Do Your Materials Measure Up?

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Materials testing is often the last step in the manufacturing process. Yet quality cannot be put in after the fact since it is the result of both the materials and the process. In forming materials, it's helpful to understand their properties in order to better predict the manufacturing outcome. For stamping and forming operations and for many products it is also helpful to have a profile of the material in order to detect variations in materials from suppliers over time.

This paper offers definitions for mechanical properties of materials that exhibit some Hookean (linear) behavior during loading. Metals and many plastics, polymers and composites exhibit Hookean behavior. This paper is intended as a tutorial or refresher for product designers and quality inspectors on the analysis of tensile test data. A glossary of important materials testing terms is included (Sidebar).

Figure 1 - Tensile specimen pulled to fracture. Depicts region where necking occurred.

Material properties that have a direct or indirect influence on formability and product quality are Tensile Strength, Yield Strength, Young's Modulus, Ductility, Hardness, the Strain Hardening Exponent and the Plastic Strain Ratio. All of these parameters, except hardness, can be determined by cutting a test specimen from the blank and performing a tensile test.

Tensile testing has several elements

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 in an optical grinding machine would produce scrap lenses, whereas a bridge truss or joist might deflect several inches. Tensile Strength, Yield Strength and Young's Modulus of Elasticity are measured properties that must be considered when designing a structure.

Another important property is ductility, defined as the ability for plastic deformation in tension or shear. Ductility controls the amount a material can be cold formed which is the process used when forming automobile bodies or wire products. Two commonly used indices of ductility are total elongation and reduction of area. For suppliers, the mechanical properties are an important measure of product quality, and often times buyers require certification of the values.

The outcome of a forming process is dependent on both material characteristics and process variables such as strain, strain rate and temperature. Stress and strain fields are so diverse during a forming process that one test cannot be used to predict the formability of materials in all situations. However, an understanding of material properties is important to determining the success of a forming process.

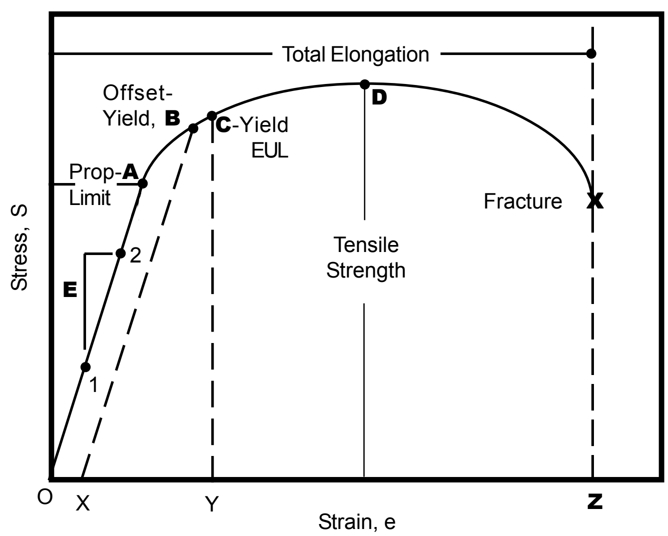

Figure 2 - Stress-Strain Curve.

A tensile test is employed to generate a stress-strain curve that provides a graphical description of the amount of deflection under load for a given material. A typical stress-strain curve is shown in Figure 2 and depicts several key measures of product quality.

The Tensile Test - The stress-strain curve is generated by pulling a metal specimen in uniaxial tension to failure. ASTM E8/E8M Standard Test Methods for Tension Testing Metallic Materials governs the methods used for the determination of Yield Strength, Ultimate Tensile Strength, Percent Elongation at Break and Reduction of Area.

Engineering stress (S) is obtained by dividing the load (P) at any given time by the original cross sectional area (A_o) of the specimen.

$$S = P/A_o \qquad \text{Eq. 1}$$

Engineering strain (e) is obtained by dividing the elongation of the gage length of the specimen ($\triangle l$) by the original gage length (l_o).

$$e = \triangle l/l_o = (l - l_o)/l_o \qquad \text{Eq. 2}$$

Figure 2 depicts a typical stress-strain curve. The shape and magnitude of the curve is dependent on the type of metal being tested. In Figure 2, point **A** represents the proportional limit of a material. A material loaded in tension beyond point **A** when unloaded will exhibit permanent deformation. The proportional limit is often times difficult to calculate, therefore, two practical measurements, Offset Yield Strength and Yield by Extension Under Load (EUL) were developed to approximate the proportional limit. The initial portion of the curve below point **A** represents the elastic region and is approximated by a straight line. It is commonly referred to as the linear elastic or Hookean region. 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.

$$E = \triangle S / \triangle e = (S_2 - S_1)/(e_2 - e_1) \qquad \text{Eq. 3}$$

Point **B** represents the Offset Yield Strength and is found by constructing a line X-B parallel to the curve in the elastic region (ie. slope of line X-B equal to Young's Modulus (E)). Line X-B is offset a strain amount O-X that is typically 0.2% of the gage length (example: offset O-X = 0.2% = 0.002 in/in and for a 2 in gage length = 0.004 in). 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 that is typically 0.5% of gage length. The Tensile Strength or peak stress is represented by point **D** in Figure 2.

Elongation at Fracture is the amount of uniaxial strain at fracture and is depicted as strain at point **Z**. It includes the amount of both elastic and plastic deformation just prior to the sudden decrease in force associated with fracture. Elongation at Fracture is generally measured with an extensometer that remains on the specimen through break. For materials that exhibit a high degree of elongation, such as plastics, crosshead travel may be substituted for direct strain measurement with an extensometer. Percent Elongation at Break is commonly determined after the test by fitting the fractured ends together and measuring the change in distance, l_o, between two gage marks punched or scribed into the specimen prior to testing. (The gage length used for measurement is reported with the result.).

$$\text{Elongation at Break(\%)} = e_Z = 100^*(l_Z - l_o)/l_o \qquad \text{Eq. 4}$$

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

$$\text{Reduction of Area(\%)} = (A_o - A_Z)/A_o \qquad \text{Eq. 5}$$

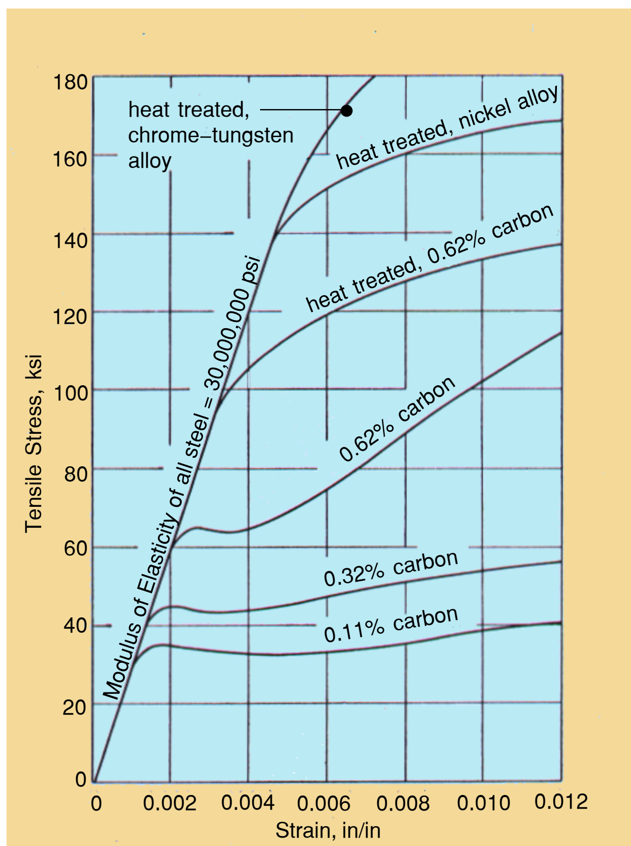

Figure 3 - Stress-strain diagram for various steels.
(from Muhlenbruch, C.W.: *Testing of Engineering Materials*, Van Nostrand, New York, 1944.)

A Few Words About Materials Characteristics

Figure 3 shows the relative magnitudes of the stress-strain curves for various steels. Figure 4 depicts the magnitudes of Tensile Strength, Yield Strength, Elongation and Reduction of Area as the carbon content of steel is varied.

- In general, as Reduction of Area increases, the minimum allowable bend radius for a sheet material decreases. Therefore, as the carbon content of steel increases the minimum bend radius increases.

- Yield Strength and Tensile Strength are not directly related to formability, however, the closer the magnitude of the two stresses, the more work hardened the metal. Therefore, as the carbon content of steel decreases the material appears as if it is more work hardened.

- Both elastic and plastic deformation occur during a forming process. Upon removal of the external forces, the internal elastic stresses relax. If the forming process is not designed properly, the stress relaxation or "springback" will cause the part to change shape or distort. A material with a lower value for Young's Modulus, E, and/or a higher value for Yield Strength will exhibit greater "springback" or shape distortion. Therefore, as the carbon content of steel increases the amount of "springback" increases.

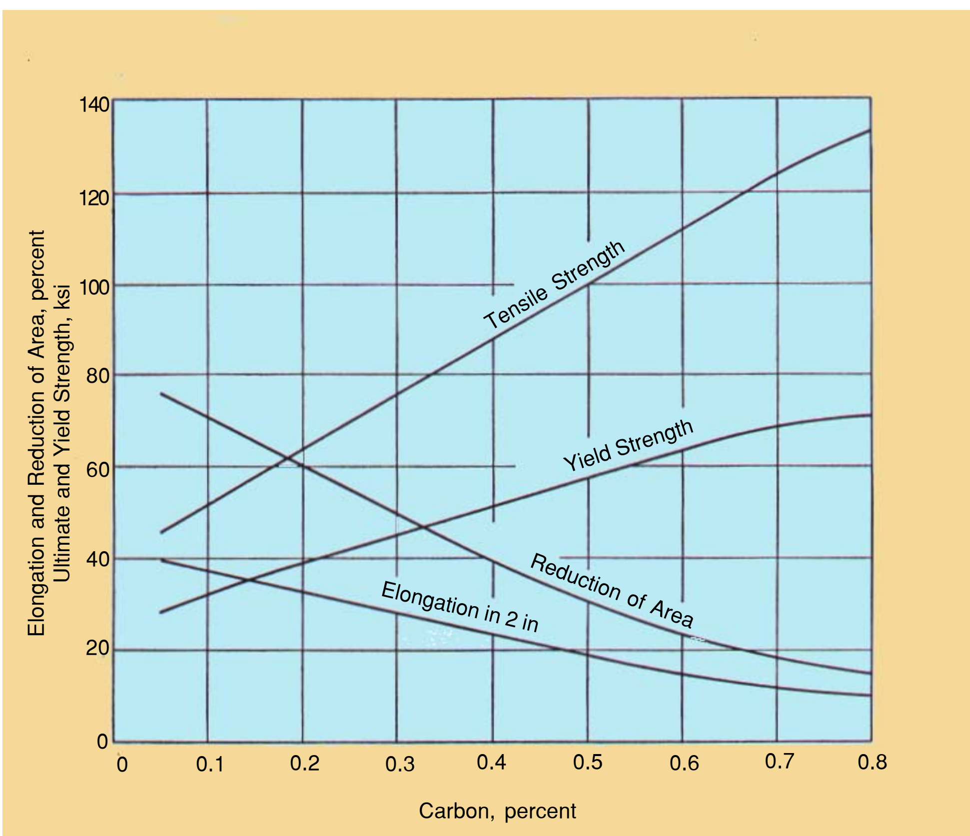

Figure 4- Effect of carbon on tensile properties of hot-worked carbon steels.
(from Sisco, F.T.: *Modern Metallurgy for Engineers*, Pitman, New York, 1948.

Some important points to keep in mind when testing

- Elongation at Fracture and Reduction of Area both increase with increasing cross-sectional area of the specimen. Percent Elongation decreases with increasing gage length because the region where localized necking occurs remains the same regardless of the gage length. Therefore, consistency in specimen dimensions and gage length are paramount for comparing results and ensuring process quality.

- The rate at which a test is performed can have a significant effect on tensile properties and is known as strain rate sensitivity. Tensile properties for plastics and polymers are very sensitive to testing rates. Steels are also sensitive to strain rates but aluminum alloys have little sensitivity. Materials that are sensitive to strain rates exhibit higher tensile strengths and lower elongations at faster speeds. Therefore, it is important that all testing rates are within the limits specified by the governing standard(s). I would even go one step further if you are comparing results across lots or batches of like materials and insist that the testing rates are identical.

- During the rolling process used to produce metals in sheet form and the subsequent annealing, the grains become elongated in the rolling direction resulting in an anisotropic material. This causes a variation in tensile properties when the direction of loading is changed in relation to the orientation of the grains. Therefore, it is common practice to test specimens cut parallel to the rolling direction and at 45^{o} and 90^{o} to this direction and include the direction with the results.

- One of our most frequent support calls is from a frantic customer who states "my Yield Strength and Modulus values are not correct". After obtaining a copy of the stress-strain curve it is determined that the strain extensometer has slipped on the specimen at some point in the linear elastic region. There are several reasons why slippage may occur, chief among them are a) the specimen has not been prepared properly or is bent; b) the gage length stop is out of adjustment; c) the knife edges are worn; d) the clamping force is too small; or e) the extensometer is damaged. It is recommended that a maintenance program based on the frequency of extensometer use be instituted.

- Oftentimes the strain goes negative or a slight amount of extensometer slippage occurs just after loading begins. As a result, calculation errors may occur in programs that automatically calculate Modulus. To eliminate the non-linearity in the test data, raise the logging threshold in the testing software.

Sidebar definitions of ten to 15 words: (even if they are defined in the paper)

Materials properties definitions:
Mechanical Properties - those properties of a material that are associated with the elastic and plastic reaction when force is applied.
Engineering Stress - the normal stress, expressed in units of applied force per unit of original cross-sectional area.
Engineering Strain - a dimensionless value that is the change in length per unit length of the original linear dimension along the loading axis of the specimen. Frequently expressed in inches per inch or percent.
Gage Length - the original length of that portion of the specimen over which strain or change in length is determined.
Extensometer - a device for measuring strain.
Ductility - the ability of a material to deform plastically before fracture.
Young's Modulus of Elasticity - the ratio of stress to corresponding strain below the proportional limit.
Elastic Limit - the greatest stress which a material is capable of sustaining without any permanent strain remaining upon complete release of stress.
Proportional Limit - the greatest stress which a material is capable of sustaining without deviation from a linear relationship of stress to strain.
Hooke's Law - within certain force limits, the stress in a material is proportional to the strain which produced it.
Yield Strength - the engineering stress at which, by convention, it is considered that plastic elongation of the material has commenced.
Tensile Strength - the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the original cross-sectional area of the specimen.
Reduction of Area - the difference between the original cross-sectional area of a tension test specimen and the area of its smallest cross-section. The reduction of area is expressed as a percentage of the original cross-sectional area.
Total Elongation - the elongation determined after fracture by realigning and fitting together the broken ends of the specimen.
Hardness - the resistance of a material to deformation, particularly permanent deformation, indentation, or scratching.
Many of these definitions are taken from ASTM E6 Standard Terminology Relating to Methods of Mechanical Testing.