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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.

ε^1 NOTE—Referenced document E606's title was editorially updated from a Practice to a Test Method in October 2013.

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 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 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 Practice for Liquid Penetrant Testing
E1444 Practice for Magnetic Particle Testing
E1823 Terminology Relating to Fatigue and Fracture Testing

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).

NOTE 1—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 Ψ 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.

NOTE 2—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.

3.2.2.1 *Discussion*—The shear strain varies linearly through the thin wall of the specimen, with the smallest and largest

[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.

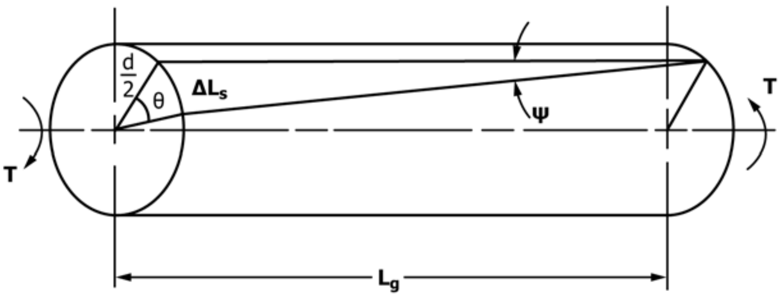

FIG. 1 Twisted Gage Section of a Cylindrical Specimen Due to a Torsional Moment

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 3—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 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 4—In plasticity literature, nonproportional loading is the generic

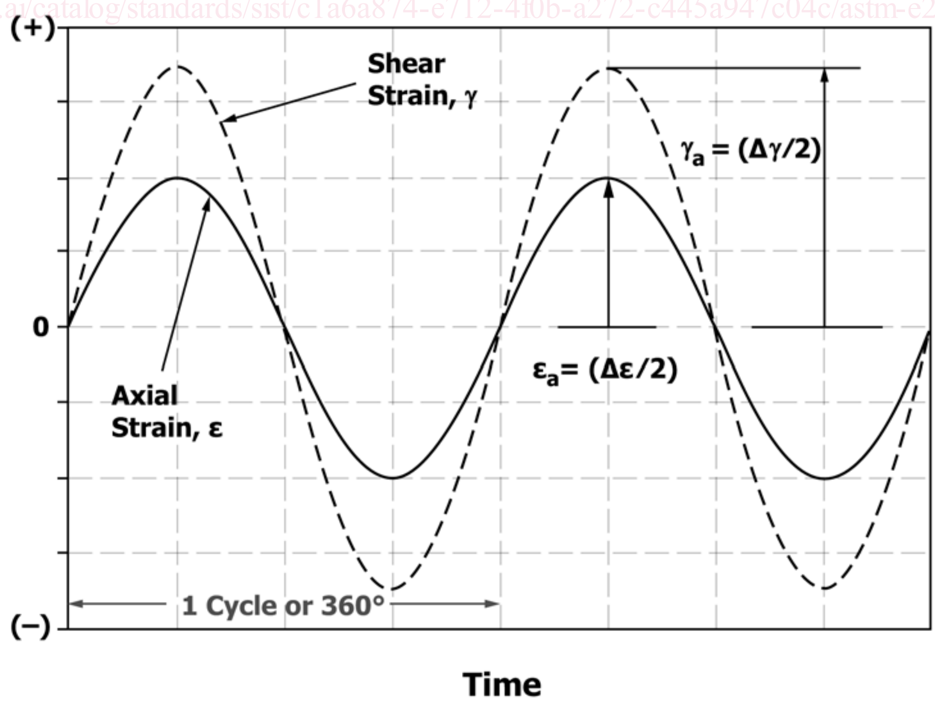

FIG. 2 Schematics of Axial and Shear Strain Waveforms for In- and Out-of-Phase Axial-Torsional Tests

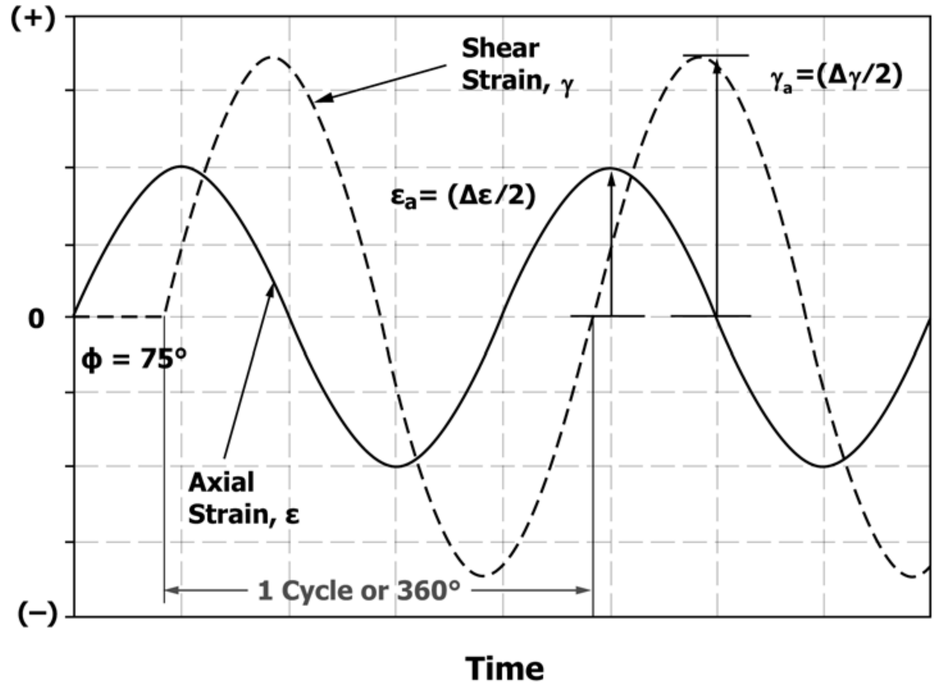

FIG. 2 Schematics of Axial and Shear Strain Waveforms for In- and Out-of-Phase Axial-Torsional Tests *(continued)*

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

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

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, $\tau(d)$ at a diameter, d in the gage section of the tubular specimen can be calculated as follows:

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

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 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 5—For combined axial-torsional loading conditions, analysis and

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

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 6—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 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 (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. 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 and E467. 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, 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 7—For tubular test specimens with mean diameter to wall 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 8—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.