Guide to Testing METALS UNDER TENSION

Determination of the mechanical properties of components is a requirement for most manufactured products.

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The performance of a structure is frequently determined by the amount of deformation that can be permitted. A deflection of a few thousandths of an inch on a machine tool would make it useless, whereas a deflection of several inches or feet is normal for the wing of an aircraft. Regardless of the amount of deflection permitted, measured properties that must be taken into consideration when designing a structure include tensile strength, yield strength, and Young's modulus of elasticity. Another important property is ductility, indicated by total elongation and reduction of area. For suppliers, these mechanical properties are an important measure of metal product quality, and buyers frequently require certification of the values.

This article describes the equipment and details the methods required to accurately determine the mechanical properties of metals. It explains how to calculate stress-strain curves, shows the differences between hydraulic and electromechanical testing machines, and tells how to prevent common measurement errors.

Stress-strain curve

The stress-strain curve is a graphical description of the amount of deflection under load for a given material (Fig. 1). Engineering stress (S) is calculated by dividing the load (P) at any given time by the original cross sectional area (A_o) of the specimen.

$$S = P/A_o$$

Engineering strain (e) is calculated by dividing the elongation of the gage length of the specimen (Δl) by the original gage length (l_o).

$$e = \Delta l/l_o = (l - l_o)/l_o$$

The shape and magnitude of the stress-strain curve depend on the type of metal being tested. In Figure 1, point A represents the proportional limit of a material. A material loaded in tension beyond point A exhibits permanent deformation even when the load is removed. The proportional limit is often difficult to calculate; therefore, two practical measurements, offset yield strength and yield by extension under load (EUL), have been developed to approximate the proportional limit. The initial segment of the curve below point A represents the elastic region and is approximated by a straight line. The slope (E) of the curve in the elastic region is defined as Young's modulus of elasticity, and is a measure of material stiffness.

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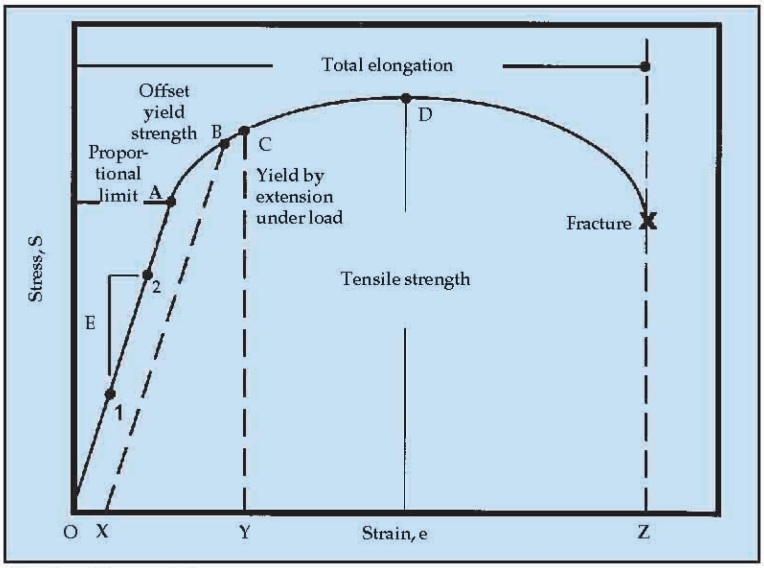

Fig. 1 — Stress-strain curve.

$$E = \Delta S / \Delta e = (S_2 - S_1)/(e_2 - e_1)$$

Point B represents the offset yield strength, and is found by constructing a line X-B parallel to the curve in the elastic region. Line X-B is offset a strain amount O-X, which is typically 0.2% of the gage length for metals.

Point C represents the yield strength by extension under load (EUL), and is found by constructing a vertical line Y-C. Line Y-C is offset a strain amount O-Y, which is typically 0.5% of gage length.

Point D represents the tensile strength or peak stress. Point Z is depicted as strain, and it represents the total elongation or the amount of uniaxial strain at fracture. It includes both elastic and plastic deformation and is commonly reported as percent elongation at break (The gage length is also reported with the result.).

$$\text{Elongation at break (\%)} = e_z = 100^*(l_z - l_o)/l_o$$

Table 1 — Average properties of selected metals

Material	Modulus of elasticity, kPa (Msi)	Yield strength, MPa (ksi)	Ultimate tensile strength, MPa (ksi)	Elongation in two inches, %
Structural steel	200 (29)	248 (36)	455 (66)	—
Steel, 0.4%C, hot-rolled	207 (30)	365 (53)	579 (84)	29
Steel, 0.8% C, hot-rolled	207 (30)	524 (76)	841 (122)	8
Cast iron, gray	103 (15)	—	172 (25)	0.5
Stainless steel, 18-8, annealed	193 (28)	248 (36)	586 (85)	55
Stainless steel, 18-8, cold-rolled	193 (28)	1138 (165)	1310 (190)	8
Aluminum, wrought, 2024-T4	73 (1.6)	331 (48)	469 (68)	19
Aluminum, wrought, 6061-T6	70 (10.0)	276 (40)	310 (45)	17
Titanium alloy, annealed	97 (14)	931 (135)	1069 (155)	13

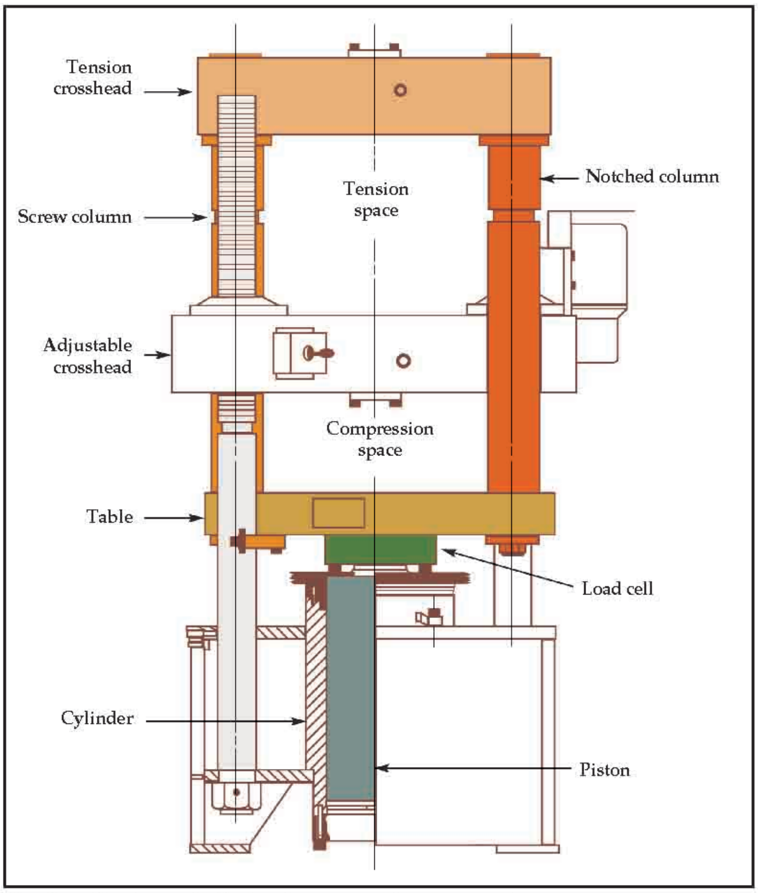

Fig. 2 — Anatomy of a hydraulic universal testing machine.

Reduction of area, like elongation at break, is a measure of ductility and is expressed in percent. Reduction of area is calculated by measuring the cross sectional area at the fracture point.

$$\text{Reduction of area (\%)} = (A_o\text{-}A_z)/A_o$$

Table 1 lists average properties for selected metals. Exact values may vary widely with changes in composition, heat treating, and cold working.

Testing machines

The most common testing machines are universal testers, which test materials in tension, compression, or bending. Their primary function is to create the stress-strain curve. Once the diagram is generated, a pencil and straight-edge, or a computer algorithm, can calculate yield strength, Young's modulus, tensile strength, or total elongation.

Testing machines are either electromechanical or hydraulic. The principal difference is the method by which the load is applied. (For purposes of this article, only static or quasi-static machines are considered.)

Electromechanical machines are based on a variable-speed electric motor; a gear reduction system; and one, two, or four screws that move the crosshead up or down. This motion loads the specimen in tension or compression. Crosshead speeds can be changed by changing the speed of the motor. A microprocessor-based closed-loop servo system can be implemented to accurately control the speed of the crosshead.

Hydraulic testing machines (Fig. 2) are based on either a single or dual-acting piston that moves the crosshead up or down. However, most static hydraulic testing machines have a single acting piston or ram. In a manually operated machine, the operator adjusts the orifice of a pressure-compensated needle valve to control the rate of loading. In a closed-loop hydraulic servo system, the needle valve is replaced by an electrically operated servo valve for precise control.

In general, electromechanical machines are capable of a wider range of test speeds and longer crosshead displacements, whereas hydraulic machines are more cost-effective for generating higher forces.

Common sources of error

Many factors affect the shape and magnitude of the stress-strain diagram. If they are not handled properly, errors may negate a test. All lab managers and test technicians should be mindful of the following common sources of error.

• *The extensometer:* When testing metals, the deflection of the load frame in comparison to the deflection of the specimen may be large enough to introduce significant error. Therefore, metals tests require an extensometer, which measures the deflection of the specimen only (Fig. 3). Most extensometers are attached directly to the specimen, but noncontacting systems are also available.

The five most important characteristics of an extensometer are the attachment mechanism, knife edges, gage length, percent travel, and accuracy. Extensometer slippage due to poor adjustment of the clamping mechanism, and/or worn knife edges, can result in an indeterminate stress-strain curve. *Slippage is the most common source of error in metals*

Fig. 3 — This extensometer has +/-20% travel and a 2-in. (50 mm) gage length.

testing. An appropriate maintenance program should be established to ensure that the knife edges are replaced when worn, and that the springs and clips create enough pressure on the specimen.

Standard extensometer gage lengths are one inch, two inches, and eight inches. The gage length needed for a given test is dictated by the size of the specimen and the test method. Care must be taken to establish the initial gage length when attaching the extensometer. Proper adjustment and operation of the mechanical stops will eliminate gage length errors.

The amount of extensometer travel should match the amount of specimen elongation. An extensometer with too much travel may make it difficult to accurately measure Young's modulus. An extensometer with insufficient travel will prevent certain measurements altogether. Many test methods require a certain extensometer accuracy class (see ASTM E83). Make sure that the extensometer meets the accuracy required prior to testing.

• *The grips:* Wedge-action grips are the most common grips in metals testing. As the axial load increases, the wedge acts to increase the squeezing pressure applied to the specimen. Wedge grips are manually, pneumatically, or hydraulically actuated. For high-volume testing, pneumatic or hydraulic grips are recommended.

Worn or dirty grip faces can result in specimen slippage, which often renders the stress-strain diagram useless. Therefore, the grip faces should be inspected periodically. Worn inserts should be replaced, and dirty inserts cleaned with a wire brush.

Proper alignment of the grips and the specimen when clamped in the grips is important. Offsets in alignment will create bending stresses and lower tensile stress readings. It may even cause the specimen to fracture outside the gage length. Some test machines require backlash nuts to hold the grips in place. The backlash nuts should be tightened while a specimen loaded to machine capacity is installed in the machine.

• *The test specimen:* Most ASTM or similar test methods require a shaped specimen that concentrates the stress within the gage length. If the specimen is improperly machined, it could fracture outside the gage length, resulting in strain errors.

Table 2 — Static universal testing machines

Machine type	Test speeds, in./min	Maximum crosshead displacement, in.	Load capacity, lb
Electromechanical	0.0001 - 40	40	100 - 60,000
Hydraulic	0.005 - 3	6 - 12	60,000 - 1,000,000

Test methods and specifications

The following is a partial list of ASTM test methods and practices for metals testing. Copies are available from ASTM, the American Society for Testing and Materials.

1 Test Method E8-00b Standard Test Methods for Tension Testing of Metallic Materials; Test Method E8M-00b Standard Test Methods for Tension Testing of Metallic Materials [Metric]
2. Test Method E111-97 Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
3. Specification A356/A356M-98e1 Standard Specification for Steel Castings, Carbon, Low Alloy, and Stainless Steel, Heavy-Walled for Steam Turbines
4. Practice E1012-99 Standard Practice for Verification of Specimen Alignment Under Tensile Loading
5. Test Method A370-97a Standard Test Methods and Definitions for Mechanical Testing of Steel Products
6. Test Method E345-93(1998) Standard Test Methods of Tension Testing of Metallic Foil
7. Practice E29-93a(1999) Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
8. Practice E83-00 Standard Practice for Verification and Classification of Extensometer
9. Test Method E21-92(1998) Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials

Improper reading of specimen dimensions also creates stress measurement errors. Therefore, worn micrometers or calipers should be replaced and care should be taken when recording specimen dimensions. Some computer-based test systems read the micrometer or caliper directly, thus eliminating data entry errors.

• *Other sources of error:* The shape and magnitude of the stress-strain diagram can be affected by the test speed. For example, some materials exhibit an appreciable increase in strength with faster test speeds. Therefore, make sure that the load rate is in accordance with the specific test method.

In addition, worn machine components can result in misalignment, creating bending stresses that lower tensile stress readings. Check the test machine's alignment and play, to ensure concentricity of the crosshead over the full travel.

Finally, with the advent of microprocessor-based test systems, applied loads can inadvertently be "zeroed out," resulting in lower stress readings. To prevent this, clamp the specimen in the upper grip, then zero the load, then close the lower grip. ■

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