Tensile Testing for Determining the Formability of Sheet Metals

by
Richard Gedney
ADMET, Inc.
Norwood, MA 02062
Tel: 781-769-0850
www.tensiletesters.com

***Introduction* -** Sheet metal forming operations consist of simple bending, to stretching to deep drawing of complex parts. The mechanical properties of the sheet material greatly influences its formability. Formability is a measure of the amount of deformation a material can withstand prior to fracture or excessive thinning. Determining the extent to which a material can deform is necessary for designing a reproducible forming operation. Testing the incoming sheet material is also essential because material properties may vary from coil to coil and effect part quality and scrap rate.

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. The standard tensile test is used to measure the characteristic properties of sheet metals. More specialized tests such as the Simple Bend Test, Limited Dome Height Test, Cup Test, Hole Expansion Test or Wrinkling Test may be performed to simulate straining conditions found during the actual process.

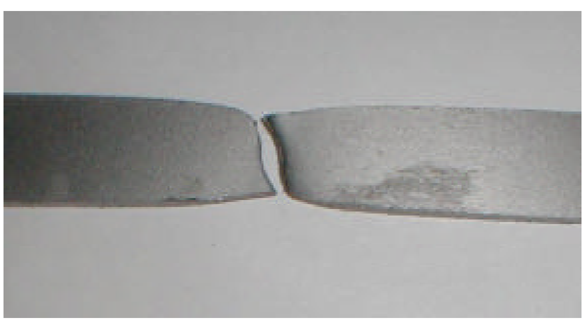

Figure 1 **-** Tensile specimen pulled to fracture.
Depicts region where necking occurred.

Material properties that have a direct or indirect influence on formability and product quality are, Ultimate 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. Most metalworking processes involve metal being deformed in various directions. Because of the resulting anisotropy of rolled metal, sample orientation can be significant to the measurement of mechanical properties. Therefore, sample orientation relative to the roll direction should be reported with each property.

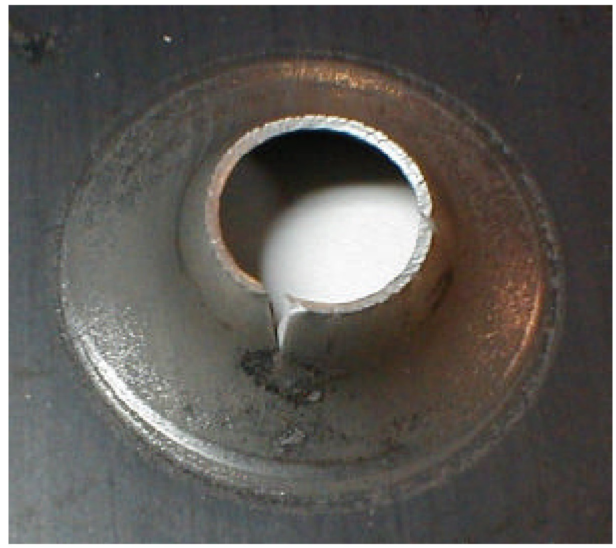

Figure 2 **-** Hole expansion specimen tested to failure.

***The Tensile Test* -** A graphical description of the amount of deflection under load for a given material is the stress-strain curve (Figure 3). 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, the latter two being measures of ductility. 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 (**r** L) by the original gage length (L_o).

$$e = \mathbf{r}\ L/L_o = (L - L_o)/L_o \qquad \text{Eq. 2}$$

Figure 3 depicts a typical stress-strain curve. The shape and magnitude of the curve is dependent on the type of metal being tested. In Figure 3, point A represents the proportional limit of a material. A material loaded in tension beyond point A when unloaded will exhibit permanent or plastic 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. 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.

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

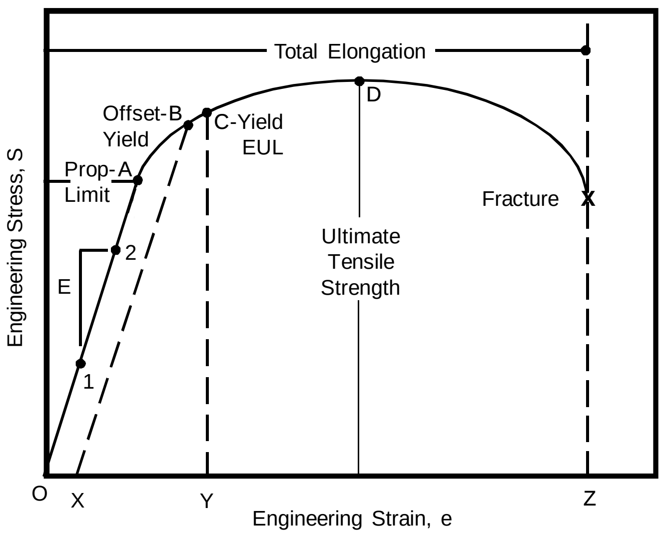

Figure 3 - Stress-Strain Curve.

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 that is typically 0.2% of the gage length. 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 Ultimate Tensile Strength or peak stress is represented by point D in Figure 3. Necking begins (dP = 0) at the peak point D on the Stress-Strain curve.

Yield Strength and Ultimate Tensile Strength are not directly related to formability, however, the closer the magnitude of the two stresses, the more work hardened the metal. A work hardened metal exhibits lower ductility which reduces its ability to stretch. Both elastic and plastic deformation occur during the 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.

Ductility is defined as the capacity for plastic deformation. Two measures of ductility governed by ASTM E8/E8M are Total Elongation and Reduction of Area. Total Elongation is the amount of uniaxial strain at fracture and is depicted as strain at point Z. It includes both elastic and plastic deformation and is commonly reported as Percent Elongation at Break (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.

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

In general, as Reduction of Area increases the minimum allowable bend radius for a sheet material decreases. Total Elongation and Reduction of Area both increase with increasing cross-sectional area of the specimen. Percent Elongation decreases with increasing gage length due to localized necking in the specimen. Therefore, consistency in specimen dimensions and gage length are paramount for comparing results and ensuring process quality.

The Strain Hardening Exponent is a measure of how rapidly a metal becomes stronger and harder due to plastic deformation. The deformation remaining after an applied load is removed is called plastic deformation. ASTM E646 Standard Test Method for Tensile Strain-Hardening Exponents of Metallic Sheet Materials governs the determination of the Strain Hardening Exponent. ASTM E646 is a tensile test that measures the stress-strain response in the plastic region prior to necking (dP=0). In Figure 4 that is the region of the curve between Yield Strength point B and Ultimate Strength point D. In the B-D strain hardening region, the stress-strain curve is approximated by the following equation.

$$\mathbf{s} = K\mathbf{e}^n \qquad \text{Eq. 6}$$

where, $\mathbf{s}$ is the true stress, K is the strength coefficient, $\mathbf{e}$ is the true strain and n is the Strain Hardening Coefficient. Equation 6 is a power curve and requires conversion to a logarithmic form (Eq. 7) in order to calculate the Strain Hardening Coefficient, n.

$$\log \mathbf{s} = \log K + n \log \mathbf{e} \qquad \text{Eq. 7}$$

The exponent, n, is obtained from the true stress-true strain curve which is derived from the engineering stress-engineering strain curve. Assuming constant specimen volume, the relationship between true stress and engineering stress and true strain and engineering strain is as follows.

True Stress $\mathbf{s} = S(1+e)$ Eq. 8

True Strain $\mathbf{e} = \ln(1+e)$ Eq. 9

Equation 7 is presented in the form of a straight line where n is the slope of the line and log K is the y-intercept. Using linear regression analysis, the equation for the Strain Hardening Exponent, n, becomes

$$n = \frac{N\mathbf{S}xy - \mathbf{S}x\mathbf{S}y}{N\mathbf{S}x^2 - (\mathbf{S}x)^2} \qquad \text{Eq. 10}$$

where, y = log (S(1+e)),
x = log (ln(1+e)),
b = log K,
N = Number of data pairs.

In order to calculate n, at least 5 data pairs between points B and D should be selected. If the stress-strain curve has a discontinuity between points B and D, then select a portion of the curve between B and D that is continuous or else discard the test.

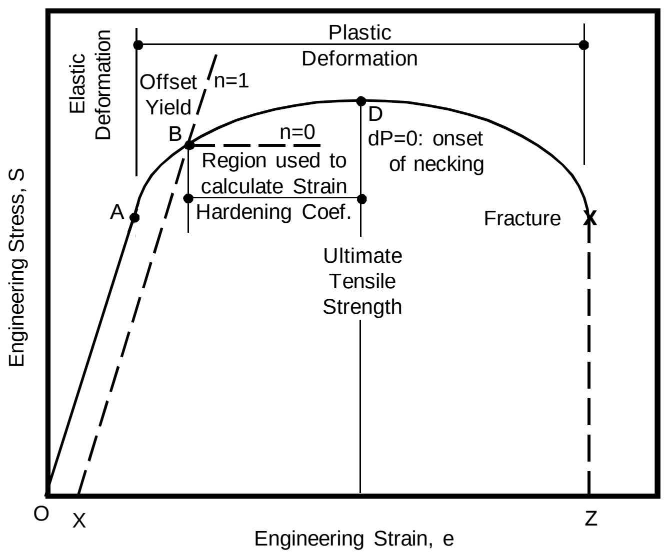

Figure 4 - Stress-Strain Curve.

The ability to form sheet metal by stretching depends on strain hardening. At the onset of necking, the material is thinned and weakened. Therefore, it is important to know the strain at the onset of necking. At any given time, true stress is given by

True Stress $\mathbf{s} = P/A_i$ Eq. 11

and true strain is given by

True Strain $d\mathbf{e} = dL/L_i$ Eq. 12

where A_i and L_i are is the instantaneous area and gauge length, respectively. Knowing that $P=\mathbf{s}A$ and at the onset of necking dP=0, the following expression can be constructed from $dP = \mathbf{s}dA + Ad\mathbf{s} = 0$.

$$d\mathbf{s}/\mathbf{s} = -dA/A \qquad \text{Eq.13}$$

The volume of a metal specimen in the plastic region remains constant. Therefore, $-dA/A = dL/L = d\mathbf{e}$. Substituting into Eq. 13 gives

$$d\mathbf{s}/d\mathbf{e} = \mathbf{s} \qquad \text{Eq. 14}$$

By substituting Eq. 6 into Eq. 14 we get $nK\mathbf{e}^{n-1} = K\mathbf{e}^n$ and

$$n = \mathbf{e} \qquad \text{Eq. 15}$$

Therefore, the true strain at the onset of necking is equal to the Strain Hardening Exponent, n. Hence, the higher the value of n, the more a piece of material can be stretched prior to necking. Said another way, the greater the value of n, the greater the difference between Yield and Ultimate and the further the material can be stretched before failure.

The Plastic Strain Ratio, r, indicates the ability of the sheet metal to resist thinning or thickening when being deep drawn into a cup for example. The r value is calculated from width and longitudinal strain and is a measure of sheet metal drawability. ASTM E517 Standard Test Method for Plastic Strain Ratio r for Sheet Metal governs it's determination. Because rolled sheet metals develop planar anisotropy, the test specimens are cut at 0°, 45° and 90°, respectively to the roll direction. The average ratio r_{avg}, is then given by

$$r_{avg} = (r_0 + 2r_{45} + r_{90})/4 \qquad \text{Eq. 16}$$

The calculation of r is as follows

$$r = \mathbf{e}_w/\mathbf{e}_t \qquad \text{Eq. 17}$$

where true width strain $\mathbf{e}_w = \ln(w_f/w_0)$,
true longitudinal strain $\mathbf{e}_t = \ln(t_f/t_0)$,
w_f = final width,
w_0 = original width,
t_f = final thickness,
t_0 = original thickness.

Assuming the volume of the specimen remains constant, the lognitudinal strain e_t can be expressed as $e_t = \ln(L_o w_o/L_f w_f)$. Invert as follows to eliminate negative values and the Plastic Strain Ratio, r, is given by

$$r = \frac{\ln(w_0/w_f)}{\ln(L_f w_f/L_0 w_0)} \qquad \text{Eq. 18}$$

where, L_f = final length,
L_0 = original length.

Equation 18 enables the Plastic Strain Ratio, r, to be calculated with two extensometers, one to measure the change in axial gage length and the other to measure the change in width (See Figure 5). The final values are usually calculated at 10, 15 and 20% elongation.

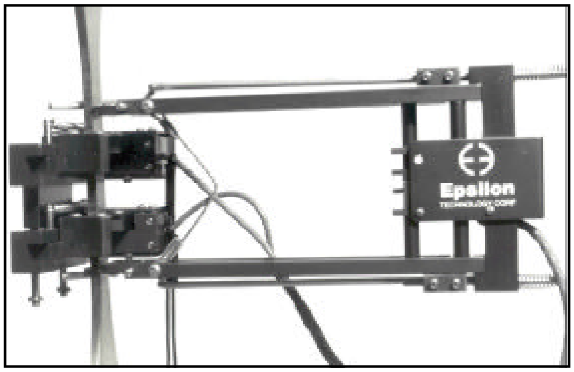

Figure 5 - Axial and Averaging Extensometers used to measure axial strain and change in specimen width for determining the Plastic Strain Ratio, r.

The limiting drawing ratio, LDR, is defined as the ratio of maximum blank diameter to punch diameter that will produce a successful component when a flat sheet is shaped into a cylindrical or boxlike shape. When r_{avg} is plotted against LDR on a log-log graph, there is a linear relationship between the two parameters. Therefore, r_{avg} is proportional to the maximum drawing depth.

Strain Rate Sensitivity **-** The speed of testing is very important because the strength properties of many materials increase at higher strain rates. ASTM E8 specifies an upper and lower limit on deformation rates based on strain rate, stress rate or crosshead separation. With some metals, the strain rate variation allowed in E8 may result in Yield Strength variations up to 20%. Variations in ductility and the strain hardening exponent may also occur. Therefore, a valid and constant strain rate should be used for comparing like tensile tests. Conversely, since strength may be dependent on the rate of straining, the tensile test can be used to measure the strain rate sensitivity, m, of a material by testing at different strain rates. The strain rate sensitivity relationship is given by

$$\sigma = C\dot{\varepsilon}^m \qquad \text{Eq. 19}$$

where σ is the true stress, C is the strength coefficient and $\dot{\varepsilon}$ is the true strain rate. *As a rule, an increase in m causes an increase in ductility, total elongation and elongation after the onset of necking. Also, the value of m decreases with metals of increasing strength.*

Hardness is measured by applying specific loads to a material with an indentor and measuring the resulting amount of permanent indentation. There are several methods for measuring hardness each with various scales. ASTM E10 Standard Test Method for Brinell Hardness of Metallic Materials and ASTM E18 Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials are two such tests.

Hardness can be used as an indirect measure of sheet metal formability. Typically, the harder the material, the stronger and more brittle the material and the less it will stretch before failure.

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

Test Methods and Specifications - Copies of the ASTM test methods mentioned in this article may be obtained from ASTM, the American Society for Testing and Materials. The test methods are available from the ASTM Web site (www.astm.org) or through Customer Service (610/832-9585; e-mail: service@astm.org). 100 Barr Harbor Drive, West Conshohocken, PA19428-2959 Phone: (610) 832-9585 Fax: (610) 832-9555.

Table 1 - Average Properties for Selected Metals at Room Temperature.

The properties shown in this table are from a variety of sources and are believed to be representative. There are so many variables which affect these properties, however, that their approximate nature must be recognized.

Material	Modulus of Elasticity (1000 ksi)	(GPa)	Yield Strength (ksi)	(MPa)	Tensile Strength (ksi)	(MPa)	Percent Elongation in 2 in.	Hardness	E646 n	E517 ravg	Strain Rate Sensitivity m
Steel, 0.2% carbon											
hot-rolled	29	200	40	275	60	415	35	120HB	0.22	1.0-1.6	0.013
cold-rolled	29	200	60	415	80	550	15	160HB	0.08	1.2-1.8	0.007
Steel, 0.8% carbon											
hot rolled	29	200	73	505	120	825	10	240HB	0.15	0.6-1.0	0.003
302 Stainless, annealed	31	215	37	255	90	622	55		0.30		
Aluminum, 2024-T4	11	73	57	395	72	495	13	80HRB	0.16	0.6-0.8	0.005
Titanium alloy, annealed	14	97	135	931	155	1069	13	37HRC		3-5	
70-30 Brass, annealed	16	110	16	110	48	331	61	66HRF	0.5	0.9	0.001

References:

1. S. Kalpakjian, *Manufacturing Processes for Engineering Materials*, 3rd ed. Addison-Wesley, 1997.
2. *Forming and Forging*, Vol. 14, *ASM Handbook*, ASM International 1988.
3. *Mechanical Testing and Evaluation*, Vol. 8, *ASM Handbook*, ASM International 2000.
4. Metals-Mechanical Testing, Vol. 3.01, ASTM Standards, American Society of Testing and Materials.
5. G.E. Dieter, Workability Testing Techniques, American Society of Metals, 1984.