Designation: ~~E646 – 07ε1~~ E646 – 15

Standard Test Method for Tensile Strain-Hardening Exponents (*n* -Values) of Metallic Sheet Materials[1]

This standard is issued under the fixed designation E646; 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.

~~ε1 NOTE—The equation in 10.3 was editorially corrected in January 2014.~~

INTRODUCTION

This test method for determining tensile strain-hardening exponents *n* utilizes stress-stain data obtained in a uniaxial tension test. Tensile data are obtained in a continuous and rate-controlled manner via displacement or strain control. The strain-hardening exponents are determined from an empirical representation over the range of interest of the true-stress versus true-strain curve. The mathematical representation used in this method is a power curve (Note 1) of the form (**1**)[2]:

$$\sigma = K\varepsilon^n$$

where:

σ = true stress,

~~ε = true plastic strain,~~

ε = plastic component of true strain, but in special cases may be the total true strain. (See 10.2),

~~K = strength coefficient, and~~

K = is a constant, often called the strength coefficient having the units of stress, and

n = strain-hardening exponent

1. Scope

1.1 This test method covers the determination of a strain-hardening exponent by tension testing of metallic sheet materials for which plastic-flow behavior obeys the power curve given in the Introduction.

NOTE 1—A single power curve may not ~~fit~~ be a satisfactory fit to the entire stress-strain curve between yield and necking. If such is the case, more than one value of the strain-hardening exponent ~~can~~may be obtained (**2**~~).~~) by agreement using this test method.

1.2 This test method is specifically for metallic sheet materials with thicknesses of at least 0.005 in. (0.13 mm) but not greater than 0.25 in. (6.4 mm). The method has successfully been and may be applied to other forms and thicknesses by agreement

1.3 The values stated in inch-pound units are to be regarded as ~~the standard. The SI equivalents shown may be approximate.~~standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

NOTE 2—The value of the strain-hardening exponent, *n*, is has no units and is independent of the units used in its determination

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

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E4 Practices for Force Verification of Testing Machines

E6 Terminology Relating to Methods of Mechanical Testing

[1] This test method is under the jurisdiction of ASTM Committee E28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.02 on Ductility and Formability.

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[2] The boldface numbers in parentheses refer to the list of references appended to this method.

[3] 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.

~~E8~~E8/E8M Test Methods for Tension Testing of Metallic Materials
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
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
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

2.2 *ISO Standard*
ISO 10275:2007 Metallic materials -- Sheet and strip -- Determination of tensile strain hardening exponent

3. Terminology

3.1 For definitions of other terms used in this test method, refer to E6 (Standard Terminology Relating to Methods of Mechanical Testing).

3.2 *Definitions:*

~~3.1.1 The definitions of terms given in Terminology E6 shall apply, with the addition of the following special terms used in this method.~~

3.2.1 *elastic true strain, ε_e, n*—elastic component of the true strain.

3.2.2 *engineering ~~strain (e)~~—strain, e, n*—a dimensionless value that is the change in length ~~(Δ(L~~ΔL) per unit length of original linear dimension (L_0) along the loading axis of the specimen; that is, e = ~~e = (ΔL)~~$\Delta L/L$~~/L~~$_0$.

3.2.3 *engineering ~~stress (S)~~stress, S ~~[~~[FL~~FL~~$^{-2}$], ~~]~~n*—the normal stress, expressed in units of applied force, ~~F,~~F per unit of original cross-sectional area, A_0; that is, ~~S = F~~S = ~~A~~F/A_0.

3.2.4 *~~necking~~—necking, n*—the onset of nonuniform or localized plastic deformation, resulting in a localized reduction of cross-sectional area.

3.2.5 *plastic true strain, ε_p, n*—the inelastic component of true strain.

3.2.6 *~~strain-hardening (n)~~—strain hardening, n*—an increase in hardness and strength caused by plastic deformation.

~~3.1.6 *strength coefficient (K)* [FL^{-2}]—an experimental constant, computed from the fit of the data to the assumed power curve, that is numerically equal to the extrapolated value of true stress at a true strain of 1.00.~~

3.2.7 *true ~~strain (ε)~~—strain, ε, n*—the natural logarithm of the ratio of instantaneous ~~gage~~gauge length, *L*, to the original ~~gage~~gauge length, L_0; that is, ~~ε = ln~~ ε = ln (~~L~~ L/L_0) or ~~ε = ln~~ ε = ln (1+*e*).

3.2.8 *true ~~stress (σ)~~stress, σ ~~[~~[FL~~FL~~$^{-2}$], ~~]~~n*—the instantaneous normal stress, calculated on the basis of the instantaneous cross-sectional area, *A*; that is, ~~σ =~~ σ = *F/A*; if no necking has ~~occurred, σ =~~ occurred , σ = S(~~S(1+e).~~1+*e*).

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *strain-hardening exponent (n), n*—an experimental constant, computed from the least squares best fit, linear slope of log σ versus log ε or data over a specific strain range where ε is the plastic component of true strain, but in special cases may be the total true strain (see 10.2).

3.3.2 *strength coefficient (K) [FL^{-2}], n*—an experimental constant, computed from the fit of the data to the assumed power curve, that is numerically equal to the extrapolated value of true stress at a true strain of 1.00.

4. Summary of Test Method

4.1 This test method applies to materials exhibiting a continuous stress-strain curve in the plastic region. The displacement or strain is applied in a continuous and rate-controlled manner while the normal tensile load and strain are monitored. The instantaneous cross-sectional area may be monitored or calculated by assuming constancy of volume in the plastic region. Equations are presented that permit the calculation of the true stress, σ, true strain, ε, strain-hardening exponent, *n*, and strength coefficient, *K*, for that continuous portion of the true-stress versus true-strain curve which follows the empirical relationships described.

NOTE 3—~~The~~This test method is recommended for use only in the plastic range for metallic sheet material for which the true-stress true-strain data follow the stated relationship.

5. Significance and Use

5.1 This test method is useful for estimating the strain at the onset of necking in a uniaxial tension test (**1**). Practically, it provides an empirical parameter for appraising the relative stretch formability of similar metallic systems. The strain-hardening exponent is also a measure of the increase in strength of a material due to plastic deformation.

5.2 The strain-hardening exponent may be determined over the entire plastic stress-strain curve or any portion(s) of the stress-strain curve specified in a product specification.

NOTE 4—The engineering strain interval 10–20% is commonly ~~utilized~~used for determining the ~~n-value~~ strain-hardening exponent, *n,* of formable ~~low carbon~~ low-carbon steel ~~products.~~products

5.3 This test method is not intended to apply to any portion of the ~~true-stress versus true-strain~~ true -stress versus true -strain curve that exhibits discontinuous behavior; however, the method may be applied by curve-smoothing techniques as agreed upon.

NOTE 5—For example, those portions of the stress-strain curves for mild ~~steel~~ steel, aluminum, or ~~aluminum~~other alloys ~~which exhibit yield-point elongation or Lüders bands~~ that exhibit yield point and Lüders band elongation, twinning, or Portevin–Le Chatelier effect (PLC) may be characterized as behaving discontinuously.

NOTE 6—Caution should be observed in the use of curve-smoothing techniques as they may affect the *n*-value.

5.4 This test method is suitable for determining the tensile stress-strain response of metallic sheet materials in the plastic region prior to the onset of necking.

5.5 The *n*-value may vary with the displacement rate or strain rate used, depending on the metal and test temperature.

6. Apparatus

6.1 *Testing Machines*—Machines used for tension testing shall conform to the requirements of Practices E4. The loads used to determine stress shall be within the loading range of the testing machine as defined in Practices E4.

6.2 *Strain-Measurement Equipment*—Equipment for measurement of extension shall conform to the requirements of Class C or better as defined in Practice E83.

7. Sampling

7.1 Samples shall be taken from the material as specified in the applicable product specification.

8. Test Specimens

8.1 *Selection and Preparation of Specimens:*

8.1.1 In the selection of specimen blanks, special care shall be taken to assure obtaining representative material that is flat and uniform in thickness.

8.1.2 In the preparation of specimens, special care shall be taken to prevent the introduction of residual stresses.

8.2 *Dimensions*—~~One of the~~Recommended metallic sheet specimen configurations are shown in Fig. 1 ~~shall be~~ . Specimen configurations shall have sides parallel to 0.001 in. and dimensions shall be reported as stated in 11.1.6. Intentionally tapered specimens shall not be used.

NOTE 7—While this test method is specifically for metallic sheet materials, it has been successfully applied to many tensile specimens having a uniform cross-sectional area, that is, round bars and flats where parallel sides have been maintained.

9. Procedure

9.1 Measure and record the original thickness T, of the reduced section of the specimen to at least the nearest 0.0005 in. (0.013 mm) and the ~~width~~ width, W, of the reduced section to at least the nearest 0.001 in. (0.025 mm).

~~NOTE 6—The rounding-off method given in Practice E29 shall be used for all measurements.~~

9.1.1 The rounding-off method given in Practice E29 shall be used for all measurements.

9.2 Grip the specimen in the testing machine in a manner to ensure axial alignment of the specimen as noted in Test Methods ~~E8~~E8/E8M and attach the extensometer.

~~NOTE 7—The order of this step may be reversed if required by the design of the extensometer or the specimen grips, or both.~~

9.2.1 The order of this step may be reversed if required by the design of the extensometer or the specimen grips, or both.

9.3 *Speed of Testing:*

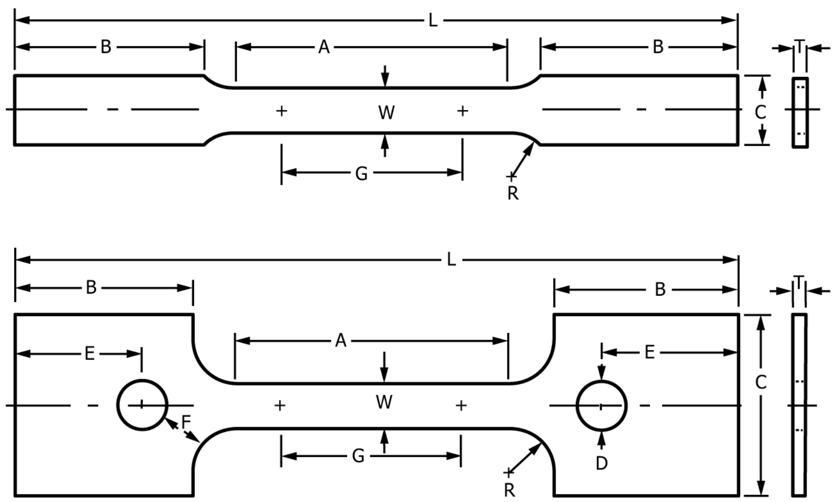
9.3.1 The speed of testing shall be such that the loads and strains are accurately indicated.

9.3.2 ~~The~~ In the absence of any specified limitations on the speed of testing (by, for example, the appropriate product specification), the test speed, defined in terms of rate of separation of heads during tests, free running crosshead speed, or rate of straining shall be between 0.05 in./in. (m/m) and 0.50 in./in. (m/m) of the length of the reduced section per minute ~~(see Test Methods~~(in accord with Test Method ~~E8~~E8/E8M~~).~~ , Standard Test Methods for Tension Testing Metallic Materials, 7.6.4 Speed of Testing When Determining Tensile Strength) The speed setting shall not be changed during the strain interval over which the strain hardening exponent, *n*, is to be ~~determined.~~determined

NOTE 8—The mode of control and the rate used may affect the values obtained.

9.3.3 If the yield point, yield-point elongation, yield strength, or any combination of these is to be determined also, the rate of stress or strain application or crosshead separation during this portion of the test shall be within the range permitted by Test Methods ~~E8~~E8/E8M or any other ~~specific~~specified value. After exceeding the strain necessary for this information, adjust the crosshead speed to within the range specified ~~prior to the next step.~~by this standard.

9.4 Record the ~~load~~force and corresponding strain for at least five approximately equally spaced levels of strain (Note ~~10~~9) ~~encompassing~~covering the strain range of interest ~~specified~~ or required in the product specification. Usually, the greatest of these



Dimensions

		in.	mm
Required Dimensions for Reduced Section of Specimen			
		Dimensions	
		in.	mm
G	Gage length	2.000 ± 0.005	50.0 ± 0.10
W	Width (Note 1)	0.500 ± 0.010	12.5 ± 0.25
T	Thickness (Note 2)	thickness of material	
R	Radius of fillet, min	½	13
L	Overall length, min	8	200
A	Length of reduced section, min	2¼	60
B	Length of grip section, min	2	50
Suggested Dimensions for Ends of Specimen			
"Plain-End" Specimens			
C	Width of grip section (Note 3 and Note 4)	¾	20
"Pin-End" Specimens			
C	Width of grip section, approximate (Note 5)	2	50
D	Diameter of hole for pin (Note 6)	½	13
E	Distance of center of pin from end, approximate	1½	38
F	Distance of edge of hole from fillet, min	½	13

NOTE 1—The width of the reduced section shall be parallel to within ±0.001 in. (±0.025 mm).

NOTE 2—The thickness of the reduced section shall not vary by more than ±0.0005 in. (0.013 mm) or 1 %, whichever is larger, within the gage length, G.

NOTE 3—It is desirable, if possible, that the grip sections be long enough to extend into the grips a distance equal to two-thirds or more the length of the grips.

NOTE 4—Narrower grip sections may be used. If desired, the width may be 0.500± 0.010 in. (12.5 ± 0.25 mm) throughout the length of the specimen, but the requirement for dimensional tolerance in the central reduced section stated in Note 1 shall apply. The ends of the specimen shall be symmetrical with the center line of the reduced section within 0.01 in. (0.25 mm).

NOTE 5—The ends of the specimen shall be symmetrical with the center line of the reduced section within 0.01 in. (0.25 mm).

NOTE 6—Holes shall be on the centerline of the reduced section, within ±0.002 in. (±0.05 mm).

FIG. 1 Specimen for Determining *n* -Values

strains is at or slightly prior to the strain at which the maximum ~~load~~force occurs, and usually the lower bound of these strains is the yield strain (for continuous-yielding material) or the end of yield-point extension (for discontinuous-yielding material). See Fig. 2. The requirement that at least five force-strain data pairs be recorded is met with an autographic recording and the selection of five or more pairs from that curve.

NOTE 9—~~There~~ Since the slope of the curve may vary slightly along its length, there is a statistical basis for choosing points equally spaced ~~in a reference frame.~~out along the strain range.

~~NOTE 10—The requirement that at least five load-strain data pairs be recorded is met with an autographic recording and the selection of five or more pairs from that curve.~~

9.4.1 The test is not valid if fewer than five data pairs are obtained.

~~NOTE 11—The test is not valid if less than five data pairs are obtained.~~

9.4.2 If multiple ~~n~~values ~~values~~ of the strain-hardening exponent are to be determined (Note 1), use at least five stress and strain values for the calculation of ~~n~~the strain-hardening exponent in each interval of strain.

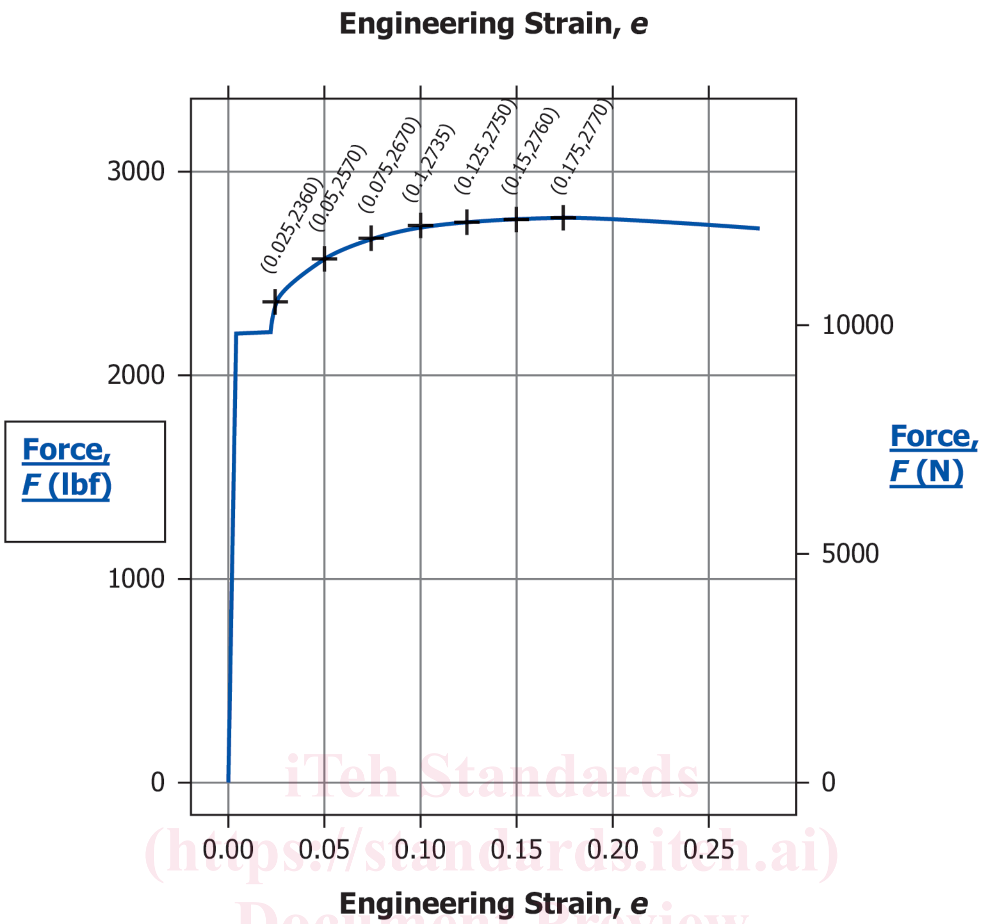


FIG. 2 ~~Examples~~ a Example Showing Load-Strain Data ~~Pairs~~Pairs: material with initial discontinuous yielding region. These data pairs are used for a sample calculation in Appendix X1

9.4.3 Other parameters may be recorded in place of ~~loads~~forces and strains provided that they can ultimately be transformed into true stress and true strain at least as accurately as those measured using the techniques already described in this test method.

10. Calculations

10.1 The calculations in this section are based on true strain and true stress (**3**, **4**, **5**). The true strain (also called the logarithmic strain) is given by (Terminology E6):

$$\varepsilon = \ln\frac{L}{L_o} = \ln(1 + e)$$

where L is the current length of the gauge length, L_o is the initial gauge length, and e is the engineering strain. If L or e is measured under load, then the true strain is the total true strain. If L or e is measured in the unloaded state, or if the elastic component of L or e is subtracted from the loaded L or e, then the true strain given by the equation is the plastic true strain. The true stress is the applied force divided by the instantaneous area (see Terminology E6). If the strain in the gauge length is uniform, the true stress is given by:

$$\alpha = \frac{FL}{A_o L_o} = S(1 + e)$$

where A_o is the initial cross sectional area and S is the engineering stress. This equation assumes constancy of volume and a Poissons ratio of ½ . These assumptions may not always be strictly met, but they introduce a negligible error in the result.

10.2 Determine the strain-hardening exponent from the logarithmic form of the power curve representation of~~ the true-stress versus true-strain curve within the plastic range (Note 12):~~

~~$\log\sigma = \log K + n\log\varepsilon$~~

(1) the true stress versus plastic true strain curve within the plastic range (Method A) or
(2) the true stress versus the total true strain curve within the plastic range (Method B).

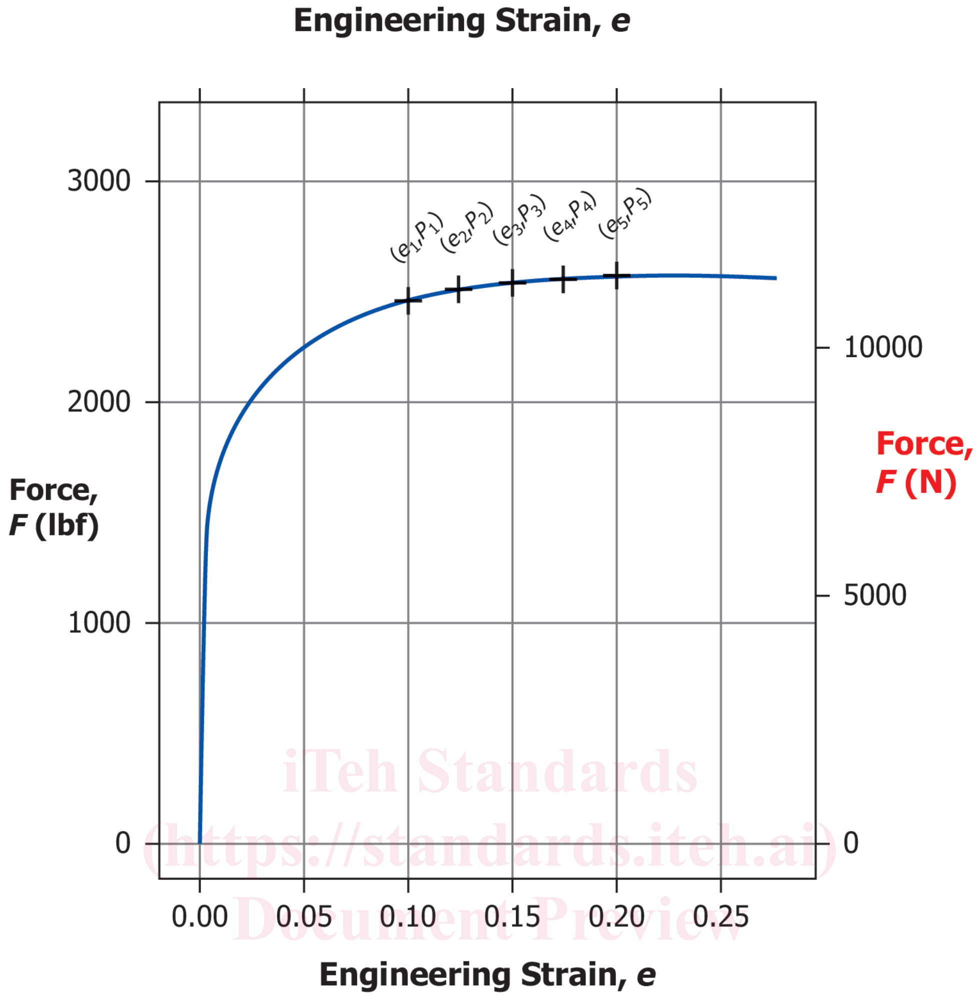


FIG. 2 b Example Showing Force-Strain Data Pairs: material with no discontinuous yielding *(continued)*

~~Calculate values of true stress and true strain from the following:~~Method B is an option only when the elastic strain is less than 10% of the total true strain for all points in the chosen strain range. Method A has no such restriction and may be used everywhere that Method B may be used as well as in strain ranges where the elastic strain is greater than or equal to 10% of the total true strain and Method B

~~True stress $\sigma = S(1+e)$~~

~~True strain $\varepsilon = \ln(1+e)$~~

would be invalid. The method used shall be reported (see 11.1.5).

~~where:~~

~~(σ, ε) = a true-stress versus true-strain pair in the selected interval,~~
~~S = engineering stress, and~~
~~e = engineering strain.~~

NOTE 10—~~Any logarithmic base may be used in these calculations unless otherwise noted. The use of the term “log” does not imply the use of base 10.~~Method A is consistent with the current version of ISO 10275:2007 and with earlier versions of this ASTM test method (5).

NOTE 11—~~For convenience~~ Method B is consistent with earlier versions of this ASTM test methodand earlier versions of ISO 10275:2007 , when the elastic strain ~~is~~ was was less than ~~10 %~~ 10 % of the total ~~strain, it is not necessary to subtract the elastic strain. Elastic strain may be calculated by dividing the true stress~~true strain ~~by~~(5). ~~the nominal value of modulus of elasticity. All data pairs used to calculate an~~Method B provides a means of comparison with data bases generated using these earlier ~~n~~versions. Method~~-value must be treated in the same manner.~~ B does not involve the subtraction of the elastic strain and is therefore simpler to implement and has a reduced uncertainty.

NOTE 12—The difference between strain-hardening exponents determined by Method A and Method B is usually less than 5% for steel, but may be higher for low modulus material with high *n*-value. For a specific material, values of the strain-hardening exponent determined by Method A are always less than those determined by Method B. Users of this standard should be aware that the value of the strength coefficient, *K*, will be different depending on the method used. Since this test method does not report *K*, nor purport to provide a standard measurement of *K*, this difference is not addressed here.