



Designation: E21 – 20

# Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials<sup>1</sup>

This standard is issued under the fixed designation E21; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

*This standard has been approved for use by agencies of the U.S. Department of Defense.*

## 1. Scope\*

1.1 These test methods cover procedure and equipment for the determination of tensile strength, yield strength, elongation, and reduction of area of metallic materials at elevated temperatures.

1.2 Determination of modulus of elasticity and proportional limit are not included.

1.3 Tension tests under conditions of rapid heating or rapid strain rates are not included.

1.4 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.5 *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.*

1.6 *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:*<sup>2</sup>

- 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

<sup>1</sup> These test methods are under the jurisdiction of ASTM Committee E28 on Mechanical Testing and are the direct responsibility of Subcommittee E28.04 on Uniaxial Testing.

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<sup>2</sup> 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.

- E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
- E74 Practices for Calibration and Verification for Force-Measuring Instruments
- E83 Practice for Verification and Classification of Extensometer Systems
- E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
- E220 Test Method for Calibration of Thermocouples By Comparison Techniques
- E633 Guide for Use of Thermocouples in Elevated-Temperature Mechanical Testing
- E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

## 3. Terminology

3.1 Definitions of terms relating to tension testing which appear in Terminology E6, apply to this test method. These terms include alignment, axial strain, bending strain, gauge length, elongation, elongation after fracture, extensometer system, necking, reduction of area, tensile strength, yield strength. In addition, the definitions of the following terms relating to tension testing are included.

3.1.1 Definitions of terms relating to tension testing which appear in E6, shall apply to the terms used in this test method.

3.2 *Definitions:*

3.2.1 *indicated temperature, n*—the temperature indicated by the temperature-measuring system that meets the requirements of this standard.

3.2.2 *specified temperature*—the test temperature requested by and reported to the customer.

3.2.3 *temperature-measuring system, n*—a system consisting of one or more temperature-measuring transducers with the appropriate indicating instruments, extension wires, reference junctions or ice points, and data acquisition devices.

3.2.3.1 *Discussion*—The temperature-measuring transducer is usually a thermocouple.

3.2.3.2 *Discussion*—The use of the term measuring system conforms to the definition of "measuring system" in the JCGM: International Vocabulary of Metrology – Basic and General Concepts and Associated terms (VIM).

\*A Summary of Changes section appears at the end of this standard

## 4. Significance and Use

4.1 The elevated-temperature tension test gives a useful estimate of the ability of metals to withstand the application of applied tensile forces. Using established and conventional relationships it can be used to give some indication of probable behavior under other simple states of stress, such as compression, shear, etc. The ductility values give a comparative measure of the capacity of different materials to deform locally without cracking and thus to accommodate a local stress concentration or overstress; however, quantitative relationships between tensile ductility and the effect of stress concentrations at elevated temperature are not universally valid. A similar comparative relationship exists between tensile ductility and strain-controlled, low-cycle fatigue life under simple states of stress. The results of these tension tests can be considered as only a questionable comparative measure of the strength and ductility for service times of many hours. Therefore, the principal usefulness of the elevated-temperature tension test is to assure that the tested material is similar to reference material when other measures such as chemical composition and microstructure also show the two materials are similar.

## 5. Apparatus

### 5.1 Testing Machine:

5.1.1 The accuracy of the testing machine shall be within the permissible variation specified in Practices E4.

5.1.2 Precaution should be taken to assure that the force on the specimens is applied as axially as possible. Perfect axial alignment is difficult to obtain especially when the pull rods and extensometer rods pass through packing at the ends of the furnace. However, the machine and grips should be capable of loading a precisely made specimen so that the maximum bending strain does not exceed 10 % of the axial strain, when the calculations are based on strain readings taken at zero force and at the lowest force for which the machine is being qualified.

NOTE 1—This requirement is intended to limit the maximum contribution of the testing apparatus to the bending which occurs during a test. It is recognized that even with qualified apparatus different tests may have quite different percent bending strain due to chance orientation of a loosely fitted specimen, lack of symmetry of that particular specimen, lateral force from furnace packing, and thermocouple wire, etc. The scant evidence available at this time<sup>3</sup> indicates that the effect of bending strain on test results is not sufficient, except in special cases, to require the measurement of this quantity on each specimen tested.

5.1.2.1 In testing of brittle material even a bending strain of 10 % may result in lower strength than would be obtained with improved axiality. In these cases, measurements of bending strain on the specimen to be tested may be specifically requested and the permissible magnitude limited to a smaller value.

5.1.2.2 In general, equipment is not available for determining maximum bending strain at elevated temperatures. The testing apparatus may be qualified by measurements of axiality made at room temperature using the assembled machine, pull

rods, and grips used in elevated temperature testing. The specimen form should be the same as that used during the elevated-temperature tests and designed so that only elastic strains occur throughout the reduced section. This requirement may necessitate use of a material different from that used during the elevated-temperature test. See Practice E1012 for recommended methods for determining specimen alignment.

5.1.2.3 Gripping devices and pull rods may oxidize, warp, and creep with repeated use at elevated temperatures. Increased bending stresses may result. Therefore, grips and pull rods should be periodically retested for axiality and reworked when necessary.

5.1.3 The testing machine shall be equipped with a means of measuring and controlling either the strain rate or the rate of crosshead motion or both to meet the requirements in 9.6.

5.1.4 For elevated-temperature testing of materials that are readily attacked by their environment (such as oxidation of metal in air), the specimen may be enclosed in a capsule so that it can be tested in a vacuum or inert gas atmosphere. When such equipment is used, the necessary corrections must be made to determine the actual forces seen by the specimen. For instance, compensation must be made for differences in pressures inside and outside of the capsule and for any variation in the forces applied to the specimen due to sealing ring friction, bellows or other features.

### 5.2 Heating Apparatus:

5.2.1 The apparatus for and method of heating the specimens should provide the temperature control necessary to satisfy the requirements specified in 9.4.

5.2.2 Heating shall be by an electric resistance or radiation furnace with the specimen in air at atmospheric pressure unless other media are specifically agreed upon in advance.

NOTE 2—The media in which the specimens are tested may have a considerable effect on the results of tests. This is particularly true when the properties are influenced by oxidation or corrosion during the test.

### 5.3 Temperature-measuring system:

5.3.1 The method of temperature measurement must be sufficiently sensitive and reliable to ensure that the indicated temperature of the specimen is within the limits specified in 9.4.4.

5.3.2 Temperature should be measured with thermocouples as part of an appropriate temperature measuring system.

NOTE 3—Such measurements are subject to two types of error. Thermocouple calibration and instrument measuring errors initially introduce uncertainty as to the exact temperature. Secondly both thermocouples and measuring instruments may be subject to variation with time. Common errors encountered in the use of thermocouples to measure temperatures include: calibration error, drift in calibration due to contamination or deterioration with use, lead-wire error, error arising from method of attachment to the specimen, direct radiation of heat to the bead, heat-conduction along thermocouple wires, etc.

5.3.3 If temperature measurements are made using thermocouples, those thermocouples shall be calibrated using Practice E220. Representative thermocouples should be calibrated from each lot of wires used for making base-metal thermocouples. Except for relatively low temperatures of exposure, base-metal thermocouples are subject to error upon reuse, unless the depth of immersion and temperature gradients

<sup>3</sup> Subcommittee E28.10 on Effect of Elevated Temperature on Properties requests factual information on the effect of nonaxiality of loading on test results.

of the initial exposure are reproduced. Consequently base-metal thermocouples should be verified by the use of representative thermocouples and actual thermocouples used to measure specimen temperatures should not be verified at elevated temperatures. Base-metal thermocouples also shall not be reused without clipping back to remove wire exposed to the hot zone and rewelding or creating a new compression junction.

5.3.3.1 Noble metal thermocouples are also subject to errors due to contamination, etc., and should be periodically annealed and verified. Thermocouples should be kept clean prior to exposure and during use at elevated temperatures.

5.3.3.2 Measurement of the emf drift in thermocouples during use is difficult. When drift is a problem during tests, a method should be devised to check the readings of the thermocouples on the specimen during the test. For reliable calibration of thermocouples after use the temperature gradient of the testing furnace must be reproduced during the recalibration.

5.3.4 The temperature-measuring system, shall be verified yearly against a secondary standard, such as a precision potentiometer and if necessary re-calibrated. Extension-wire error should be checked with the extension wires in place as they normally are used.

#### 5.4 Extensometer System:

5.4.1 Practice E83, is recommended as a guide for selecting the required sensitivity and accuracy of extensometers. For determination of offset yield strength at 0.1 % or greater, a Class B-2 extensometer may be used. The extensometer should meet the requirements of Practice E83 and should, in addition, be tested to assure its accuracy when used in conjunction with a furnace at elevated temperature. One such test is to measure at elevated temperature the stress and strain in the elastic range of a metal of known modulus of elasticity. Combinations of stress and temperature which will result in creep of the specimen during the extensometer system evaluation should be avoided.

NOTE 4—If an extensometer of Class B-2 or better is attached to the reduced section, the slope of the stress-strain curve will usually be within 10 % of the modulus of elasticity.

5.4.2 Non-axiality of loading is usually sufficient to cause significant errors at small strains when strain is measured on only one side of the specimen.<sup>4</sup> Therefore, the extensometer should be attached to and indicate strain on opposite sides of the specimen. The reported strain should be the average of the strains on the two sides, either a mechanical or electrical average internal to the instrument or a numerical average of two separate readings.

5.4.3 When feasible the extensometer should be attached directly to the reduced section. When necessary, other arrangements (discussed in 9.6.3) may be used by prior agreement of the parties concerned. For example, special arrangements may be necessary in testing brittle materials where failure is apt to be initiated at an extensometer knife edge.

5.4.4 To attach the extensometer to miniature specimens may be impractical. In this case, separation of the specimen holders or crossheads may be recorded and used to determine strains corresponding to the 0.2 % offset yield strength. The value so obtained is of inferior accuracy and must be clearly marked as “approximate yield strength.” The observed extension should be adjusted by the procedure described in 9.6.3 and 10.1.3.

5.4.5 The extensometer system shall include a means of determining strain rate.

5.5 *Room-Temperature Control*—Unless the extensometer is known to be insensitive to ambient temperature changes, the range of ambient temperature should not exceed 10 °F (6 °C) while the extensometer is attached. The testing machine should not be exposed to perceptibly varying drafts.

## 6. Sampling

6.1 Unless otherwise specified the following sampling procedures shall be followed:

6.1.1 Samples of the material to provide test specimens shall be taken from such locations as to be representative of the lot from which it was taken.

6.1.2 Samples shall be taken from material in the final condition (temper). One test shall be made on each lot.

6.1.3 A lot shall consist of all material from the same heat, nominal size, and condition (temper).

## 7. Test Specimens and Sample

7.1 The size and shape of the test specimens should be based primarily on the requirements necessary to obtain representative samples of the material being investigated.

7.2 Unless otherwise specified, test specimens shall be oriented such that the axis of the specimen is parallel to the direction of fabrication, and located as follows:

7.2.1 At the center for products 1.5 in. (38 mm) or less in thickness, diameter, or distance between flats.

7.2.2 Midway from the center to the surface for products over 1.5 in. (38 mm) in thickness, diameter, or distance between flats.

7.3 Specimen configurations described in Test Methods E8/E8M, are generally suitable for tests at elevated temperatures; however, tighter dimensional tolerances are recommended in 7.6. The particular specimen used should be mainly governed by the requirements specified in 7.1. When the dimensions of the material permit, except for sheet and strip, the gauge length of the specimens should have a circular cross section. The largest diameter specimen consistent with that described in 7.1 should be used, except that the diameter need not be greater than 0.500 in. (12.7 mm). The ratio of gauge length to diameter should be 4, as for the standard specimens described in Test Methods E8/E8M. If different ratios are used, the specifics should be reported in the results. (See 11.1.4)

NOTE 5—Specimen size in itself has little effect on tensile properties provided the material is not subject to appreciable surface corrosion, lack of soundness, or orientation effects. A small number of grains in the specimen cross section, or preferred orientation of grains due to fabrication conditions, can have a pronounced effect on the test results. When corrosion is a factor in testing, the results do become a function of

<sup>4</sup> Tishler, D. N., and Wells, C. H., “An Improved High-Temperature Extensometer,” *Materials Research and Standards*, American Society for Testing and Materials, MTRSA, Vol 6, No. 1, January 1966, pp. 20–22.

specimen size. Likewise, surface preparation of specimens, if affecting results, becomes more important as the specimen size is reduced.

7.4 Specimens of circular cross section should have threaded, shouldered, or other suitable ends for gripping which will meet the requirements of 5.1.2.

NOTE 6—Satisfactory axial alignment may be obtained with precisely machined threaded ends. But at temperatures where oxidation and creep are readily apparent, precisely fitted threads are difficult to maintain and to separate after test. Practical considerations require the use of relatively loose-fitting threads. Other gripping methods have been successfully used.<sup>5,6</sup>

7.5 For rectangular specimens some modifications of the standard specimens described in Test Methods E8/E8M are usually necessary to permit application of the force to the specimen in the furnace with the axiality specified in 5.1.2. If the material available is sufficient, the use of elongated shoulder ends to permit gripping outside the furnace is the easiest method. When the length of the specimen is necessarily restricted, several methods of gripping may be used as follows:

7.5.1 A device that applies the force through a cylindrical pin in each of the enlarged ends of the specimen. The pin holes should be accurately centered on extensions of the centerline of the gauge section. Grips of this type can provide good axiality of loading.<sup>5</sup>

7.5.2 High-temperature sheet grips similar to those illustrated in Test Methods E8/E8M and described as self-adjusting grips. These have proven satisfactory for testing sheet materials that cannot be tested satisfactorily in the usual type of wedge grips.

7.5.3 Extension tabs may be welded or brazed to the specimen shoulders and extended to grips outside the furnace. When these are used, care must be exercised to maintain coaxiality of the centerlines of the extensions and the gauge length. Any brazing or welding should be done in a jig or fixture to maintain accurate alignment of the parts. Any machining should be done after brazing or welding.

7.5.4 Grips that conform to and apply force against the fillets at the ends of the reduced section.

7.6 The diameter (or width) at the ends of the reduced section should not be less than the diameter (or width) at the center of the reduced section. It may be desirable to have the diameter (or width) of the reduced section slightly smaller at the center than at the ends. This difference should not exceed 0.5 % of the diameter (or width). When specimens of this form are used to test brittle materials, failure may regularly occur at the fillets. In these cases, the center of the reduced section may be made smaller by a gradual taper from the ends and the exception to the requirements above noted in the report. (See 11.1.4 and 11.1.10.) Specimen surfaces shall be smooth and free from undercuts and scratches. Cold work introduced through machining or handling can produce high residual

stresses or other undesired effects and should be minimized. The axis of the reduced section should be straight within  $\pm 0.5$  % of the diameter. Threads of the specimen should be concentric with this axis within the same tolerance. Other means of gripping should have comparable tolerances.

7.7 For cast-to-size specimens it may not be possible to adhere to the diameter, straightness, and concentricity limitations of 7.6, but every effort should be made to approach these as closely as possible. If the specimen does not meet the requirements specified in 7.6, the report should so state (see 11.1.4 and 11.1.10). The magnitude of the deviations should be reported (see 11.1.10.)

## 8. Calibration and Standardization

8.1 The following devices should be calibrated against standards traced to the National Institute of Standards and Technology. Applicable ASTM methods are listed beside the device.

Force-measuring system	E4 and E74
Extensometer	E83
Thermocouples <sup>A</sup>	E220
Potentiometers	
Micrometers	

<sup>A</sup> Melting point methods are also recommended for thermocouple calibration.

8.1.1 Axiality of the loading apparatus should be measured as described in 5.1.2.

8.2 Calibrations should be as frequent as is necessary to assure that the errors in all tests do not exceed the permissible variations listed in this test method. The maximum period between calibrations of the testing machine shall be one year. Instruments in either constant or nearly constant use should be calibrated more frequently; those used only occasionally should be calibrated before each use.

## 9. Procedure

9.1 *Measurement of Cross-Sectional Area*—Determine the minimum cross-sectional area of the reduced section as specified in 7.2 of Test Methods E8/E8M. In addition measure the largest diameter (or width) in the reduced section and compare with the minimum value to determine whether the requirements of 7.6 are satisfied.

### 9.2 *Measurement of Original Length:*

9.2.1 Unless otherwise specified, base all values for elongation on a gauge length equal to four diameters in the case of round specimens and four times the width in the case of rectangular specimens, the gauge length being punched or scribed on the reduced section.

NOTE 7—Elongation values of specimens with rectangular cross sections cannot be compared unless all dimensions including the thickness are equal. Therefore, an elongation specification should include the specimen cross-sectional dimensions as well as the gauge length. Using a gauge length equal to 4.5 times the square root of the cross-sectional area compensates somewhat for variations in specimen thickness but even this does not result in the same value of elongation when specimens of the

<sup>5</sup> Schmieder, A. K., "Measuring the Apparatus Contributions to Bending in Tension Specimens," *Elevated Temperature Testing Problem Areas*, ASTM STP 488, American Society for Testing and Materials, 1971, pp. 15–42

<sup>6</sup> Penny, R. K., Ellison, E. G., and Webster, G. A., "Specimen Alignment and Strain Measurement in Axial Creep Tests," *Materials Research and Standards*, American Society for Testing and Materials, MTRSA, Vol 6, No. 2, February 1966, pp. 76–84.

same material are machined to different thicknesses and tested.<sup>7</sup>

9.2.2 When testing metals of limited ductility gauge marks punched or scribed on the reduced section may be undesirable because fracture may occur at the stress concentrations so caused. Then, place gauge marks on the shoulders or measure the over-all length of the specimen. Also measure the adjusted length of the reduced section to the nearest 0.01 in. (0.2 mm) as described in 9.2.3. If a gauge length, other than that specified in 9.2.1 is employed to measure elongation, describe the gauge length in the records (see 11.2.1). In the case of acceptance tests, any deviation from 9.2.1 must be agreed upon before testing.

NOTE 8—The availability of flexible ceramic fiber cords for mounting of high temperature extensometers with high purity ceramic rods with chisel or vee-chisel ends, provides a good measure of ductility without excessive damage to the gauge section caused by other types of extensometers or traditional punch or scribe marks. Damage to the rods from specimen failure may be minimized through the use of spring loaded attachment fixtures. Non contact extensometers may also be used for this purpose.

9.2.3 When the extensometer is to be attached to the specimen shoulders, measure the adjusted length of the reduced section between points on the two fillets where the diameter (or width) is 1.05 times the diameter (or width) of the reduced section. The strain rate and offset yield calculations are based on this dimension (see 9.6.3, 10.1.2, and 10.3).

NOTE 9—In the yield region, stress is approximately proportional to offset strain to a power which usually lies in the range from zero to 0.20. For specimens of circular cross section the above value of adjusted length of the reduced section was found by calculation to give an error in yield stress of less than ½ % within this range of exponents and for fillet radii ranging from 0.5 to 1 times the diameter of the reduced section. The method of calculation was similar to that used by Thomas and Carlson.<sup>8</sup>

9.3 *Cleaning Specimen*—Wash carefully the reduced section and those parts of the specimen which contact the grips in clean alcohol, acetone, or other suitable solvent that will not affect the metal being tested.

#### 9.4 *Temperature Control:*

9.4.1 Form the thermocouple measuring junction in accordance with Guide E633.

9.4.2 In attaching thermocouples to a specimen, the measuring junction shall be kept in intimate contact with the specimen and shielded from radiation. Shielding may be omitted if, for a particular furnace and specified temperature, the difference in indicated temperature from an unshielded measuring junction and a measuring junction inserted in a hole in the specimen has been shown to be less than one half the variation listed in 9.4.4. The measuring junction should be as small as possible and there should be no shorting of the circuit (such as could occur from twisted wires behind the measuring junction but not in intimate contact with the specimen). Ceramic insulators should be used on the thermocouples in the hot zone. If some other electrical insulation material is used in

<sup>7</sup> Stickley, G. W., and Brownhill, D. J., "Elongation and Yield Strength of Aluminum Alloys as Related to Gage Length and Offset," *Proceedings, American Society for Testing and Materials, ASTEA*, Vol 65, 1965, pp 597–616.

<sup>8</sup> Thomas, J. M., and Carlson, J. F., "Errors in Deformation Measurements for Elevated Temperature Tension Tests," *ASTM Bulletin*, ASTM, May 1955, pp. 47–51.

the hot zone, it should be determined that the electrical insulating properties are maintained at higher temperatures.

9.4.3 When the length of the reduced section is less than 2 in. (50 mm), attach at least two thermocouples to the specimen, one near each end of the reduced section. For reduced sections greater-than or equal to 2.0 in. (50 mm) add a third thermocouple near the center of the reduced section.

9.4.4 For the portion of the test from the first application of force through the yield strength determination, the difference between the indicated temperature from any thermocouple and the specified temperature shall not exceed the following limits (see 11.1.5).

Specified temperatures up to and including 1800 °F ±5 °F (±3 °C) (980 °C)

Specified temperatures greater than 1800 °F (980 °C) ±10 °F (±6 °C)

9.4.4.1 The temperature limits of 9.4.4 should be maintained as long as practical after the determination of yield. After yield strength determination, the difference between the indicated temperature and the specified temperature may exceed the limits specified in 9.4.4. The indicated temperature at the maximum deviation and the reason for the deviation shall be reported. More restrictive requirements may be placed on the temperature control during the test if agreed to by the laboratory and the customer.

NOTE 10—Deformation of the test specimen can change the indicated temperature for many reasons that are difficult for the laboratory to control. Internal (adiabatic) heating due to plastic working can raise the temperature of the test specimen. Elongation of the test specimen, for example from necking, can carry the thermocouples outside the hot zone of the furnace. Reduction of the diameter of the test specimen due to plastic deformation can cause thermocouples to lose intimate contact with the test specimen.

9.4.5 The term "indicated temperature" means the temperature that is indicated by the temperature measuring device using good quality pyrometric practice.

NOTE 11—It is recognized that true temperature may vary more than the indicated temperature. The permissible indicated temperature variations in 9.4.4 are not to be construed as minimizing the importance of good pyrometric practice and precise temperature control. All laboratories should keep both indicated and true temperature variations as small as practicable. It is well recognized, in view of the extreme dependency of strength of materials on temperature, that close temperature control is necessary. The limits prescribed represent ranges which are common practice.

9.4.6 Indicated temperature overshoots during heating shall not exceed the above limits, unless agreed upon by the customer and the supplier. The heating characteristics of the furnace and the temperature control system should be studied to determine the power input, temperature set point, proportioning control adjustment, and control-thermocouple placement necessary to limit transient temperature overshoots. It may be desirable to stabilize the furnace at an indicated temperature from 10 to 50 °F (6 to 28 °C) below the specified temperature before making the final adjustments. The magnitude and duration of all temperature overshoots shall be reported. (See 11.1.5.)

9.4.7 The time of holding at indicated temperature prior to the start of the test should be governed by the time necessary to ensure that the specimen has reached equilibrium and that the indicated temperature can be maintained within the limits