Designation: E3414 – 23

Standard Test Method for Constant Torque Thermal Cycling of Cylindrical Shape Memory Alloy Specimens[1]

This standard is issued under the fixed designation E3414; 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 will define procedures for thermomechanical cycling of shape memory alloys (SMA) material and components with circular cross-sections under constant torque. This test method will measure the transformation properties such as transformation temperatures, actuation shear strain and residual shear strain, when a shape memory alloy is thermally cycled through the phase transformation under a constant applied torque. This test is done to provide data for the characterization selection of shape memory alloy materials, quality control, design allowables and actuator design.

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

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *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]

E4 Practices for Force Calibration and Verification of Testing Machines
E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E83 Practice for Verification and Classification of Extensometer Systems
E209 Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates
E606/E606M Test Method for Strain-Controlled Fatigue Testing
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1169 Practice for Conducting Ruggedness Tests
E2207 Practice for Strain-Controlled Axial-Torsional Fatigue Testing with Thin-Walled Tubular Specimens
E2368 Practice for Strain Controlled Thermomechanical Fatigue Testing
E3097 Test Method for Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys
E3098 Test Method for Mechanical Uniaxial Pre-strain and Thermal Free Recovery of Shape Memory Alloys
F2004 Test Method for Transformation Temperature of Nickel-Titanium Alloys by Thermal Analysis
F2005 Terminology for Nickel-Titanium Shape Memory Alloys

2.2 *Other Standards:*

IEEE/ASTM SI 10 American National Standard for Metric Practice[2]
ASQ C1 General Requirements for a Quality Program[3]
ISO 9001 Quality Management Systems—Requirements[4]

3. Terminology

3.1 *Definitions*—The terms specific to this test method are defined in this section. All other terms used in this test method are in accordance with Terminologies in Terminology F2005, Practice E2207, Test Method E3097 and Test Method E3098. All shear stress and shear strain defined in this test method are determined on the outer diameter in accordance with Practice E2207, unless otherwise stated.

[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.

[3] Available from American Society for Quality (ASQ), 600 N. Plankinton Ave., Milwaukee, WI 53203, http://www.asq.org.

[4] Available from International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, https://www.iso.org.

3.1.1 *Discussion*—During thermomechanical cycling of shape memory alloys (SMA) material shear stain typically varies non-linearly through the wall of the specimen, with the smallest and largest values occurring at the inner and outer diameters of the specimen, respectively. Furthermore, this test method allows for testing of specimens that do not meet the thin-walled condition as described in Practice E2207. Therefore, shear strain and shear stress results determined on the outer diameter should be considered representative of specimens of the NiTi based material and outer to inner diameter ratio being tested.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *actuation shear strain (γ_{act}), n*—the shear strain recovery obtained when heating from LCT to UCT at a specified shear stress.

$$\gamma_{act} = \gamma_{LCT} - \gamma_{UCT}$$

3.2.2 *austenite finish shear strain (γ_{Af}), n*—shear strain determined at the austenite finish temperature during final heating as described in 10.3. (See Fig. 1.)

3.2.3 *austenite start shear strain (γ_{As}), n*—shear strain determined at the austenite start temperature during final heating as described in 10.3. (See Fig. 1.)

3.2.4 *cooling transformation shear strain (γ_{ct}), n*—the shear strain recovery due to the martensitic transformation obtained when cooling at a specified shear stress.

$$\gamma_{ct} = \gamma_{Ms} - \gamma_{Mf}$$

3.2.5 *heating transformation shear strain (γ_{ht}), n*—the shear strain recovery due to the austenitic transformation obtained when heating at a specified shear stress.

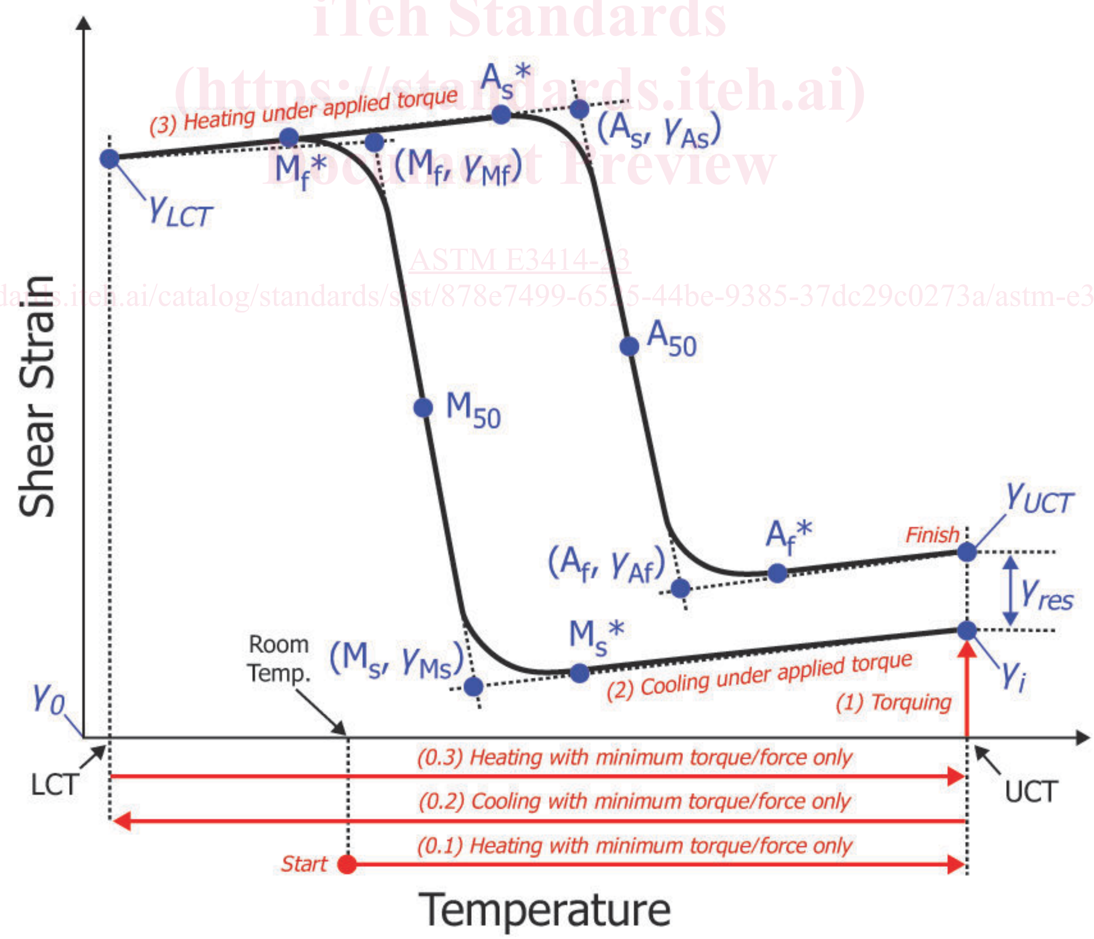
$$\gamma_{ht} = \gamma_{As} - \gamma_{Af}$$

3.2.6 *initial loading shear strain (γ_i), n*—initial specimen strain after normalization and before cooling when loaded at the UCT. (See Fig. 1.)

3.2.7 *initial shear strain (γ_0), n*—specimen shear strain at UCT after normalizing (see 10.1) and prior to loading the specimen. (See Fig. 1.)

3.2.8 *martensite finish shear strain (γ_{Mf}), n*—shear strain determined at the martensite finish temperature during cooling as described in 10.3. (See Fig. 1.)

3.2.9 *martensite start shear strain (γ_{Ms}), n*—shear strain determined at the martensite start temperature during cooling as described in 10.3. (See Fig. 1.)



NOTE 1—In cases where the starting point labeled "Start" coincides with the UCT, such as for the case of low temperature SMAs that are austenitic at room temperature, the same procedure applies with the exception that the normalization step labeled (0.1) is no longer needed.

FIG. 1 Typical Constant Torque Thermal Cycle and Test Methods Terms

3.2.10 *residual shear strain* (γ_{res}), *n*—the final shear strain at the upper cycle temperature (UCT) minus the initial shear strain at the UCT.

$$\gamma_{res} = \gamma_{UCT} - \gamma_i$$

3.2.11 *shear strain at the lower cycle temperature* (γ_{LCT}), *n*—specimen shear strain at the LCT after cooling from the UCT to the LCT under the specified shear stress. (See Fig. 1.)

3.2.12 *shear strain at the upper cycle temperature* (γ_{UCT}), *n*—specimen shear strain at the UCT after cooling to the LCT and heating to the UCT at the specified shear stress. (See Fig. 1.)

3.3 *Acronyms:*

3.3.1 *CTTC, n*—constant torque thermal cycling of cylindrical shape memory alloy specimens

3.3.2 *LCT, n*—lower cycle temperature

3.3.3 *TWSME, n*—two way shape memory effect

3.3.4 *UCT, n*—upper cycle temperature

3.4 See also Terminology E4.

4. Significance and Use

4.1 Constant torque thermal cycling tests determine the effect of shear stress on the transformation properties such as transformation temperatures, actuation shear strain and residual shear strain of a shape memory alloy. This test is done to provide data for the characterization selection of shape memory alloy materials, quality control, design allowables and actuator design (**1-3**).[5] The tests should be used for one thermal cycle but may be used for repeated thermal cycles as agreed upon between supplier and customer.

4.2 Measurement of the specimen's motion closely parallels many shape memory actuator applications and provides a result that is applicable to the function of the material.

4.3 This test method may be used for cylindrical specimens such as wire, round tube or bar forms. Thus, it is able to provide an assessment of the product in its semi-finished form.

4.4 This test method provides a simple method for determining transformation temperatures by heating and cooling specimens through their full thermal transformation under torque.

4.5 This test method may also be used to evaluate partial transformation cycles as set by the LCT and UCT and agreed upon between the user and customer. Examples of partial and full transformation thermal cycles are provided in Fig. 2.

4.6 This test method can be used on trained and processed material in a semi-finished form to measure Two Way Shape Memory Effect (TWSME) by comparing the shear strain at the LCT and UCT with a torque set such that the corresponding shear stress shall not exceed 7 MPa. For determining TWSME in this manner it is suggested that a full transformation cycle be performed in accordance with 5.7.

4.7 This test method is useful for quality control, specification acceptance, and research.

4.8 Transformation temperatures derived from this test method may not agree with those obtained by other test methods due to the effects of shear strain and shear stress on the transformation.

4.9 Components such as springs, specimens with non-circular cross-sections or other semi-finished parts can be tested using this method as agreed upon by the customer and supplier. Test parameters and results shall be determined with respect to torque and rotation measured at the ends of the active region of the specimen.

5. Interferences

5.1 The initial condition of the test specimen can significantly impact test results.

NOTE 1—Care should be taken to assure the material is free of unintended residual stresses from fabrication, processing, or handling. Cutting and grinding can cause cold work which affects the transformation temperatures. Oxidation during heat treatment can change the thermal properties of the specimen and affect the temperature uniformity. Such effects are magnified by specimens with smaller gauge diameters.

5.2 When testing cylindrical bar, rod, tube and wire with clamped end connections, make sure that the gripping mechanism does not cause errors in strain measurement, for example slipping in the grips.

5.3 The extensometer design and size shall be chosen so that the extensometer measures relevant deformation, respectively, within a representative section of the gauge length of the sample.

5.4 Complete thermal transformation is required for accurate results. The material's martensite finish and austenite finish temperatures may be estimated prior to the test by Differential Scanning Calorimetry (Test Method F2004), Uniaxial Constant Force Thermal Cycling (Test Method E3097) or Uniaxial Pre-strain and Thermal Free Recovery (Test Method E3098).

5.5 Make sure that the heating and cooling system maintains a uniform specimen temperature within ± 3 °C, along the specimen length, over the gauge section. Temperature gradients in the specimen will affect the apparent transformation temperatures and strains. See 9.1 for details on temperature measurement.

5.6 The heating and cooling rate for the test shall be consistent with the sample thickness so that the test section of the specimen is at a uniform temperature within ± 3 °C, transverse to the specimen length, over the gauge section. See 9.1 for details on temperature measurement.

NOTE 2—Requirements specified in interferences 5.5 and 5.6 may be achieved by selecting hold times at the UCT and LCT to ensure the specimen and temperature control system are fully equilibrated before starting/continuing the thermal cycle.

5.7 For full transformation cycle make sure the specimen is fully austenitic at the UCT for all stress levels to be tested. This is shown graphically in Fig. 2. It is selected to be higher than the A_f determined by a DSC test in accordance with Test Method F2004. For example, a temperature between 10 °C to

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