This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: E2368 – 24

Standard Practice for Strain Controlled Thermomechanical Fatigue Testing[1]

This standard is issued under the fixed designation E2368; 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 practice covers the determination of thermomechanical fatigue (TMF) properties of materials under uniaxially loaded strain-controlled conditions. A "thermomechanical" fatigue cycle is here defined as a condition where uniform temperature and strain fields over the specimen gage section are *simultaneously varied and independently controlled*. This practice is intended to address TMF testing performed in support of such activities as materials research and development, mechanical design, process and quality control, product performance, and failure analysis. While this practice is specific to strain-controlled testing, many sections will provide useful information for force-controlled or stress-controlled TMF testing.

1.2 This practice allows for any maximum and minimum values of temperature and mechanical strain, and temperature-mechanical strain phasing, with the restriction being that such parameters remain cyclically constant throughout the duration of the test. No restrictions are placed on environmental factors such as pressure, humidity, environmental medium, and others, provided that they are controlled throughout the test, do not cause loss of or change in specimen dimensions in time, and are detailed in the data report.

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

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

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E3 Guide for Preparation of Metallographic Specimens
E4 Practices for Force Calibration and Verification of Testing Machines
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
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E220 Test Method for Calibration of Thermocouples By Comparison Techniques
E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E467 Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System
E606 Test Method for Strain-Controlled Fatigue Testing
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

3. Terminology

3.1 The definitions in this practice are in accordance with definitions given in Terminology E1823 unless otherwise stated.

3.2 *Definitions:*

3.2.1 Additional definitions are as follows:

3.2.2 *stress,* σ—stress is defined herein to be the engineering stress, which is the ratio of force, P, to specimen original cross sectional area, A:

$$\sigma = P/A \tag{1}$$

The area, A, is that measured in an unloaded condition at

[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 www.astm.org/contact. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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room temperature. See 7.2 for temperature state implications.

3.2.3 *coefficient of thermal expansion,* α—the fractional change in free expansion strain for a unit change in temperature, as measured on the test specimen.

3.2.4 *total strain,* ε_t—the strain component measured on the test specimen, and is the sum of the thermal strain and the mechanical strain.

3.2.5 *thermal strain,* ε_{th}—the strain component resulting from a change in temperature under free expansion conditions (as measured on the test specimen).

$$\varepsilon_{th} = \alpha \cdot \Delta T \tag{2}$$

NOTE 1—For some materials, α may be nonlinear over the temperature range of interest.

3.2.6 *mechanical strain,* ε_m—the strain component resulting when the free expansion thermal strain (as measured on the test specimen) is subtracted from the total strain.

$$\varepsilon_m = \varepsilon_t - \varepsilon_{th} \tag{3}$$

3.2.7 *elastic strain,* ε_{el}—the strain component resulting when the stress is divided by the temperature-dependent Young's Modulus (in accordance with Test Method E111).

$$\varepsilon_{el} = \sigma / E(T) \tag{4}$$

3.2.8 *inelastic strain,* ε_{in}—the strain component resulting when the elastic strain is subtracted from the mechanical strain.

$$\varepsilon_{in} = \varepsilon_m - \varepsilon_{el} \tag{5}$$

3.2.9 *strain ratio,* $R\varepsilon$—the ratio of minimum mechanical strain to the maximum mechanical strain in a strain cycle.

$$R\varepsilon = \varepsilon_{min}/\varepsilon_{max} \tag{6}$$

3.2.10 *mechanical strain/temperature true phase angle,* φ—for the purpose of assessing phasing accuracy, this is defined as the waveform shift (expressed in degrees) between the maximum temperature response as measured on the specimen and the maximum mechanical strain response. For reference purpose, the angle φ is considered positive if the temperature response maximum leads the mechanical strain response maximum by 180° or less, otherwise the phase angle is considered to be negative.

3.2.11 *in-phase TMF,* (φ = 0°)—a cycle where the maximum value of temperature and the maximum value of mechanical strain occur at the same time (see Fig. 1a).

3.2.12 *out-of-phase (anti-phase) TMF,* (φ = 180°)—a cycle where the maximum value of temperature leads the maximum value of mechanical strain by a time value equal to ½ the cycle period (see Fig. 1b).

4. Significance and Use

4.1 In the utilization of structural materials in elevated temperature environments, components that are susceptible to fatigue damage may experience some form of *simultaneously varying* thermal and mechanical forces throughout a given cycle. These conditions are often of critical concern because they combine temperature dependent and cycle dependent (fatigue) damage mechanisms with varying severity relating to the phase relationship between cyclic temperature and cyclic mechanical strain. Such effects can be found to influence the evolution of microstructure, micromechanisms of degradation, and a variety of other phenomenological processes that ultimately affect cyclic life. The strain-controlled thermomechanical fatigue test is often used to investigate the effects of simultaneously varying thermal and mechanical loadings under idealized conditions, where cyclic theoretically uniform temperature and strain fields are externally imposed and controlled throughout the gage section of the specimen.

5. Test Apparatus

5.1 *Testing Machine*—All tests shall be performed in a test system with tension-compression loading capability and verified in accordance with Practices E4 and E467. The test system (test frame and associated fixtures) shall be in compliance with the bending strain criteria specified in Practices E606, E1012, and E467. The test system shall be able to independently control both temperature and total strain. In addition it shall be capable of adding the measured thermal strain to the desired mechanical strain to obtain the total strain needed for the independent control.

5.2 *Gripping Fixtures*—Any fixture, such as those specified in Practice E606, is acceptable provided it meets the alignment criteria specified in Practice E606, and the specimen fails within the uniform gage section. Specimens with threaded ends typically tend to require more effort than those with smooth shank ends to meet the alignment criteria; for this reason, smooth shank specimens are preferred over specimens with threaded ends. Fixtures used for gripping specimens 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-actuated collet grips and smooth shank specimens provide good alignment and high lateral stiffness.

5.3 *Force Transducer*—The force transducer shall be placed in series with the load train and shall comply with the specifications in Practices E4 and E467.

5.4 *Extensometers*—Axial deformation in the gage section of the specimen should be measured with an extensometer. The extensometers (including optical extensometers, using an appropriate calibration procedure) should qualify as Class B-2 or better in accordance with Practice E83.

5.5 *Transducer Calibration*—All 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).

5.6 *Heating Device*—Specimen heating can be accomplished by various techniques including induction, direct resistance, radiant, or forced air heating. In all such cases, active specimen cooling (for example, forced air) can be used to achieve desired cooling rates provided that the temperature related specifications in 7.4 are satisfied.

NOTE 2—If induction is used, it is advisable to select a generator with a frequency sufficiently low to minimize "skin effects" (for example, preferential heating on the surface and near surface material with respect to the bulk, that is dependent on RF generator frequency) on the specimen during heating.

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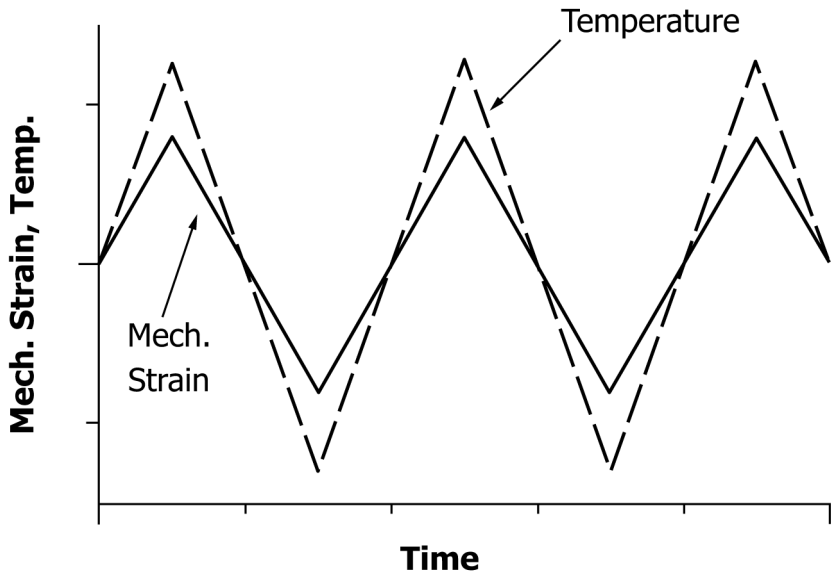
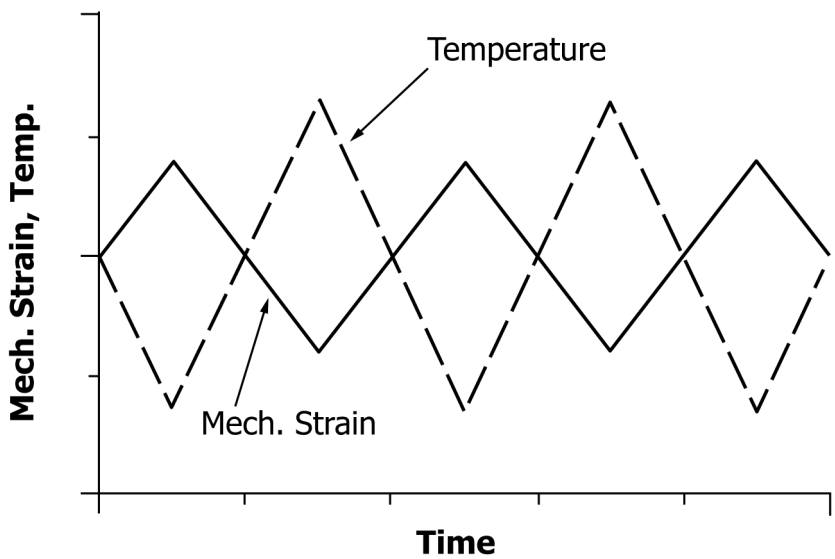


(a) In-phase TMF test (ϕ = 0)



(b) Out-of-phase TMF test (ϕ = 180)

FIG. 1 Schematics of Mechanical Strain and Temperature for In- and Out-of-Phase TMF Tests

5.7 *Temperature Measurement System*—The specimen temperature shall be measured using thermocouples in contact with the specimen surface in conjunction with an appropriate temperature indicating device or non-contacting sensors that are adjusted for emisivity changes by comparison to a reference such as thermocouples.

NOTE 3—Direct contact between the thermocouple and the specimen is implied and shall be achieved without affecting the test results (for example, test data for a specimen when initiation occurred at the point of contact of the thermocouple shall be omitted from consideration). Commonly used methods of the thermocouple attachment are: resistance spot welding (outside the gage section), fixing by binding or pressure.

NOTE 4—Under inductive heating, thermocouple wires may act as heat sinks, and can thus lower the local specimen surface temperature. This effect may be substantial at high temperatures. (**1**)

5.7.1 Calibration of the temperature measurement system shall be in accordance with Method E220.

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