



Designation: E9 – 19

# Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature<sup>1</sup>

This standard is issued under the fixed designation E9; 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 the apparatus, specimens, and procedure for axial-force compression testing of metallic materials at room temperature (**Note 1**). For additional requirements pertaining to cemented carbides, see **Annex A1**.

**NOTE 1**—For compression tests at elevated temperatures, see Practice **E209**.

1.2 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.

1.3 *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 health 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:<sup>2</sup>

**B557** Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products

<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](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

- E4** Practices for Force Verification of Testing Machines
- E6** Terminology Relating to Methods of Mechanical Testing
- E83** Practice for Verification and Classification of Extensometer Systems
- E111** Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
- E177** Practice for Use of the Terms Precision and Bias in ASTM Test Methods
- E209** Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates
- E251** Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gages
- E691** Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
- E2658** Practices for Verification of Speed for Material Testing Machines

## 3. Terminology

3.1 *Definitions:* The definitions of terms in Terminology **E6** shall apply to these test methods. These terms include compressive strength, extensometer system, modulus of elasticity, necking, proportional limit, stress-strain curve, stress-strain diagram, tangent modulus, testing machine, upper yield strength, yield strength, and Young's modulus. The terms precision, bias, coefficient of variation, repeatability, reproducibility, and accuracy are used as defined in Practice **E177**.

### 3.2 Definitions of Terms Specific to This Standard:

3.2.1 *alignment device*—a fixture for compression testing in a testing machine that is an integral part of the load train and that aids in achieving and maintaining axial forces.

3.2.2 *anti-buckling fixture, n*—a device that applies lateral support to a thin-sheet specimen to prevent it from buckling, but does not interfere with axial deformation.

3.2.3 *solid cylindrical specimen, n*—a specimen with solid cylindrical cross section that does not require lateral support to

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

prevent buckling, but can require testing with an alignment device or subpress to ensure that compressive forces are axial.

3.2.4 *subpress, n*—a fixture for compression testing in a testing machine that is designed to be easily inserted into and removed from the load train and that aids in achieving and maintaining axial forces.

3.2.5 *thin-sheet specimen, n*—a specimen that requires lateral support from an anti-buckling fixture to prevent buckling during a compression test.

## 4. Summary of Test Methods

4.1 The specimen is subjected to an increasing axial compressive force; both force and strain may be monitored either continuously or in finite increments, and the mechanical properties in compression determined.

## 5. Significance and Use

5.1 *Significance*—The data obtained from a compression test may include the yield strength, the upper yield strength, the Young's modulus, the stress-strain curve, and the compressive strength (see Terminology E6). In the case of a material that does not fail in compression by a shattering fracture, compressive strength is a value that depends on total strain and specimen geometry.

5.2 *Use*—Compressive properties are of interest in the analyses of structures subject to compressive forces or bending moments or both and in the analyses of metal working and fabrication processes that involve large compressive deformation such as forging and rolling. For brittle or nonductile metals that fracture in tension at stresses below the yield strength, compression tests offer the possibility of extending the strain range of the stress-strain data. While the compression test is not complicated by necking as is the tension test for certain metallic materials, buckling and barreling (see Appendix X1) can complicate results and should be minimized.

## 6. Apparatus

6.1 *Testing Machines*—Machines used for compression testing shall conform to the requirements of Practices E4 and shall be calibrated in compression.

6.1.1 The bearing surfaces of the heads of the testing machine shall be parallel at all times with 0.0002 in./in. (m/m) unless an alignment device or subpress of the type described in 6.3 is used.

6.1.2 The dynamic response of the force-measuring system shall be sufficient to accurately measure the rate of force change on the specimen.

NOTE 2—This requirement is of particular importance when testing short specimens of materials with high modulus of elasticity.

6.1.3 Where verification of the testing machine speed is required, unless otherwise specified, Practices E2658 shall be used, and the testing machine shall meet Class E.

### 6.2 Bearing Blocks:

6.2.1 If the axial force is transmitted through the ends of the solid cylindrical or thin-sheet specimen, they shall bear on blocks with surfaces flat and parallel within 0.0002 in./in.

(m/m). Lack of initial parallelism may be overcome by using adjustable bearing blocks (Note 3). The blocks shall be made of, or faced with, hard material. The specimen shall be carefully centered with respect to the testing machine heads, alignment device, or subpress if used (see 6.3, Alignment Device or Subpress).

NOTE 3—The purpose of an adjustable bearing block is to give the specimen as even a distribution of initial force as possible. An adjustable bearing block cannot be relied on to compensate for any tilting of the heads that can occur during the test. Tungsten carbide bearing blocks are suitable for testing steel. Hardened steel bearing blocks (55 HRC or greater) are suitable for testing nonferrous materials such as aluminum and copper.

NOTE 4—Appendix X2 describes some bearing blocks that have been used successfully.

6.2.2 The bearing faces of adjustable bearing blocks that contact the specimen shall be made parallel before the force is applied to the specimen. If a bearing block with a spherical seat is used, the spherical surface of the block shall be defined by a radius having its point of origin in the flat surface that bears on the specimen.

### 6.3 Alignment Device or Subpress:

6.3.1 Alignment devices and subpresses shall apply the force axially, uniformly, and with negligible “slip-stick” friction.

NOTE 5—It is usually necessary to use an alignment device or subpress, unless the testing machine has been designed specifically for axial alignment. Appendix X2 shows some examples of alignment devices and subpresses that have been used successfully.

6.3.2 The bearing blocks of the alignment device or subpress shall have the same requirements for parallelism and flatness as given in 6.2.1

6.4 An anti-buckling fixture may be used to prevent thin-sheet specimens from buckling.

NOTE 6—Appendix X2 describes some anti-buckling fixtures and thin-sheet specimens that have been used successfully.

### 6.5 Strain Measurements:

6.5.1 Extensometer systems shall comply with the requirements for the applicable class described in Practice E83 and shall be verified in compression.

NOTE 7—In using these methods, a Class B-2 extensometer, as described in Practice E83, is sufficiently sensitive for most materials.

6.5.2 Automatic devices that determine offset yield strength without plotting a stress-strain curve may be used if their accuracy has been demonstrated to be satisfactory.

6.5.3 Electrical-resistance strain gages (or other single-use devices) may be used provided the measuring system has been verified and found to be accurate to the degree specified in Practice E83. Electrical resistance strain gages shall have performance characteristics established by the manufacturer in accordance with Test Methods E251.

6.6 *Qualification of Test Apparatus*—The complete compression-test apparatus, which consists of the testing machine and when applicable, the alignment device or subpress, the anti-buckling fixture and the extensometer system, shall be qualified by the procedure in 6.6.1-6.6.2.

6.6.1 Conduct tests to establish the elastic modulus of five replicate thin-sheet specimens of 2024-T3 aluminum alloy sheet or five replicate solid cylindrical specimens of 2024-T4 aluminum alloy bar in accordance with Test Method E111. These qualification specimens shall be machined from sheet or bar in the location specified in Test Methods B557. The thickness of the sheet or diameter of the bar may be machined to the desired thickness or diameter. The extensometer shall be properly seated on the specimen when this test is performed. When the qualification specimens each provide a modulus value of  $10.7 \times 10^6$  psi (73.8 GPa)  $\pm 5\%$ , the apparatus qualifies.

6.6.2 The qualification procedure shall be performed using the thinnest thin-sheet specimen or smallest diameter solid cylindrical specimen to be tested in the apparatus.

### 7. Test Specimens

7.1 *Specimens in Solid Cylindrical Form*—Where feasible, compression test specimens should be in the form of solid circular cylinders. Three forms of solid cylindrical specimens for metallic materials are recognized, and designated as short, medium, and long (Note 8). Suggested dimensions for solid cylindrical specimens for general use are given in Table 1.

NOTE 8—Short specimens typically are used for compression tests of such materials as bearing metals, which in service are used in the form of thin plates to carry load perpendicular to the surface. Medium-length specimens typically are used for determining the general compressive strength properties of metallic materials. Long specimens are best adapted for determining the modulus of elasticity in compression of metallic materials. The specimen dimensions given in Table 1 have been used successfully. Specimens with a *L/D* (length/diameter ratio) of 1.5 or 2.0 are best adapted for determining the compressive strength of high-strength materials.

7.2 *Thin-sheet Specimens*—Test specimens shall be flat and should be the full thickness of the material. The length shall be sufficient to allow the specimen to shorten the amount required to define the yield strength, or upper yield strength, but not long enough to permit buckling in the unsupported portion.

NOTE 9—Where lateral support is necessary, the width and length depend upon the dimensions of the anti-buckling fixture used to support the specimen.

NOTE 10—Appendix X2 describes dimensions of thin-sheet specimen

TABLE 1 Suggested Solid Cylindrical Specimens<sup>A</sup>

NOTE 1—Metric units represent converted specimen dimensions close to, but not the exact conversion from inch-pound units.

Specimens	Diameter		Length		Approx <i>L/D</i> Ratio
	in.	mm	in.	mm	
Short	1.12 ± 0.01	30.0 ± 0.2	1.00 ± 0.05	25 ± 1	0.8
	0.50 ± 0.01	13.0 ± 0.2	1.00 ± 0.05	25 ± 1	2.0
Medium	0.50 ± 0.01	13.0 ± 0.2	1.50 ± 0.05	38 ± 1	3.0
	0.80 ± 0.01	20.0 ± 0.2	2.38 ± 0.12	60 ± 3	3.0
	1.00 ± 0.01	25.0 ± 0.2	3.00 ± 0.12	75 ± 3	3.0
	1.12 ± 0.01	30.0 ± 0.2	3.38 ± 0.12	85 ± 3	3.0
Long	0.80 ± 0.01	20.0 ± 0.2	6.38 ± 0.12	160 ± 3	8.0
	1.25 ± 0.01	32.0 ± 0.2	12.50 min	320 min	10.0

<sup>A</sup> Other length-to-diameter ratios may be used when the test is for compressive yield strength.

dimensions and examples of anti-buckling fixtures that have been used successfully.

7.3 *Preparation of Solid Cylindrical and Thin-Sheet Specimens*—Lateral surfaces in the gauge length shall not vary in diameter, width, or thickness by more than 1 % or 0.002 in. (0.05 mm), whichever is less. If a reduced section is used, this requirement applies only to the surface of the reduced section. The centerlines of all lateral surfaces of the specimens shall be coaxial within 0.01 in. (0.25 mm).

7.3.1 *Surface Roughness*—Machined surfaces of solid cylindrical and thin-sheet specimens shall have a surface roughness of 63 μin. (1.6 μm) Ra or better. Machined lateral surfaces to which lateral support is applied shall have a surface roughness of 40 μin. (1.0 μm) Ra or better

7.3.2 *Flatness and Parallelism*—The ends of solid cylindrical specimens from Table 2 and of thin-sheet specimens where the force is applied through the ends of the specimen shall be flat and parallel within 0.0005 in./in. (mm/mm) and perpendicular to the lateral surfaces to within 3' of arc.

NOTE 11—In most cases meeting this requirement can only be achieved by machining or grinding of the ends of the specimen.

7.3.3 *Edges of thin-sheet Specimens*—A width of material equal to at least the thickness of the thin-sheet specimen shall be machined from all sheared or stamped edges in order to remove material with potentially altered properties. If a reduced section is used, this requirement applies only to the edges of the reduced section. Thin-sheet specimens shall be finished so that the surfaces are free of nicks, grooves, and burrs.

7.4 *Gauge Length Location*—The ends of the gauge length shall not be closer to the ends of the solid cylindrical or thin-sheet specimen or the ends of the reduced section, than one half of the diameter or one half of the width of the specimen.

### 8. Procedure

8.1 *Specimen Measurement*—Measure the width and thickness, or the diameter of the specimen along the gauge section. Specimen dimensions greater than or equal to 0.10 in. (2.5 mm) should be measured to the nearest 0.001 in. (0.02 mm), and those less than 0.10 in. (2.5 mm) should be measured to the nearest 1 % of the dimension being measured. Calculate the average cross-sectional area of the specimen gauge section.

8.2 *Cleaning*—Clean the ends of the specimen and fixture bearing blocks with acetone or another suitable solvent to remove all traces of grease and oil.

8.3 *Lubrication*—Bearing surfaces, including the ends of solid cylindrical specimens and the ends and faces of thin-sheet specimens may be lubricated.

NOTE 12—Bearing surface friction can affect test results (see Fig. X1.2). Friction has been successfully reduced by lubricating the bearing surfaces with TFE-fluorocarbon sheet, molybdenum disulfide, and other materials summarized in (1).<sup>3</sup>

8.4 *Specimen Installation*—Place the specimen in the test fixture and carefully align the specimen to the fixture to ensure

<sup>3</sup> The boldface numbers in parentheses refer to the list of references at the end of this standard.

**TABLE 2 Precision**

Material	YS(0.02% offset)	Repeatability standard deviation	Reproducibility standard deviation	95 % Repeatability limit (within a laboratory)	95 % Reproducibility limit (between laboratories)
	$\bar{X}$ MPa	$S_r$ MPa	$S_R$ MPa	$r$ MPa	$R$ MPa
AA2024-T351	346.2	3.8	6.8	10.7	19.1
		Repeatability coefficient of variation $CV_r = \frac{S_r}{\bar{X}}$	Reproducibility coefficient of variation $CV_R = \frac{S_R}{\bar{X}}$	$r$ %	$R$ %
AA2024-T351		1.1 %	2.0 %	3.1 %	5.5 %

The table was calculated using the relationship limit = 2.8 × standard deviation. The quantity 1.96√2 rounds to 2.77 or 2.8.

coaxial loading. Check that the specimen loading/reaction surfaces mate with the respective surfaces of the fixture. If the fixture has lateral supports, the sides of thin-sheet specimens should contact the supports with the clamping pressure recommended by the anti-buckling fixture manufacturer, or as determined during the fixture-qualification tests. If screws are used to adjust lateral support pressure, a torque wrench should be used to ensure consistent pressure.

**8.4.1 Transducer Attachment**—If required, attach the extensometer or other transducers, or both, to the specimen gauge section. The gauge length of solid cylindrical specimens shall be at least one half diameter away from the ends of the specimen, and should be a full diameter away from the ends of the specimen. The gauge length of the thin-sheet specimen shall be at least one half the width away from the ends of the specimen or ends of the reduced section, and should be at least full width away. See 7.4.

**8.5 Force-Strain Range Selection**—Set the force range of the testing machine so the maximum expected force is at least one third of the range selected. If an autographic recorder is used, select the strain or deflection scale so that the elastic portion of the force-versus-strain or force-versus-deflection, is between 30° and 60° to the force axis.

**8.6 Testing Speed**—For testing machines equipped with strain-rate control, set the machine to strain the specimen at a nominal rate of 0.005 in./in./min (m/m/min). For machine with force control or with crosshead speed control, set the nominal rate so the specimen is tested at a rate equivalent to 0.005 in./in.·min (m/m·min) strain-rate in the elastic portion. A nominal rate of 0.003 in./in./min (m/m/min) may be used if the material is strain-rate sensitive.

**8.6.1** For machines without automatic feedback control systems, maintain a constant crosshead speed to obtain the desired average strain-rate from the start of loading to the end point of the test.

**NOTE 13**—The average strain rate can be determined from a time-interval-marked force-strain record, a time-strain graph, or from the time of the start of loading to the end point of test as determined from a time-measuring device, for example a stopwatch. Constant rate of crosshead movement does not ensure constant strain rate throughout a test. The free-running crosshead speed can differ from the speed under load for the same machine setting. Specimens of different stiffnesses can also result in different rates, depending upon the testing machine and fixturing.

**8.6.2** Whatever the method, the specimen should be tested at a uniform rate without reversals or sudden changes.

**8.7 Test Conduct**—After the specimen has been installed and aligned, and the strain- or deflection-measuring transducer installed, activate the recording device(s) and initiate the test at the prescribed rate. Continue the test at a uniform rate until the test has been completed as stated below.

**8.7.1 Ductile Materials**—For ductile materials, if allowed by the material specification, the test may be halted after the strain is large enough to determine the yield strength or upper yield strength, or the strength at a strain greater than the yield strain. For materials that exhibit a sharp-kneed stress-strain curve or a distinctive yield point, the test may be terminated either after a sharp knee or after the drop in force is observed.

**NOTE 14**—For materials without sharp-kneed stress-strain diagrams, it is useful to estimate the strain or deflection at yield and test the specimen sufficiently beyond this estimate to ensure that the yield strength can be determined after the test (see 9.3).

**8.7.2 Brittle Materials**—Brittle materials that fail by crushing or shattering may be tested to failure.

**8.8 Number of Specimens**—Specimen blanks shall be taken from bulk materials according to applicable specifications. The number of specimens to be tested should be sufficient to meet the requirements as determined by the test purpose, or as agreed upon between the parties involved.

**NOTE 15**—The larger the sample, the greater the confidence that the sample represents the total population. In most cases, between five and ten specimens are sufficient to determine the compressive properties of a sample with reasonable confidence.

### 8.9 Precautions:

**8.9.1 Buckling**—Long, slender specimens that are not laterally supported can buckle elastically and fly from the test setup. A protective device should be in place to prevent injury.

**8.9.2 Shattering Fracture**—Some materials fail by shattering, which will cause pieces to be expelled from the test setup. A protective device should be in place to prevent injury.

## 9. Calculations

**9.1** Determine the properties of the material from the dimensions of the specimen and the stress-strain diagram as described in the following paragraphs. For testing machines

that record force units instead of stress, convert the force-versus-strain diagram to units of stress by dividing the force by the original cross-sectional area of the specimen gauge section.

9.2 *Modulus of Elasticity*—Calculate the modulus of elasticity.

9.2.1 If the modulus of elasticity is the prime quantity to be determined, follow the procedure and additional requirements of Test Method E111.

NOTE 16—Meeting the extensometer class and configuration requirements of E111 can be challenging for short specimens and be outside the scope of normal testing.

9.3 *Yield Strength*—On the stress-strain diagram (Fig. 1) lay off  $O_m$  equal to the specified value of the offset, draw  $mn$  parallel to  $OA$ , and thus locate  $r$ , the intersection of  $mn$  with the stress-strain curve. The stress corresponding to the point  $r$  is the yield strength for the specified offset.

9.3.1 In reporting values of yield strength obtained by these methods, the specified value of offset used should be stated in parentheses after the term yield strength. Thus:

$$\text{Yield strength (offset = 0.2\%)} = 52.0 \text{ ksi (359 MPa)} \quad (1)$$

9.3.2 If the force drops before the specified offset is reached, technically the material does not have a yield strength (for that offset). In this case, the stress at the maximum force before the specified offset is reached may be reported instead of the yield strength and shall be designated as the upper yield strength.

9.4 *Upper Yield Strength*—For testing machines without strain- or deflection-recording capabilities, the upper yield strength may be determined by noting the force at which the force suddenly drops with the testing machine running at a steady rate.

NOTE 17—Materials that exhibit a sharp-kneed stress-strain diagram often exhibit a distinct drop in stress with increasing strain. The upper

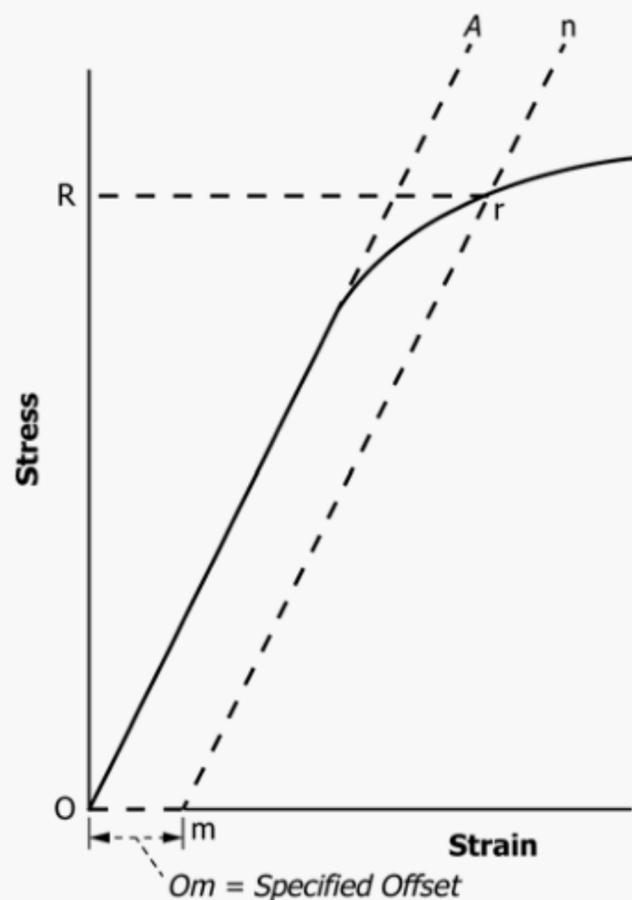


FIG. 1 Stress-Strain Diagram for Determination of Yield Strength by the Offset Method

yield strength is the maximum stress attained just prior to the sudden drop in stress.

9.5 *Compressive Strength*—For a material that fails in compression by crushing or fracturing, the compressive strength is the maximum stress at or before fracture, as determined by dividing the maximum force by the initial cross-sectional area. For ductile materials, compressive strength may be determined from the stress-strain diagram at a specified total strain. The strain at which this stress was determined shall be specified.

## 10. Report

10.1 Include the following information in the test report:

10.1.1 *Specimen Material*—Describe the specimen material, alloy, heat treatment, mill batch number, grain direction, etc., as applicable.

10.1.2 *Specimen Configuration*—Include a sketch of the specimen configuration or reference to the specimen drawing.

10.1.3 *Specimen Dimensions*—State the actual measured dimensions for each specimen.

10.1.4 *Test Fixture and Lubricant*—If used, describe the alignment device or subpress, anti-buckling fixture, test fixture, or refer to drawings of these. Specify the lubricant used, if any.

10.1.5 *Testing Machine*—Include the make, model, and force range of testing machine.

10.1.6 *Speed of Testing*—Record the test rate and mode of control.

10.1.7 *Stress-Strain Diagram*—Include, if possible, the stress-strain diagram with scales, specimen number, test data, rate, and other pertinent information.

10.1.8 *Modulus of Elasticity*—Report the modulus of elasticity when required, as determined according to 9.2.

10.1.9 *Yield Strength*—Report the yield strength or upper yield strength when required and the method of determination, as calculated in 9.3 and 9.4.

10.1.10 *Compressive Strength*—Report the compressive strength for material exhibiting brittle failure. A compressive strength at a specified total strain may be reported for ductile materials. If so, report the strain at which the compressive strength was determined.

10.1.11 *Type of Failure*—When applicable, describe the type of specimen failure.

10.1.12 *Anomalies*—State any anomalies that occurred during the test that possibly affected the test results.

10.2 For commercial acceptance testing the report may be limited to four parts: 10.1.1, 10.1.2, 10.1.9, and 10.1.11.

## 11. Precision and Bias

11.1 *Interlaboratory Test Program*—Ten laboratories participated in an interlaboratory study (ILS) in 2009. Each laboratory conducted compression strength tests using AA2024-T351 solid cylindrical specimens with nominal diameter  $d = 12.6$  mm and nominal length,  $l = 47.6$  mm. This specimen is similar to, but longer than the suggested medium cylindrical specimen in Table 1. Each laboratory used an extensometer to measure the specimen strain. The nominal strain rate was  $\dot{\epsilon} = 0.005$  in./in./min (0.005 mm/mm/min). The design and analysis of the ILS followed Practice E691 and are

documented in ASTM Research Report No. E28-1042<sup>4</sup> and (2).

11.2 *Test Result*—Each laboratory reported the 0.2% offset yield strength,  $YS(0.2\% \text{ offset})$  determined for the stress-strain curve for  $n=7$  tests. The precision information in 11.3 is based on those results.

11.3 *Precision*—Table 2 summarizes the precision of the test method based on the ILS. Results are given for the 95 % repeatability limit (within a laboratory),  $r$ , and the 95 % reproducibility limit (between laboratories),  $R$ . In addition the values of  $r$  and  $R$  are expressed as their respective coefficients

<sup>4</sup> Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report: RR:E28-1042. Contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org).

of variation. These terms (95 % repeatability limit,  $r$ , and 95 % reproducibility limit,  $R$ ) are used in as specified in Practice E177. Their respective standard deviations,  $s_r$  and  $s_R$ , which are also shown in Table 2 can be obtained by dividing by 2.8.

11.4 *Bias*—Since there is no accepted reference material, method, or laboratory suitable for determining the bias for the procedure in this test method for measuring compressive strength of metallic materials at room temperature, no statement of bias is being made.

## 12. Keywords

12.1 anti-buckling fixture; axial compression; barreling; bearing blocks; buckling; stress-strain diagram; subpress; testing machine

## ANNEX

### (Mandatory Information)

#### A1. SPECIAL REQUIREMENTS IN THE DETERMINATION OF THE COMPRESSIVE STRENGTH OF CEMENTED CARBIDES

##### A1.1 Characteristics of Cemented Carbides

A1.1.1 Cemented carbides are manufactured in a range of compositions having hardness from 81.0 HRA to 93.0 HRA and compressive strengths 300 ksi to over 800 ksi (2100 MPa to 5500 MPa). They fail by shattering fracture (see 6.1.2 and 8.9.2).

##### A1.2 Apparatus and Fixtures

A1.2.1 *Bearing Blocks*—Cemented carbide bearing blocks shall be used. They shall be of a hardness such that the block faces will not suffer significant permanent deformation during test (suggested hardness of 92 HRA).

A1.2.2 *Bearing Block Preparation*—The block diameter shall be at least three times the diameter of the specimen. Its thickness shall be at least two thirds the block diameter. Faces of the bearing blocks shall be flat within  $\pm 0.0002 \text{ in./in. (m/m)}$ , parallel within  $0.0005 \text{ in./in. (m/m)}$ , and have a surface finish of  $8 \mu\text{in. (0.2 } \mu\text{m)}$  arithmetic average (aa). The blocks shall be used in conjunction with devices such as those shown in Appendix X2.

A1.2.3 The total accumulated lack of parallelism in the test assembly shall not exceed  $0.0005 \text{ in./in. (m/m)}$ .

A1.2.4 In order to minimize detrimental end effects, a shim of  $0.001 \text{ in. (0.025 mm)}$  in thickness, of standard cold-rolled steel shim stock, shall be interposed between each specimen end and the bearing block. Each shim shall be used only once (see 3).

##### A1.3 Test Specimens

A1.3.1 *Size and Shape*—The solid cylindrical specimens shall be in the form of circular cylinders  $0.375 \pm 0.01 \text{ in. (10.0 } \pm 0.2 \text{ mm)}$  in diameter and  $1.00 \pm 0.05 \text{ in. (25.0 } \pm 1.0 \text{ mm)}$  long.

A1.3.2 *Preparation of Solid Cylindrical Specimens*—The ends of a specimen shall be plane and normal to the specimen longitudinal axis. They shall be parallel within a maximum of  $\pm 0.0005 \text{ in./in. (m/m)}$ , flat within  $\pm 0.0002 \text{ in./in. (m/m)}$ , and have a surface roughness of  $8 \mu\text{in. (0.2 } \mu\text{m)}$  Ra.

##### A1.4 Speed of Testing

A1.4.1 Speed of testing shall be specified in terms of rate of stressing the specimen, and shall not exceed  $50.0 \text{ ksi/min (345 MPa/min)}$ .

APPENDIXES

(Nonmandatory Information)

X1. BUCKLING AND BARRELING

X1.1 Buckling

X1.1.1 In addition to compressive failure by crushing or shattering of the material, compressive failure can occur by (1) elastic instability over the length of a column specimen due to nonaxiality of loading, (2) inelastic instability over the length of a column specimen, (3) a local instability, either elastic or inelastic, over a small portion of the gauge length, or (4) a twisting or torsional failure in which cross sections rotate over each other about the longitudinal specimen axis. These types of failures are all termed *buckling*.

X1.1.2 The critical buckling stress is the axial uniform stress that causes a column to be on the verge of buckling. The critical force is calculated by multiplying the critical buckling stress by the cross-section area. If the buckling stress is less than or equal to the proportional limit of the material its value may be calculated using the Euler equation:

$$S_{cr} = \frac{C\pi^2 E}{\left(\frac{L}{\rho}\right)^2} = \frac{C\pi^2 E}{AL^2} \quad (X1.1)$$

where:

- $S_{cr}$  = critical buckling stress,
- $E$  = Young's modulus,
- $L$  = column length,
- $C$  = end-fixity coefficient,
- $I$  = moment of inertia of the cross section about centroidal axis (for specimens without lateral support, the smaller value of  $I$  about the two centroidal axes is the critical value).
- $\rho$  = radius of gyration,  $\rho = \left(\frac{I}{A}\right)^{1/2}$
- $A$  = cross-sectional area.

X1.1.3 If the buckling stress is greater than the proportional limit of the material its value may be calculated from the modified Euler equation:

$$S_{cr} = \frac{C\pi^2 E_t}{\left(\frac{L}{\rho}\right)^2} = \frac{C\pi^2 E_t}{AL^2} \quad (X1.2)$$

where:

- $E_t$  = Tangent modulus at the buckling stress.

Methods of calculating the critical stress using Eq X1.2 are given in (4).

The moments of inertia,  $I$ , about the centroidal axis for a circle and a thin rectangle are:

$$I = \frac{1}{64}\pi D^4 \text{ circle} \quad (X1.3)$$

$$I = \frac{1}{12}\pi bh^3 \text{ rectangle} \quad (X1.4)$$

where:

- $D$  = Solid cylindrical specimen diameter,
- $b$  = Thin-sheet specimen width, and
- $h$  = Thin-sheet specimen thickness

Three ideal specimen end-fixity conditions exist for which theory defines the value of the constant  $C$  (see Fig. X1.1). These  $C$  values are:

Freely rotating ends (pinned or hinged)	$C = 1$	Fig. X1.1 (a)
One end fixed, the other free to rotate	$C = 2$	Fig. X1.1 (b)
Both ends fixed	$C = 4$	Fig. X1.1 (c)

For flat-end specimens tested between flat rigid anvils, (4) shows that a value of  $C = 3.75$  is appropriate.

X1.2 Barreling

X1.2.1 Short specimens often deform non-uniformly and assume a barrel shape. Barreling is the restricted deformation of the end regions of a test specimen under compressive force due to friction at the specimen end sections. The resulting nonuniform transverse deformation as shown schematically and in the photograph in Fig. X1.2. (5) provides additional theoretical and experimental information on barreling as illustrated in Fig. X1.2

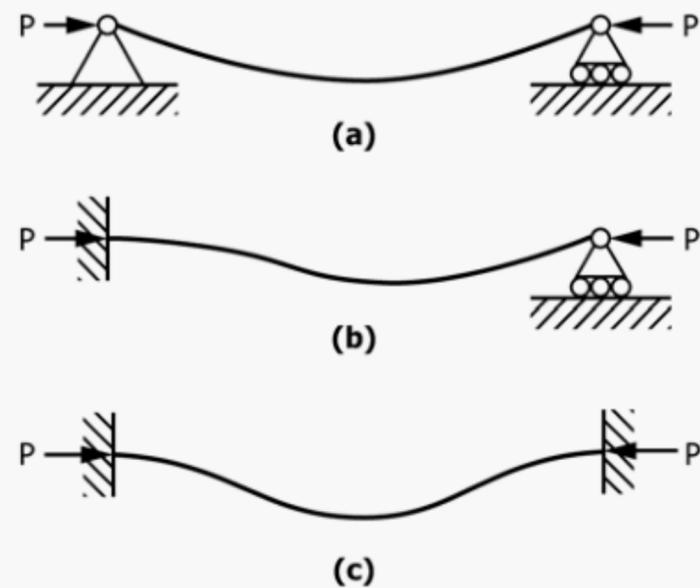
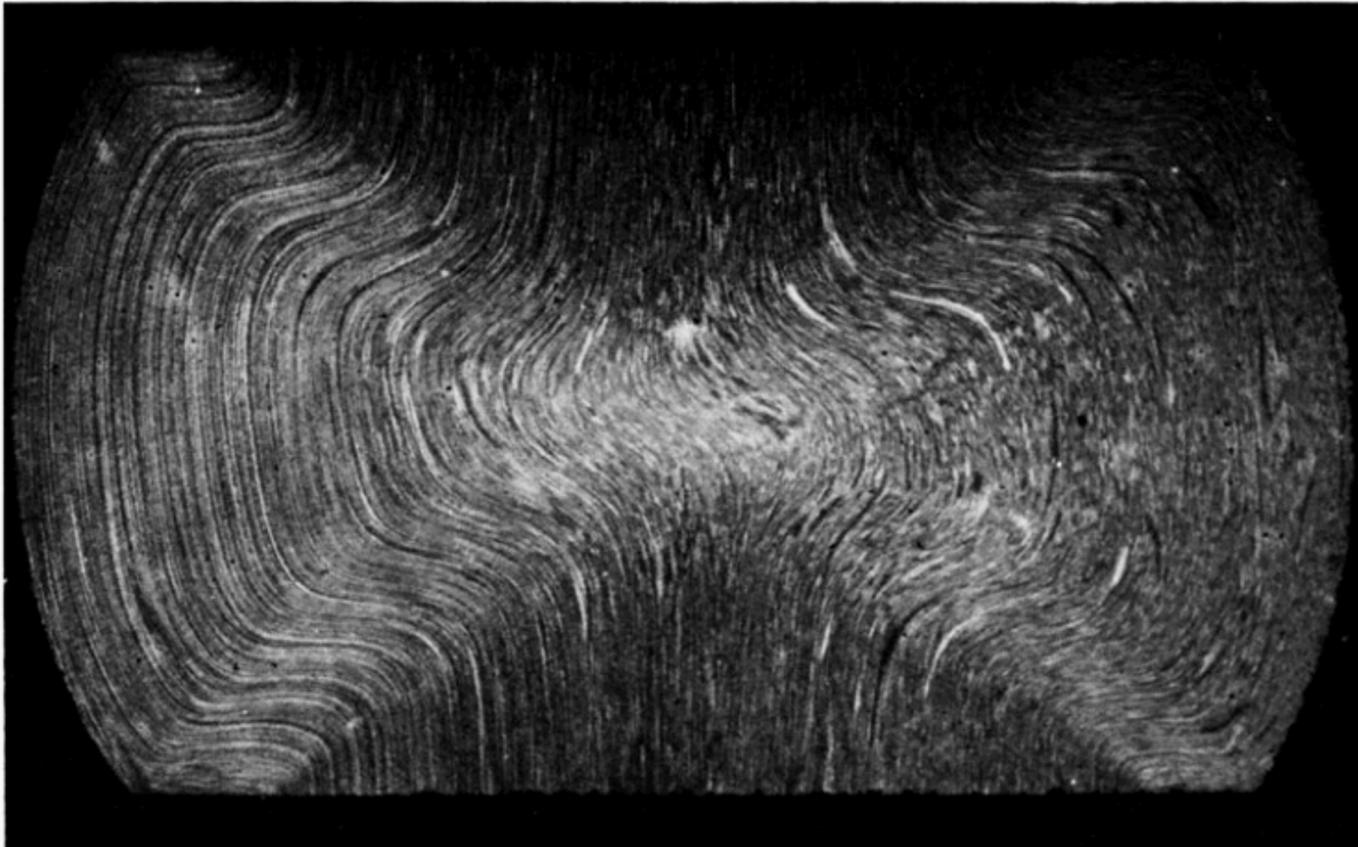
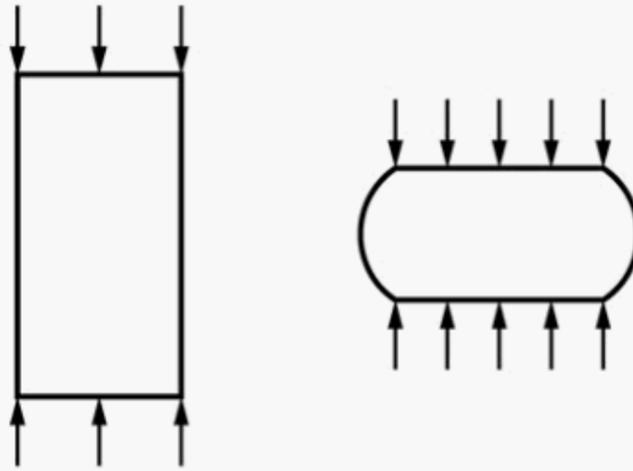


FIG. X1.1 Diagrams Showing Fixity Conditions and Resulting Buckling of Deformation



NOTE 1—A cylindrical specimen of AISI 4340 steel (HRC = 40) was compressed 57 % (see upper diagram). The photo macrograph was made of a polished and etched cross section of the tested specimen. The highly distorted flow lines are the result of friction between the specimen ends and the loading fixture. Note the triangular regions of restricted deformation at the ends and the cross-shaped zone of severe shear.

FIG. X1.2 Illustration of Barreling

## X2. BEARING BLOCKS, ALIGNMENT DEVICES AND SUBPRESSES, AND ANTI-BUCKLING FIXTURES

### X2.1 Bearing Blocks

X2.1.1 One type of adjustable bearing block that has proven satisfactory is illustrated in Fig. X2.1. Another arrangement involving the use of a spherical-seated bearing block that has been found satisfactory for testing material other than in sheet form is shown in Fig. X2.2. The spherical-seated bearing block should be at the upper end of the test specimen (for specimens tested with the force axis vertical).

### X2.2 Alignment Devices or Subpresses

X2.2.1 The design of the alignment device or subpress depends on the size and strength of the specimen. Suitable designs prevent the ram or other moving parts from jamming or tilting the device or the frame of the machine as a result of loading. A suitable alignment device is shown in Fig. X2.3 and described in (1). Other alignment devices of the subpress type

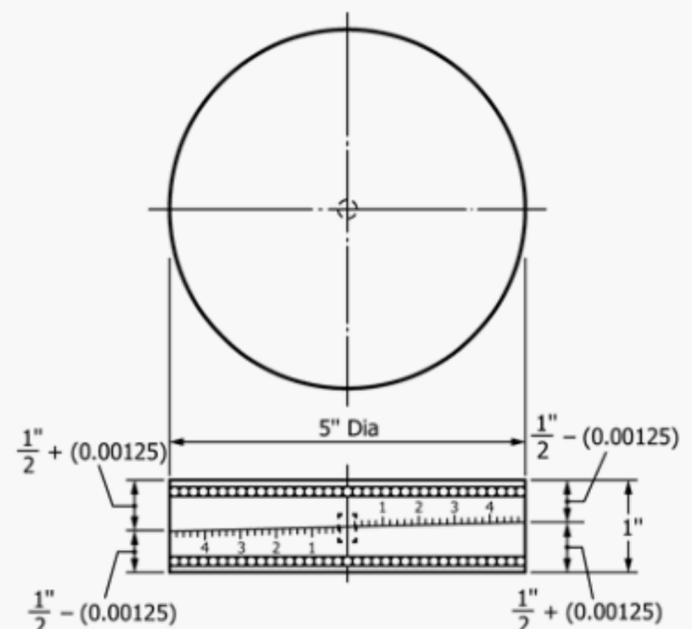


FIG. X2.1 Adjustable Bearing Block for Compression Testing

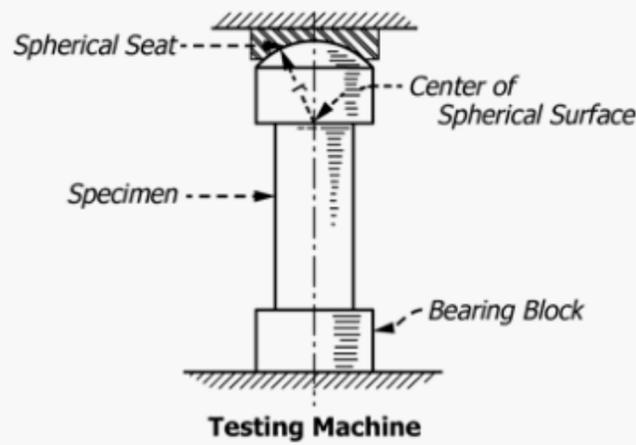


FIG. X2.2 Spherical-Seated Bearing Block

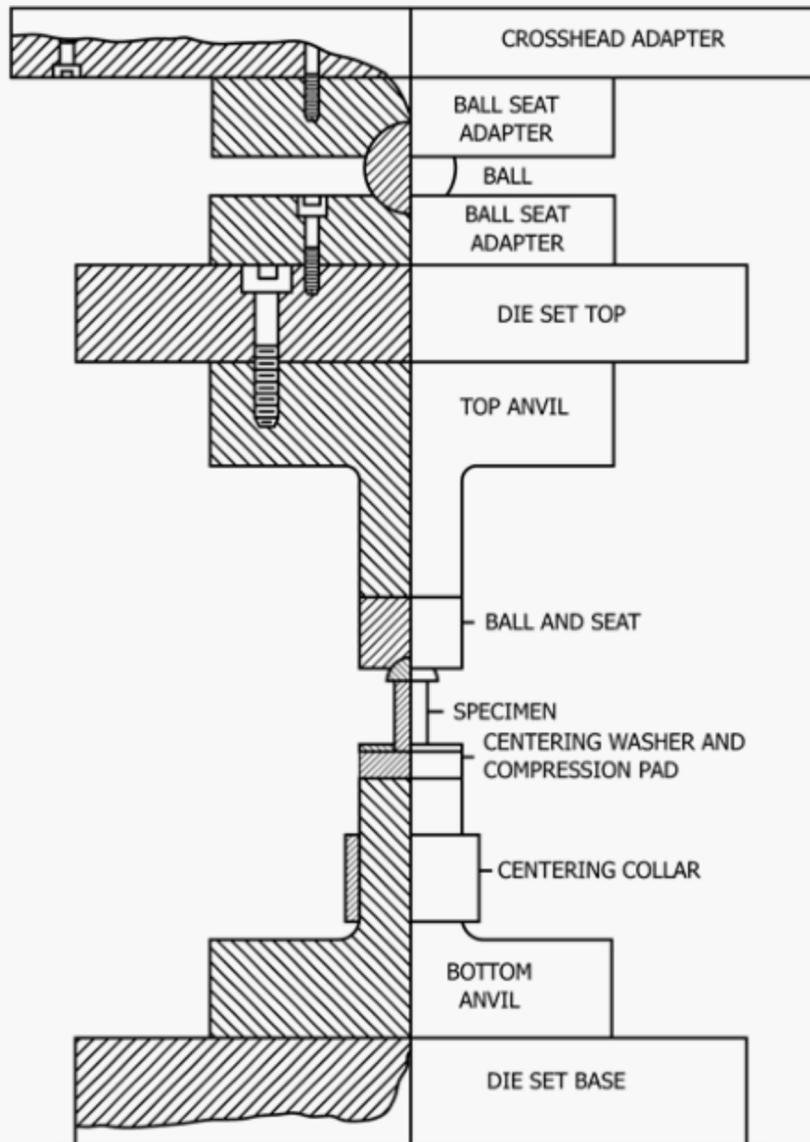


FIG. X2.3 Example of Compression Testing Apparatus

have also been used successfully. Reference (6) shows an example of a subpress that has been used.

**X2.3 Anti-buckling fixtures for thin-sheet specimens**

X2.3.1 In testing thin specimens, such as sheet material, an unsupported specimen can buckle during loading. One method to prevent buckling uses an anti-buckling fixture containing side-support plates that bear against the wide sides of the thin-sheet specimen. A suitable anti-buckling fixture produces a combination of lateral-support pressure and spring constant to prevent buckling, but does not interfere with axial deformation of the thin-sheet specimen. Although suitable combinations depend on specimen material and thickness, testing temperatures, and accuracy of alignment, acceptable results have been obtained with rather wide ranges of lateral-support pressure and spring constant. Generally, the higher the spring constant of the anti-buckling fixture, the lower the lateral-support pressure that is required. These variables can be established during the qualification of the equipment (see 6.6).

X2.3.2 It is not the intent of these methods to designate specific anti-buckling fixtures for testing sheet materials, but merely to provide a few illustrations and references to anti-buckling fixtures that have been used successfully, some of which are cited in Table X2.1. Many other anti-buckling fixtures can produce acceptable results, prevent buckling, and pass the qualification test in 6.6. Lubrication on the supported sides of the thin-sheet specimen can prevent extraneous friction forces from occurring at the support points.

TABLE X2.1 Representative Anti-Buckling Fixtures and Specimen Dimensions for Testing of Thin Sheet<sup>A</sup>

Type of Anti-Buckling Fixture	Ref	Thickness		Width		Length		Gage Length	
		in.	mm	in.	mm	in.	mm	in.	mm
Montgomery-Templin:	(7 and 8)								
General use		0.016 and over	0.40 and over	0.625	16.0	2.64	67.0	1	25
Magnesium alloys		0.016 and over	0.40 and over	0.750 <sup>B</sup>	20.0	2.64	67.0	1	25
NACA (Kotanchik et al)	(9)	0.020 and over	0.50 and over	0.53	13.6	2.53	64.5	1	25
Moore-McDonald	(10)	0.032 and over	0.80 and over	0.75 <sup>C</sup>	20.0	2.64	67.0	1	25
LaTour-Wolford	(11)	0.010 to 0.020	0.25 to 0.50	0.50	12.5	1.95	49.5	1	25
		0.020 and over	0.50 and over	0.50	12.5	2.00	51.0	1	25
		0.020 and over	0.50 and over	0.50	12.5	2.25	57.0	1	25
Miller	(12-14)	0.006 to 0.010	0.15 to 0.25	0.48	12.2	2.22	56.5	1	25
		0.010 to 0.020	0.25 to 0.50	0.50	12.5	2.23	56.5	1	25
		0.020 and over	0.50 and over	0.50	12.5	2.25	57.0	1	25
Sandorff-Dillon:	(15)								
General use		0.010 and over	0.25 and over	0.50	12.5	4.12	104.5	2	50
High-strength steel		0.010 and over	0.25 and over	0.50	12.5	3.10	78.5	2	50

<sup>A</sup> See Ref. (16) for additional anti-buckling fixtures and thin-sheet specimen dimensions.

<sup>B</sup> Reduced to 0.625 in. (16.0 mm) for 1.25 in. (30 mm) at the mid-length.

<sup>C</sup> Reduced to 0.650 in. (16.5 mm) for 1.25 in. (30 mm) at the mid-length.

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## SUMMARY OF CHANGES

Committee E28 has identified the location of selected changes to this standard since the last issue (E9–09(2018)) that may impact the use of this standard.

- (1) Definitions were created for the terms alignment device, anti-buckling fixture, solid cylindrical specimen, subpress, and thin-sheet specimen.
- (2) Non-normative material about buckling and barreling was moved to [Appendix X1](#).
- (3) Non-normative material about bearing blocks, alignment devices and subpresses, and anti-buckling fixtures that have been used in E9 tests was moved to [Appendix X2](#).
- (4) Non-normative material was moved to create or augment [Note 2](#), [Note 3](#), [Note 4](#), [Note 5](#), [Note 9](#), [Note 10](#), [Note 11](#), [Note 12](#), [Note 13](#), [Note 14](#), [Note 15](#), and [Note 16](#).

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