 % of the nominal absolute test temperature (K), whichever is greater.

NOTE 9—If any temperature excursions occur outside the specified limits, then those temperature values shall be included in the test report.

8.4 *Guidelines for Computing Axial and Shear Strains*—For controlling the test, axial and shear strain values shall be computed over the gage length of the test specimen. The shear strain, which varies linearly through the thin wall of the specimen, shall be computed by using the outer diameter of the tubular specimen.

8.5 *Control-Mode*—The axial, torsional, and combined axial-torsional (in- and out-of-phase) fatigue tests shall be performed in strain control. In order to conduct an axial fatigue test (no torsional loading) in strain control, the torsional controller should be in torque control at zero torque. Similarly, while conducting a torsional fatigue test (no axial loading) in strain control, the axial controller should be in force control at zero force.

8.6 *Command Waveforms*—The command waveforms for axial and shear strains may be either triangular or sinusoidal type. For room temperature tests, the strain rate (triangular waveform) or frequency (sinusoidal waveform) employed should be low enough to prevent excessive heating of the tubular specimen due to plastic work (that is, hysteretic heating). The strain rate or frequency used in the test must not increase the temperature of the specimen by more than 5K or 1 % of the nominal absolute test temperature (K), whichever is greater. For an out-of-phase axial-torsional fatigue test, the required phase shift should be included between the axial and shear strain waveforms with the axial waveform leading the shear strain waveform.

NOTE 10—For metallic materials, fatigue life could be dependent on strain rate or frequency. For example, fatigue data generated with strain rates differing by a factor of 10 or more may not produce similar fatigue lives. Therefore, for establishing fatigue life relationships under such conditions, it is recommended that either strain rate or frequency be used for generating the data set and that strain rate or frequency be reported with that data set.

NOTE 11—At certain temperatures the fatigue lives of some materials might exhibit a slight dependence on the waveform of loading, for example, triangular or sinusoidal. For characterizing the combined axial-torsional cyclic deformation behavior of materials, the triangular waveforms are preferred over the sinusoidal waveforms, because triangular waveforms produce a constant effective strain rate.

8.7 *Starting the Test*—Initial cyclic deformation exhibited by the material depends upon the procedure used to start the test. All the fatigue tests within a series should be started in similar directions. For example, in an axial-torsional fatigue test, the axial portion of the test is normally started in tension (positive direction) and the shear portion of the test is normally started in the positive shear strain direction. Typical starting waveforms for in- and out-of-phase axial-torsional fatigue tests are shown in Fig. 2(a) and Fig. 2(b), respectively. For large amplitude tests the axial and shear strains may be increased to their respective final amplitudes within 10 cycles to minimize overshoots. Such a gradual increase of amplitudes is required for materials that exhibit discontinuous yielding (also referred to as serrated yielding) phenomenon. In soft metallic materials (for example, alloys in annealed condition) application of the full amplitudes during the very first cycle may cause the extensometer to slip from the test specimen. Gradual increase of the amplitudes can mitigate this problem.

NOTE 12—Positive shear strain direction is defined by the right-handed coordinate system. For example, if one end of the test specimen is held in the right hand of an individual, with the thumb aligned with the axis and extending beyond the test specimen and the other four fingers wrapped around the specimen, then the thumb indicates positive tensile direction and the four fingers wrapped around the specimen indicate the direction of twist that produces a positive shear strain in the test specimen.

8.8 *Monitoring the Test*—The control variables (specimen temperature, axial and shear command waveforms) shall be monitored during the course of the fatigue test. Amplitudes of the strain control variables should not vary by more than 1 % of the respective nominal values. Phase angle between the axial and shear strain waveforms should not deviate from the required phase shift by more than 3° in the in- and out-of-phase axial-torsional fatigue tests. The temperature of the specimen (control variable) should not vary by more than 5K or 1 % of the nominal test temperature (K), whichever is greater, during the course of the fatigue test.

NOTE 13—If during the course of the test any control variables deviate from their respective specified limits, then those aberrations must be included in the test report.

8.9 *Recording of Data*—Axial force, axial strain, torque and shear strain shall be recorded during the first ten cycles of the fatigue test to document the initial cyclic hardening/softening behavior of the material. Thereafter these values shall be recorded at logarithmic intervals in cycles (for example, cycle numbers 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, etc.) throughout the fatigue test.

NOTE 14—Usually near the end of the test, when cracking is significant in the test specimen, it is desirable to reduce the interval between the recorded cycles to detect specimen failure.

8.10 *Determination of Test Specimen Failure*—Failure of the test specimen needs a precise definition in an axial-torsional fatigue test. Unlike axial fatigue, the specimen may not separate into two pieces in torsional fatigue. The percent force drop method or the surface replication technique or a method based on the cyclic stress-strain behavior (hardening or softening) can be used for determining failure of the specimen. In the percent force drop method a test specimen is considered to have failed when there is either a 5 or 10 % force drop from the previously recorded axial or torsional peak forces. In the second method, the fatigue test is interrupted at predetermined cyclic intervals to replicate the surface of the specimen with acetyl cellulose film. The film is subsequently examined for surface connected cracks and failure is defined by the length of the largest crack observed (usually either 0.1 or 1.0 mm). In the third method, failure definition takes the cyclic hardening/softening behavior of the material into consideration. Usually in constant strain range axial-torsional fatigue tests, both for the axial and torsional directions, during a major portion of the lifetime, the slope of the force range versus cycle number is nearly constant (either zero or slightly positive for cyclically hardening materials and negative for cyclically softening materials). Failure is defined by the intersection of either the axial force or torque range versus cycle number curve and a lower line that is 10 % below the actual cyclic hardening/softening curve and has a slope identical to the one exhibited by the material during the major portion of the test. In any instance, the definition of failure shall be included in the test report.

NOTE 15—For cyclically softening materials, it may be difficult to implement the percent force drop method for determining failure of the specimen. In such materials, the method based on the slope of the force range versus cycle number curve (the cyclic softening rate) may be used for detecting specimen failure. Alternatively, the surface replication method can also be used to determine failure of a specimen in the cyclically softening materials. In any instance, the definition of failure shall be included in the test report.

NOTE 16—For elevated temperature tests, the test specimen needs to be cooled to room temperature before replicating the surface with acetyl cellulose film. The number of such cool down and heat-up interruptions during the test should be reported.

NOTE 17—Nondestructive techniques such as liquid penetrant examination (Practice E1417/E1417M) and for ferromagnetic materials, magnetic particle examination (Practice E1444/E1444M) may also be used for detecting fatigue induced cracks in the test specimen. Alternatively, surface profilometry may be conducted to measure the length of the surface crack on the test specimen. It is recommended that the test specimen be left in the test machine while the nondestructive techniques are employed to detect fatigue cracks. However, some of the nondestructive techniques may require the test specimen to be removed from the grips and the test machine. If these techniques are used then care should be exercised to prevent damage to the test specimen during the gripping/ungripping sequences and the cycle number for each interruption during the test should be reported. Often a compromise has to be reached between the resolution and the ease of implementation, while selecting the appropriate crack detection method for a given material and test temperature.

NOTE 18—At a given percentage force drop the surface crack length(s) on the test specimen tend to vary from one material to another and from one life level to another for a given material. For example, a single dominant crack may be visible in some materials, whereas several small cracks may be present in others.

9. Reporting the Raw Test Data

9.1 Reporting of all the material details (heat treatment, microstructures and grain sizes both along the length and through the thin-wall of the tubular specimen) is highly recommended but is not required for testing the test specimens in accordance with this standard. Test specimen details (geometry and fabrication techniques), and testing methodology including the criterion used for defining failure of the specimen shall be reported. The data report shall include test temperature, frequency or strain rate, axial and shear strain amplitudes, and phase angle between the axial and shear strain waveforms. The report shall also contain axial and torsional hysteresis loops and peak axial and shear stresses at logarithmic intervals in cycles for each fatigue test. Orientation of the dominant crack(s) that lead to test specimen failure and the fatigue life associated with each test specimen shall be documented in the report. Any fatigue cracks in the test specimen associated with the contact points of the extensometer shall be reported. In addition, any deviations in the values of the control variables outside the specified limits shall be reported.

NOTE 19—The initial ramp-up cycles at the beginning of the fatigue test (see 8.7) should not be counted towards the fatigue life because they are applied at less than the intended final amplitudes.

NOTE 20—Typically, cracks initiating from extensometer contact points in a test specimen lead to early failures and the cyclic life generated from such a test may not accurately represent the fatigue durability of the material.

10. Data Reduction and Analysis

10.1 The half-life cycle data from each of the axial and torsional tests shall be used for analysis with the mathematical functions in the Appendix to determine axial and shear cyclic stress-strain curves and axial and shear strain range-fatigue life relationships. For combined axial-torsional loading conditions, additional details on analyzing the cyclic deformation behavior and interpreting the fatigue life patterns under in- and out-of-phase loading conditions are available in Refs (**2-5**).

11. Keywords

11.1 axial strain; axial stress; axial-torsional fatigue; in-phase axial-torsional fatigue test; out-of-phase axial-torsional fatigue test; shear strain; shear stress; strain-controlled testing; thin-walled tubular test specimen

APPENDIX

(Nonmandatory Information)

X1. MATHEMATICAL FUNCTIONS

INTRODUCTION

The cyclic deformation behavior and fatigue life relationships for most of the engineering alloys (Refs (**4**, **6**, **10**)) can be characterized by the following equations.

X1.1 Axial Cyclic Stress-Strain Curve X1.1

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} \qquad (X1.1)$$

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}$$

where:

ε = total axial strain,
ε_e = elastic axial strain,
ε_p = plastic axial strain,
σ = axial stress,
E = Young's modulus,
K' = cyclic axial strength coefficient (axial stress at plastic axial strain of unity),
n' = cyclic axial strain hardening exponent, and
Δ = range of a variable.

X1.2 Torsional Cyclic Stress-Strain Curve

$$\frac{\Delta\gamma}{2} = \frac{\Delta\gamma_e}{2} + \frac{\Delta\gamma_p}{2} \qquad (X1.2)$$

$$\frac{\Delta\gamma}{2} = \frac{\Delta\tau}{2G} + \left(\frac{\Delta\tau}{2K'_\gamma}\right)^{\frac{1}{n'_\gamma}}$$

where:

γ = shear strain,
γ_e = elastic shear strain,
γ_p = plastic shear strain,
τ = shear stress,
G = shear modulus,
K'_γ = cyclic torsional strength coefficient (shear stress at plastic shear strain of unity),
n'_γ = cyclic torsional strain hardening exponent, and
Δ = range of a variable.

X1.3 Axial Strain Range-Fatigue Life Relationship

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \qquad (X1.3)$$

where:

σ'_f = axial fatigue strength coefficient,
ε'_f = axial fatigue ductility coefficient,
b = axial fatigue strength exponent,
c = axial fatigue ductility exponent,
E = Young's modulus,
N_f = number of cycles to failure, and
$\Delta\varepsilon$ = axial strain range.

X1.4 Shear Strain Range-Fatigue Life Relationship

$$\frac{\Delta\gamma}{2} = \frac{\tau'_f}{G}(2N_f)^{b_\gamma} + \gamma'_f(2N_f)^{c_\gamma} \qquad (X1.4)$$

where:

τ'_f = torsional fatigue strength coefficient,
γ'_f = torsional fatigue ductility coefficient,
b_γ = torsional fatigue strength exponent,
c_γ = torsional fatigue ductility exponent,
G = shear modulus,
N_f = number of cycles to failure, and
$\Delta\gamma$ = shear strain range.

X1.4 Test Methods E111 and E143 describe procedures to determine Young's modulus, E and shear modulus, G respectively, for structural materials.

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