2 The Tension Test (from ME 330)

2.1 Objective

The uniaxial stress state is one of the most common loading conditions used to characterize a material's strength and deformation properties. Several engineering materials will be tested to provide an overview of the variety of mechanical responses that can be anticipated in actual structures and machines. An understanding of the distinctions between engineering stress-strain and true stress-strain will help you interpret various material properties. Some of the results obtained will be compared to data from other stress states in future laboratories to enhance your understanding of yield and failure mechanisms.

2.2 Background

Bar sizes and instrumentation techniques vary between tensile tests, so it is useful to introduce the concepts of stress and strain to form a uniform nomenclature that allows comparison of the experimental results. In basic mechanics there are two reference frames, the Lagrangian and the Eulerian, that generally refer to initial and instantaneous states, respectively. In tensile testing these two reference frames refer to the engineering (Lagrangian) and true (Eulerian) definitions of stress and strain.

2.2.1 Engineering stress and strain

Engineering stress and strain properties are based on original specimen dimensions (Fig. 1). Hence, the engineering stress is defined as:

$$\sigma = \frac{P}{A_o} \tag{1}$$

where

P = axial load

A_o = original cross sectional area

In a similar fashion engineering strain is defined as:

$$\varepsilon = \frac{L_i - L_o}{L_o} = \frac{\Delta L}{L_o} \tag{2}$$

with

L_o = original gage length

L_i = instantaneous gage length

Common material properties associated with these definitions are shown in Table 1.

Table 1
Engineering Stress-Strain Properties

Property, units	Description	Definition
E, MPa or GPa	Linear elastic modulus	$E = \Delta\sigma / \Delta\varepsilon$ Initial slope of the stress-strain curve.
σ_y, MPa	Proportional Limit	$\sigma_y = P_y / A_o$
σ_{ly} , MPa	Lower Yield Strength	$\sigma_{ly} = P_{ly} / A_o$ Common only for low carbon steels.
σ_{uy}, MPa	Upper Yield Strength	$\sigma_{uy} = P_{uy} / A_o$ Common only for low carbon steels.
$\sigma_{0.2\%y}$, MPa	0.2% Offset Yield Strength	$\sigma_{0.2\%y} = P_{0.2\%y} / A_o$ The intersection of a line with the slope of the elastic modulus which is offset by 0.2% and the stress-strain curve.
σ_u,, MPa	Ultimate Strength	$\sigma_u = P_u / A_o$ Maximum load divided by the original area.
%EL	Percent Elongation	$\%EL = 100\% (L_f - L_o) / L_o$ Change in the gage length.
υ	Poisson's Ratio	An elastic parameter, typically the ratio of transverse to longitudinal strain in a uniaxial test.

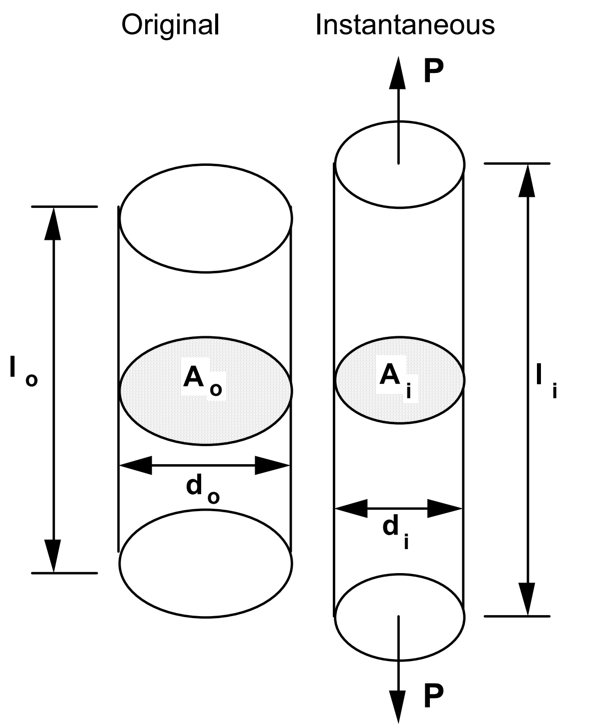

Figure 1 Definition of specimen dimensions

Several of the properties cited in Table 1 assume initial linear elastic deformation. The linear elastic modulus, E, is the initial slope of the stress strain curve (Fig. 2). While the linear elastic modulus is well defined for most wrought metals, for other processing variables such as castings and materials such as plastics, nonlinear behavior is typical at stress levels that are low in comparison to the ultimate strength.

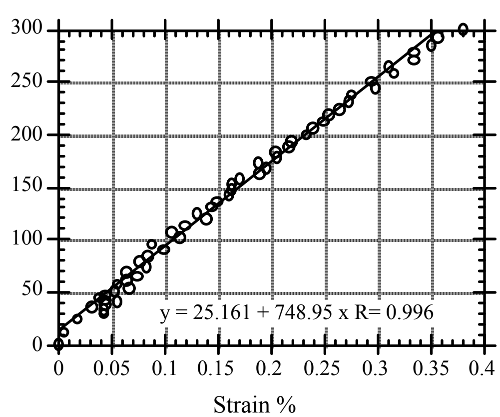

Figure 2 Typical elastic modulus calculation

It is worthwhile to note that strain in units of percent were used to fit the data in Fig. 2. Hence the modulus value is 74,895 MPa or 74.9 GPa (move decimal point two places to the right for MPa). Strains are often separated into elastic and plastic components, while no similar distinction is made for stresses.

$$\varepsilon = \varepsilon^E + \varepsilon^P \tag{3}$$

The elastic strain is defined as follows,

$$\varepsilon^E = \frac{\sigma}{E} \tag{4}$$

One property of interest is the 0.2% offset yield strength. Deviation from linearity, as defined by the proportional limit, is often difficult for different researchers to define with consistency. Pen width, visual acuity, and personal interpretation play a major role in the value determined for this property. In order to introduce more uniformity the concept of an offset yield strength was developed. This is the stress required to cause a 0.2% (0.002) plastic strain, or the intersection of a line with the slope of the elastic modulus which is offset by a strain of 0.2% from the engineering stress-strain curve. Figure 3 illustrates this concept.

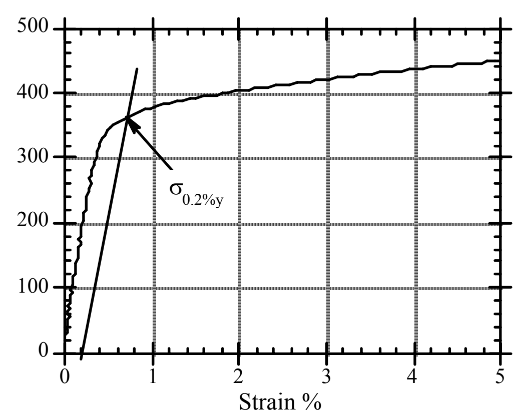

Figure 3 Typical initial portion of the stress-strain curve for an aluminum alloy

Low carbon steels exhibit a unique stress-strain curve. For steels, the proportional limit corresponds to the upper yield strength, which is very dependent on the rate of testing and therefore does not lend itself to generalized comparison.

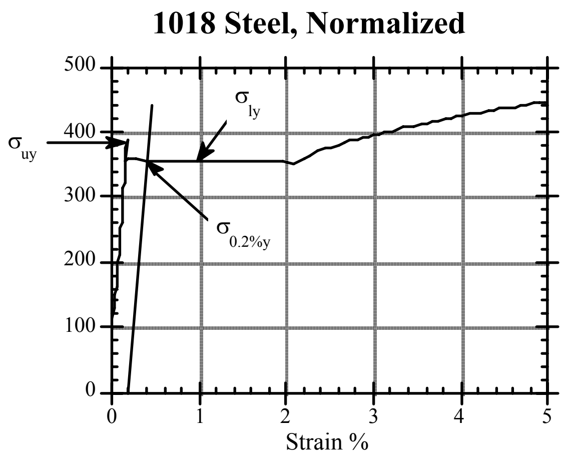

Figure 4 Typical initial portion of the stress-strain curve for a low carbon steel

The lower yield strength is not highly rate dependent and provides a more reliable material property when many testing variables are encountered. It is usually approximately equal to the 0.2% offset yield strength (Fig. 4).

Another property frequently cited is percent elongation. Individual test instrumentation and specimen plastic deformation characteristics largely determine this value. For relatively brittle materials, percent elongation may provide an adequate basis for comparison, but as a generalized material property its usefulness is restricted.

Poisson's ratio, υ, is a linear elastic property that represents dimensional changes in dimensions (i.e. directions) other than the one being loaded. This can be envisioned by considering a rubber band that is being stretched, and observing the thickness decreasing. For most wrought metals, a value of 0.3 is appropriate. The value is not as consistent for castings, polymeric and ceramic materials.

3.2.2 True stress and strain

True stress and strain are based on the instantaneous dimensions of the specimen (Fig. 1). True stress is defined as:

$$\sigma_t = \frac{P}{A_i} = \frac{P}{A_i}\left(\frac{A_o}{A_o}\right) = \frac{P}{A_0}\left(\frac{A_o}{A_i}\right) = \sigma\left(\frac{A_o}{A_i}\right) \quad (5)$$

Since most metals are comparatively stiff (i.e., they have high linear elastic modulus), significant dimensional changes do not occur. Therefore, there is very little difference between true and engineering stress. Major differences may occur at larger deformations, which for metals implies considerable plastic strains. If a value for constant volume is assumed during plastic deformation, and the linear elastic region can be ignored ($\varepsilon^P >> \varepsilon^E$), then further modifications to Eq. 5 can be made. For a typical sample, constant volume implies:

$$V = A_o L_o = A_i L_i \quad (6)$$

hence:

$$\frac{A_o}{A_i} = \frac{L_i}{L_o} \quad (7)$$

and since:

$$L_i = L_o + \Delta L \quad (8)$$

Eq. 5 can be rewritten as:

$$\sigma_t = \frac{P}{A_0}\left(\frac{A_o}{A_i}\right) = \sigma\left(\frac{L_i}{L_o}\right) = \sigma(1+\varepsilon) \quad (9)$$

Table 2
True Stress-Strain Properties

Property	Description	Definition
%RA	Percent Reduction in Area	$100(A_o-A_f)/A_o$ or $100(d_o^2-d_f^2)/d_o^2$
σ_f	True Fracture Strength	Fracture load divided by fracture area, P_f/A_f. Often corrected for triaxial state of stress caused by necking (Bridgman correction).
ε_f	True Fracture Strain	$\ln(A_o/A_f)$, Related to %RA by $\ln(100/(100-\%RA))$
n	Ramberg-Osgood strain Hardening Exponent	Slope of the log-log plot of true stress and plastic strain (Fig. 3).
K, MPa or ksi	Ramberg-Osgood strain Hardening Coefficient	Intercept of the log-log plot of true stress and plastic strain at a true plastic strain =1.

True strain is defined as:

$$\varepsilon_t = \int_{L_o}^{L_i} (1/L)\,dL = \ln\left(\frac{L_i}{L_o}\right) \tag{10}$$

Again using Eq. 8, the more familiar form of true strain in terms of engineering strain is:

$$\varepsilon_t = \ln(1+\varepsilon) \tag{11}$$

Note that the assumption of constant volume was not necessary for the derivation of true strain in terms of engineering strain. However, when using Eq. 9 it is important to keep the assumptions used in mind. *Equations 9 and 11 are valid only before necking.* Furthermore, strain must be in dimensionless form when performing these calculations, not in units of percent. After necking there is no longer uniform deformation of the gage section. In terms of the behavior of a typical metal, this suggests that these two formulas should not be used after maximum load has been achieved. A drop in load for increased deformation does not always indicate necking for polymeric and composite specimens. Hence the extension of these two formulas is possible past the maximum load if there is no necking.

2024-T4 Aluminum

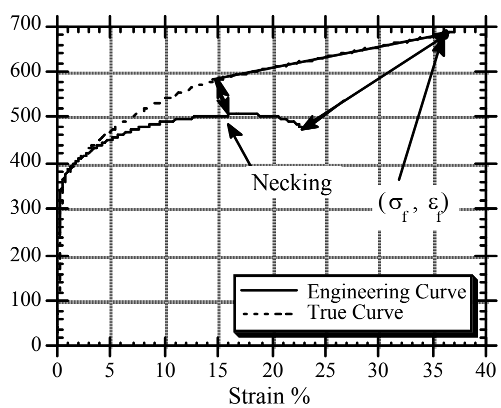

Figure 5 True and Engineering stress strain curves for an aluminum alloy

Figure 5 shows the difference between true and engineering stress-strain for a typical aluminum alloy. Note that when using an axial extensometer, only one data point, the final fracture, can be determined after necking. This point consists of the failure load and final diameter from which σ_f and ε_f are calculated. The solid portion of the true stress-strain curve in Fig. 5 illustrates the typical smooth transition constructed between necking and this point.

For the most part, in designing engineering structures and machines it makes little difference whether engineering or true stress-strain quantities are used. This is because we generally design in the elastic region with relatively stiff materials. Forging, extrusion, and stamping operations for metals are some cases where it may be important to use true stress-strain definitions. Additionally, for many polymeric materials the stiffness is markedly lower, which means the knowledge of whether true or engineering quantities are being used is significant.

2024-T4 Aluminum

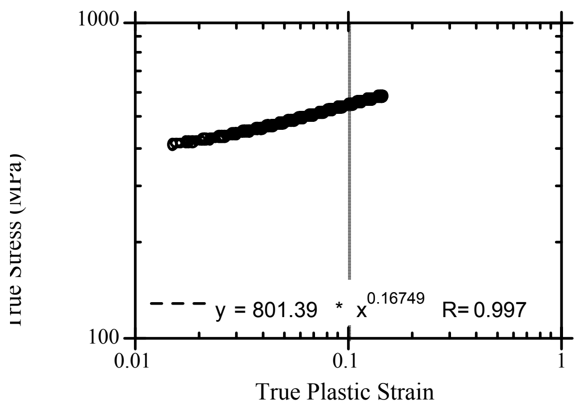

Figure 6 The use of log-log paper to determine Ramberg-Osgood constants

Just as the familiar elastic modulus is used to relate stress and strain in the linear elastic region (Eq. 4), it may be desirable to have a similar relation for plastic strains. The Ramberg-Osgood relation is the most common format used:

$$\sigma_t = K\left(\varepsilon_t^P\right)^n \tag{12}$$

True stress and true plastic strain plotted on log-log coordinates should result in a linear relation for the data if Eq. 12 is valid. This construction is shown in Fig. 6.

Common sense must be used when reporting material properties. Not all materials will exhibit every property listed in Tables 1 and 2. For example, consider a material that fails during the linear elastic portion of a test. It is not appropriate to report any yield related quantities such as proportional limit, yield strength, or percent elongation; however, an ultimate strength does exist.

Some properties, such as upper and lower yield strength, are unique to a specific group of metals (low carbon steels) and have no meaning for other materials. If there is limited plastic deformation, the constants n and K cannot be determined. Although many materials have a designation based on chemistry, processing variables such as hot or cold rolling can affect the material properties. Heat treatment can also significantly alter material properties as shown in Figure 7 for 1018 steel.

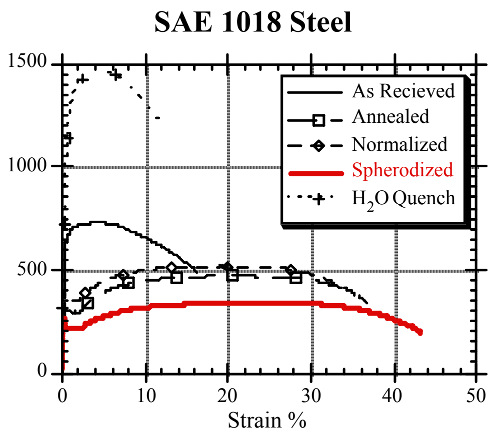

Figure 7 Typical data for 1018 steel.

To obtain meaningful monotonic tensile properties for design purposes, care must be taken to insure that the material being tested indeed represents the material to be used in real structures. Small scale test specimens are often machined from components that contain a variety of manufacturing defects. Material properties for specimens that fail due to "abnormal" gross defects such as porosity, blow holes, quench cracks, and so on should be reported. The question becomes whether these defects are typical of the structure the data are intended to represent. Care should be exercised when interpreting any experimental data.

2.2.3 Bridgman necking correction

In tension tests the neck causes a triaxial state of stress in the critical location of the specimen. Bridgman[1] mathematically analyzed the specimen geometry shown in Fig. 4, assuming the following:

1) The contour of the neck can be approximated by a circular arc.
2) The cross section remains circular.
3) A von Mises criterion applies for yielding.
4) Strains are constant over the cross section of the notch.

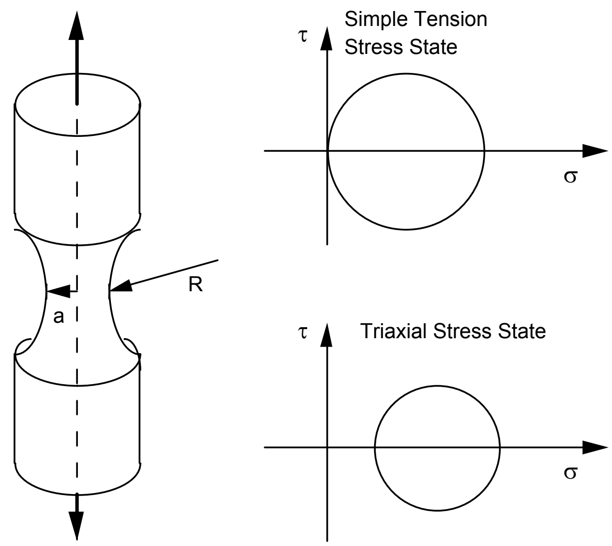

Figure 8 Necked specimen approximation

The mathematical representation of this is:

$$\frac{\sigma}{\sigma_{av}} = \frac{1}{\left(1+\frac{2R}{a}\right)\left(\ln\left(1+\frac{a}{2R}\right)\right)} \qquad (13)$$

where σ_{av} is the average axial stress (P/A_i), calculated ignoring the effect of the notch, and σ is the true deviatoric axial stress at the notch.

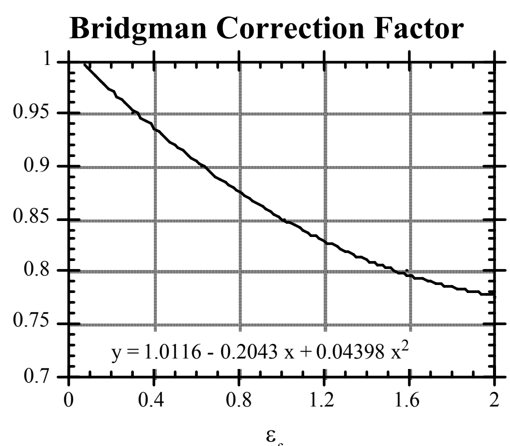

Figure 9 Bridgman necking correction factor

In Fig. 8, Mohr's circle of stress is shown for both simple tension and a triaxial stress state. Shear stresses are assumed to dictate plastic deformation in metals. The radii of the Mohr's circles here are indicative of the shear stresses.

[1]Bridgman, P.W., Trans ASM, Vol.32, p. 553, 1944.

For a given longitudinal stress, simple tensile loading results in a larger diameter circle.

When relating the triaxial state of stress at the necked region to simple tension, a reduction in experimental fracture strength, σ_f, is implied. Bridgman measured the specimen dimensions for steels exhibiting a variety of true fracture strains, ε_f, and noted the relationship indicated in Fig. 5. A second order polynomial has been fit to this data by the author to ease calculations.

The important point is: the uniaxial strength in a specimen that displays necking has been modified with regard to a *shear* criterion.

2.3 Equipment and Materials

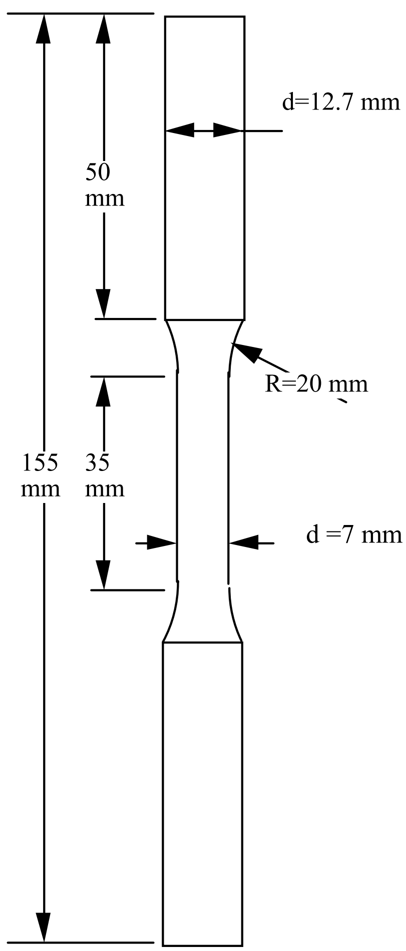

Figure 10 Cylindrical tensile test specimen

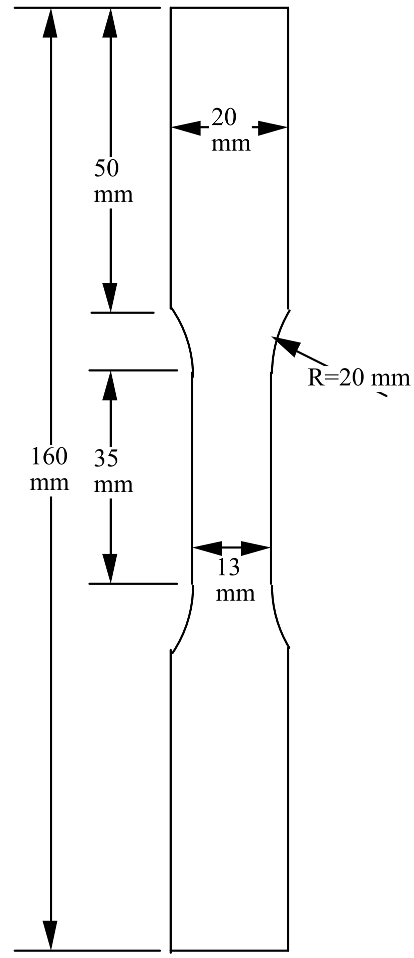

Figure 11 Plate specimen dimensions

ASTM[2] has published several guides to material testing methods, including E6-81, Definition of terms relating to Methods of Mechanical Testing; E8-81, Tension Testing of Metallic Materials; D3039-76, Standard Test Method for Tensile Properties of Fiber-Resin Composites; and many others. For the most part E8-81 will be used as a basis for this laboratory, even though some nonmetals will be tested.

The uniaxial tension tests for all the materials will be performed on the 100 kN screw driven testing machines. Please refer to Appendix I and II for a summary of the LabView software and an overview of the test machine. Serrated wedge-type grips will be used to grip both the cylindrical and plate type samples (Figs. 10 and 11).

[2]Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA.

Specimen deformations will be measured with a 25.4 mm gage length extensometer. Load, strain and crosshead displacement data will be recorded by the computerized data acquisition system. Loading rates of 1.0 to 5.0 mm / min are typical for tensile tests.

Materials that may be tested are from these general categories:

1) Low Carbon Steel: 1045 hot rolled steel is a common structural steel which contains approximately 0.45 wt. % carbon. It is easily welded and has some heat treatability options that will be the topic of a subsequent laboratory. Cold rolled 1018 steel has 0.18 wt. % carbon. The low carbon limits some heat treatment options. Cylindrical samples (Fig. 10) will be used for these tests. Cold rolling involves prior plastic deformation and strain hardening at lower temperatures.

2) Aluminum Alloys: 6061-T6 aluminum is a common grade of aluminum with excellent formability, good weldability, and corrosion resistance. Pontoon boats, outdoor furniture, and bridge railings are some common applications for this material. An aircraft alloy, 7075-T6 aluminum, with a strength of more than 500 MPa. Again, cylindrical samples (Fig. 10) will be used for these tests. Another alloy, 2024-T4, has additions of copper. All alloys considered have been precipitation hardened.

3) Stainless steel - Additions of chromium and nickel to an iron matrix results in improved corrosion resistance. 304 stainless steel has 17 to 21 % chrome and 8 to 12 % nickel with low carbon content. Again, cylindrical samples (Fig. 10) will be used for these tests.

4) Plastics: PMMA (polymethylmethacrylate) is a common polymeric material used as a replacement for glass. Polyethylene or polypropylene are both opaque polymers. All polymers considered will be thermoplastic. A plate specimen (Fig. 11) will be used for this sample.

5) Cast Iron: Gray cast iron is used for engine blocks and many other ground vehicle castings typically contain about 3.25 wt. % carbon and 2 wt. % silicon. Much of the carbon is in the form of graphite flakes. Nodular or ductile cast iron has a similar carbon content, but a rounded geometry for the graphite particles. Cylindrical samples (Fig. 10) will be used for these tests as well.

6) Brass: A general category of copper-zinc alloys that possess qualities such as corrosion resistance (boat hardware), wear resistance (bushings), and ease of machinability. Strength is usually lower than stainless steel, especially at elevated temperatures.

2.4 Experimental Procedure

1) Obtain a Rockwell hardness for all metal specimens. Use the grip section and record the data in Table 3, and the class computer.

2) Using digital calipers, measure the diameter of each cylindrical specimen or width and thickness of the plate specimen. Take the average of three measurements for each sample to calculate the initial area. Table 3 is provided to record these and other data.

3) You will collect complete load, strain and crosshead deflection data, which will be stored in a text data file (see Appendix A for file structure). Consult you TA for details on how the data will be accessed.

4) Insert the specimen into the load frame and attach the extensometer.

5) Start computer data acquisition/control (see Appendix A) and load each specimen at a rate of 5 mm / min for the "ductile" metals and 1 mm /min for the PMMA or cast iron. Carefully observe the output data and specimen for signs of necking. Continue loading and observing the load output to monitor the final failure load.

6) After fracture measure the final fracture surface dimensions so that a final area can be computed. Remember to input this value into the computer program.

7) Note the appearance of the fracture surface. A Stereo microscope may be provided to highlight certain details.

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Table 3
Tension Test Data

Measurement or Property			**Material**				
Quantity	*Symbol*	*Units*					
Specimen and Fixture Dimensions							
Cross Section Shape	—	—					
Rockwell Hardness							
Initial Diam. or Width	d_o or W_o						
Initial Diam. or Width	d_o or W_o						
Initial Diam. or Width	d_o or W_o						
Initial Thickness	t						
Initial Thickness	t						
Initial Thickness	t						
Final Diam. or Width	d_f or W_f						
Final Thickness	t_f						
Gage Length	L						
Crosshead Loading Rate	$d\delta/dt$						
Calculated Property							
Initial Area	A_o						
Final Area	A_f						
Experimental Quantities							
Proportional Limit	P_y						
Offset yield Load	$P_{0.2\%y}$						
Maximum Load	P_{max}						

DATA FILENAME							

CLASS HARDNESS DATA FILENAME:________________________

Notes and sketches:

Table 4
Tensile Material Properties

Property			**Material**				
Quantity	*Symbol*	*Units*					
Elastic Modulus	E						
Yield Strength	σ_y						
Offset Yield Strength	$\sigma_{y.2\%}$						
Ultimate Strength	σ_u						
Fracture Stress	σ_f						
Fracture Strain	ε_f						
% Reduction in Area	% RA						
% Elongation	% EL						
Strain Hardening Coefficient	K						
Strain Hardening Exponent	n						

Notes and sketches: