

## Objective

The primary objective of this investigation is to conduct a standard tensile test for determining the stress-strain behavior of a material sample (mild steel or aluminum) and to analyze the results of the tensile test to find the mechanical/material properties of the sample.

## Abstract

The mechanical properties of a material are directly related to the response of the material when it's subjected to mechanical stresses. Since characteristic phenomena or behavior occur at discrete engineering stress and strain levels, the basic mechanical properties of a material are found by determining the stresses and corresponding strains for various critical occurrences. A wealth of information about a material's mechanical behavior can be determined by conducting a simple tensile test in which a cylindrical or flat specimen of uniform cross-section is pulled until it ruptures or fractures into separate pieces. The original cross sectional area,  $A_0$ , and gage length,  $l_0$ , are measured prior to conducting the test and the applied load and gage displacement are continuously measured throughout the test using computer-based data acquisition. Based on the initial geometry of the sample, the engineering stress-strain behavior (stress-strain curve) can be easily generated from which numerous mechanical properties, such as yield strength and elastic modulus, can be determined. Universal testing machines, which can be hydraulic or screw based, are generally utilized to apply the test displacement/load in a continuously increasing (ramp) manner according to ASTM specifications.

## Background

The mechanical properties of a material are related its' behavior when subjected to continuously increasing elongations up to rupture/fracture. A thorough understanding of a material's mechanical properties is required for engineers if catastrophic failures are to be avoided. The Tensile Test is a common standard test and is a valuable method of determining important mechanical properties of engineering materials. The procedural details of the test vary for different material types, but tensile tests are generally conducted at room temperature at relatively slow loading rates although various temperatures and loading rates may be required for the determination of material behavior under specific conditions.

The output of a standard tensile test is load versus displacement data. Since load-displacement characteristics are dependent on specimen size, for example it will require twice the load to produce the same elongation if the cross-sectional area of the specimen is doubled, load-displacement data is routinely converted to engineering stress-strain data. For axial loading, Engineering Stress,  $\sigma$ , is defined by the well known relationship

$$\sigma = \frac{P}{A_0} \quad (1)$$

where  $P$  is the Instantaneous Load applied perpendicular to the specimen cross section, in units of pounds force (lb<sub>f</sub>) or Newton's (N), and  $A_0$  is the Original Cross-Sectional Area of the specimen before any load is applied (in<sup>2</sup> or m<sup>2</sup>). The units of stress are generally kips per square inch (ksi) or megapascals (MPa). Engineering Strain,  $\epsilon$ , along the loading axis of an uniaxially loaded sample is defined according to

$$\epsilon = \frac{l_1 - l_0}{l_0} = \frac{\Delta l}{l_0} \quad (2)$$

in which  $l_1$  is the original length before any load is applied and  $l_0$  is the instantaneous length. Engineering strain is unitless, but inches per inch or meters per meter are often used; the value of strain is clearly independent of the units system applied! Strain may also be expressed as a percentage, in which case the strain value is simply multiplied by 100.

In Tensile Testing, the test specimen is deformed, usually until complete rupture or fracture occurs, with a gradually applied increasing tensile load that is applied uniaxially along the longitudinal axis of the specimen. Normally the test specimen is circular, but rectangular specimens can also be used. Each specimen is of a

specific shape and dimensions that should be in accordance with ASTM (American Society for Testing and Materials) specifications for standardization. During testing, deformation is confined to the narrow center region which has a uniform cross section along its length.

## Definitions

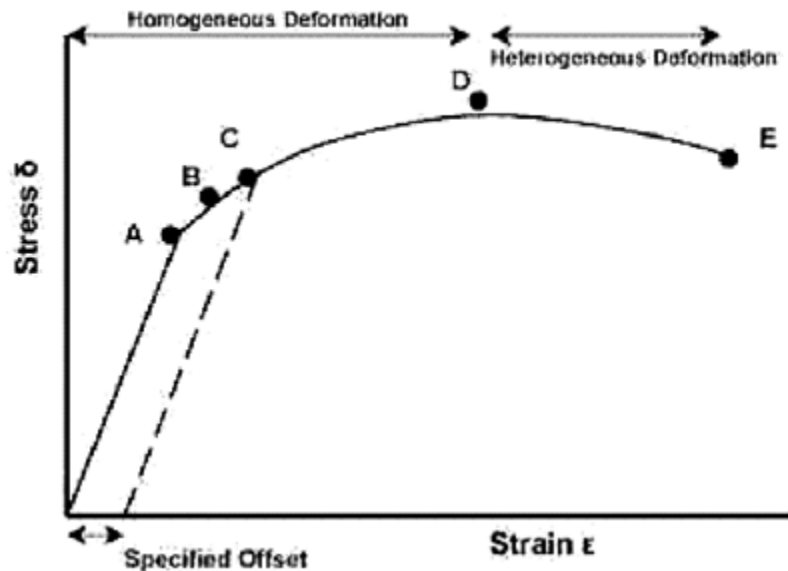


Figure 1 - Typical Ductile Material Stress-Strain Diagram. [Flinn & Trojan, 1992]

1. **Proportional Limit ( $S_{PL}$ )** - The Proportional Limit is the maximum stress at which stress and strain remain directly proportional. The proportional limit is determined from the stress-strain diagram by drawing a straight-line tangent to the curve at the origin and noting the first deviation of the curve from linearity. Because the proportional limit depends on the precision of the measurement instrument it is not widely used in engineering calculations.
2. **Elastic Limit ( $S_{EL}$ )** - The Elastic Limit is the maximum stress that the material can withstand without causing permanent deformation. An exact determination of the elastic limit requires loading to successively higher stresses followed by unloading and measurements to detect permanent deformation. Its actual value is, like the proportional limit, dependent on instrument precision. Due to this and the difficulty in its determination, its' engineering usefulness is limited.
3. **Yield Strength ( $S_{YS}$ )** - The Yield Strength is the stress at which a material exhibits a specified limiting permanent set. Below the elastic limit, the stress-strain relationship in loading and unloading are identical for practical purposes. Therefore, it is not necessary to unload a specimen in order to determine the yield strength. Rather, a line parallel to the initial straight-line portion of the curve is constructed. The construction line is displaced from the origin of the curve by an amount equal to the specified permanent set. The stress at the intersection of the parallel line with the stress-strain curve is the yield strength. The offset most commonly used is 0.2% strain or 0.002 in/in or mm/mm. The yield strength is a practical measure of the limit of elastic action. It is always greater than the elastic limit and is only minimally sensitive to measurement instrument precision.
4. **Ultimate or Tensile Strength ( $S_{UL}$ )** - The Ultimate Strength, also referred to as the Tensile Strength, is calculated by dividing the maximum load sustained by the specimen by the original cross-sectional area of the specimen.
5. **Fracture or Rupture Strength ( $S_{RU}$ )** - The Rupture Strength (ductile behavior), also referred to as the Fracture Strength (brittle behavior), is determined by dividing the load sustained at rupture by the original cross-sectional area of the specimen. This load will be less than the maximum load because the cross section of the specimen is reduced drastically after the maximum load is reached. The reduction of cross-section produced has an "Hour-Glass" shape and is known as Necking or Necking Down.

6. **Modulus of Elasticity (E)** - The Modulus of Elasticity is a measure of material stiffness and is termed Young's Modulus for tensile loading. The Modulus of Elasticity, E, is the constant of proportionality between stress,  $\sigma$ , and strain,  $\epsilon$ , at stresses below the proportional limit:

$$E = \sigma/\epsilon \quad (3)$$

The Modulus of Elasticity is found by measuring the slope of the straight-line portion of the stress-strain curve:

$$E = \frac{(\sigma_1 - \sigma_2)}{(\epsilon_1 - \epsilon_2)} \quad (4)$$

7. **Modulus of Toughness ( $U_T$ )** - The Toughness of a material refers to the ability of the material to absorb energy up to the point of rupture. The Modulus of Toughness is determined by measuring the area under the stress-strain curve. This is not an exact indication of toughness because the specimen does not strain uniformly over its length, and hence does not absorb energy uniformly throughout its volume. The units of toughness are determined by multiplying stress by strain.
8. **Modulus of Resilience ( $U_R$ )** - The Resilience of a material refers to the amount of elastic energy, which a material can absorb. The Modulus of Resilience is determined by measuring the area under the elastic portion of the stress-strain curve or by the expression:

$$U_R = \frac{1}{2} \frac{S_{PL}^2}{E} \quad (5)$$

9. **Percent Elongation (%EL)** - The Percent Elongation refers to the elongation at rupture and can be expressed as:

$$\%EL = 100 \left( \frac{\Delta l}{l_o} \right) \quad (6)$$

Where  $\Delta l_i$  represents total elongation and equals  $= l_f - l_o$ .

10. **Percent Reduction in Area (%RA)** - The Reduction in Area refers to the reduction in cross-sectional area at rupture and can be expressed as:

$$\%RA = 100 \left( \frac{\Delta A_f}{A_o} \right) \quad (7)$$

Where  $\Delta A_f$  represents total reduction in area;  $\Delta A_f = A_o - A_f$ .

11. **Ductility** - The Ductility of a material refers to the ability of a material to deform plastically before fracturing. Ductility is usually evaluated by considering values of Percent Elongation or Reduction in Area.

12. **True Strain\* ( $\epsilon_{TR}$ )** - True Strain is the change in length divided by the Instantaneous Length and can be simply determined as:

$$\epsilon_{TR} = \ln (\epsilon_{ENG} + 1) \quad (8)$$

13. **True Stress\* ( $\sigma_{TR}$ )** - True Stress is the applied load divided by the Instantaneous cross-sectional Area and can be simply determined as:

$$\sigma_{TR} = \sigma_{ENG} (\epsilon_{ENG} + 1) \quad (9)$$

\*True Strain & True Stress should be applied when  $S_{ys}$  of a material is exceeded.

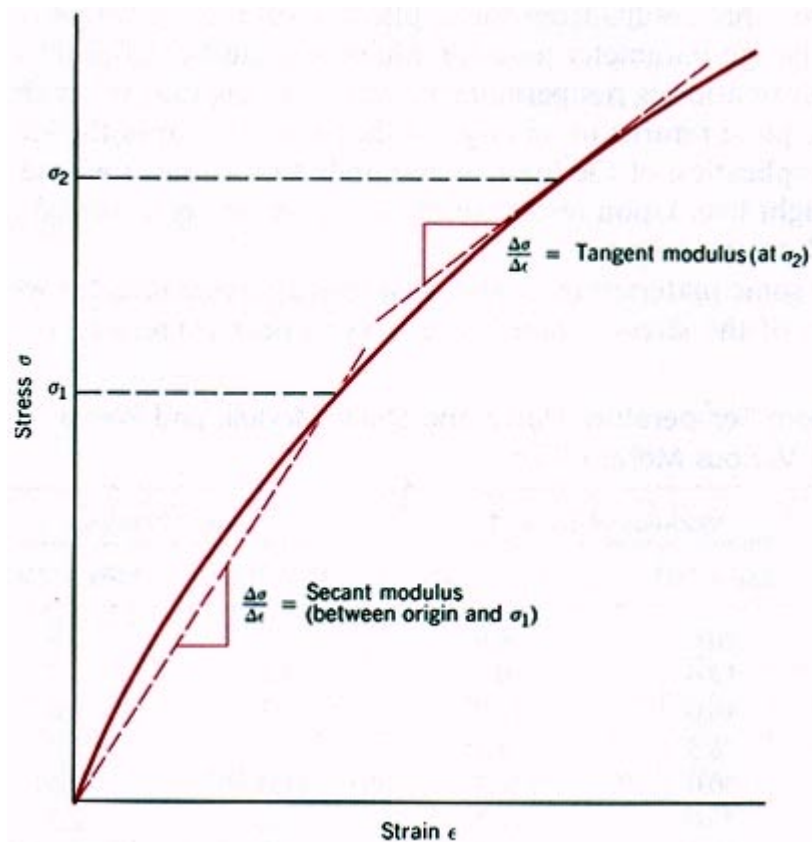


Figure 2 - Schematic stress-strain curve illustrating the determination of the tangent and secant moduli. [Callister, 1991]

For some materials (e.g., concrete, gray cast iron) the initial elastic portion of the stress-strain curve is non-linear as depicted in Figure 2 where it is impractical to determine a standard modulus of elasticity. Furthermore, the modulus of elasticity is restricted to the initial linear portion of a standard stress-strain diagram and is invalid beyond this region. For non-linear behavior, either the Tangent or Secant Modulus is generally utilized.

14. **Tangent Modulus ( $E_T$ )** - The Tangent Modulus is taken as the slope of the stress-strain curve at a specified stress level.
15. **Secant Modulus ( $E_s$ )** The Secant Modulus represents the slope of a secant drawn from the origin to a point at a specified stress level of the stress-strain curve.
16. **Strain Hardening** - Following yielding, additional load may be applied which results in a stress-strain curve that continuously rises up to  $S_{UL}$  indicating that the material is becoming stronger. When loaded beyond the yield point, ductile materials plastically deform and are subjected to cold working; this is referred to as Strain Hardening. In this range, the material's elastic region increases, but its' ductility decreases.

Strain hardening is generally modeled using the expression

$$\sigma_{TR} = N (\epsilon_{TR})^n \quad (10)$$

Where  $N$  is the Strength Constant, and  
 $n$  is the Strain Hardening Coefficient.

Taking the logarithm of both sides:

$$\ln(\sigma_{TR}) = n[\ln(\epsilon_{TR})] + \ln(N) \quad (11)$$

Note that this is the equation of a straight line! A simple  $\ln(\sigma_{TR})$  versus  $\ln(\epsilon_{TR})$  should result in a straight line with a slope  $n$  (strain hardening exponent). The strength constant from the plastic region data is equivalent to the elastic modulus for the elastic region and has similar units.

Alternatively, given the true stress and strain values for two data points within the plastic region of stress-strain curve, the values can be plugged into Equation 11 generating two equations that can be solved simultaneously for the Strength Constant ( $N$ ) and the Strain Hardening Coefficient ( $n$ ).

### Example

Representative True Stress and True Strain values for low-carbon steel are given below. Determine the Strength Constant and Strain Hardening Coefficient for this material:

$$\sigma_{TR1} = 47,150 \text{ psi}, \epsilon_{TR1} = 0.0247 \text{ in/in}$$

$$\sigma_{TR2} = 67,100 \text{ psi}, \epsilon_{TR2} = 0.0953 \text{ in/in}$$

$$\text{Ans: } n = 0.2613, N = 124,000$$

17. **Necking** - When a specimen is loaded beyond its' ultimate strength the cross-sectional area begins to decrease in a localized region instead of over its' entire length creating a so-called "neck" which rapidly forms in this region as the specimen elongates. Since the cross-sectional area within this region is continually decreasing, the localized stress rapidly increases causing further localized elongation up to rupture.

## Testing Equipment

In Tensile Testing, loads are generally applied either mechanically with screw drives or hydraulically with pressurized oil in one of the two types of readily available Universal Testing Machines. The mechanical method of applying loads has the advantage of providing a convenient means of accurately controlling the rate of deformation. The hydraulic systems are generally preferred because of their higher load capacities and lower cost; furthermore, the hydraulic systems have been significantly improved with the introduction of digital control loops thus the accuracy of hydraulic systems are no longer vastly inferior to the mechanical systems. The general term which encompasses both machine types is "Universal Testing Machine"; the term is used because the machine can be adapted to test in tension, compression, flexure and bending.

The *50 Kip Capacity Instron* machine available for tensile testing at the mechanical engineering department at LSU is a servohydraulic system where the load is applied by a hydraulic pump which controls the flow of oil into a cylinder thereby controlling the position of the piston within the cylinder. The cross-head can be moved between tests to accommodate specimens of various size, but the cross-head and table are fixed during testing. The machine is digitally controlled and can be operated in the Load, Position or Strain mode. Load, Position and/or Strain can all be simultaneously monitored by the system regardless of the control mode. A data acquisition system has been connected to the Instron controllers and readouts of Load from the Load Cell and Deflection (Strain) from the Extensometer can be continuously sampled during testing. The test specimen is held in grips which are attached to the cross-head and piston. The oil in the cylinder is controlled by means of coarse and fine - load and unload valves. In Tensile Testing, proper grip alignment eliminates bending loads and assures that the specimen is subjected to axial loads only. If bending loads are exerted on the test specimen then stresses will not be uniform across the thickness.

A Load Cell is a device based on a strain-gaged beam with a mounted wheatstone bridge. The load signals are actually strain readings calibrated to appropriate loading levels. The LSU-ME Instron is capable of loads up to 50,000 pounds. Extensometers are devices that specifically measure deflection. Extensometers are also strain-gauge based and electronically transmit strain-gauge output which is calibrated based on deflection. During Tensile Testing, the Load Cell and mounted Extensometer will send analog electronic signals to the Instron control tower; both of these can be routinely sampled by the data acquisition system and loaded into a spreadsheet file. The data can be retrieved, converted to stress versus strain data, and the resulting stress-strain diagram can be easily generated. Various material properties can then be determined utilizing the resulting stress-strain diagram.

## Apparatus



8500 Series *Instron* Servohydraulic Universal Testing Machine - 50,000 Pound Capacity



Load Cell



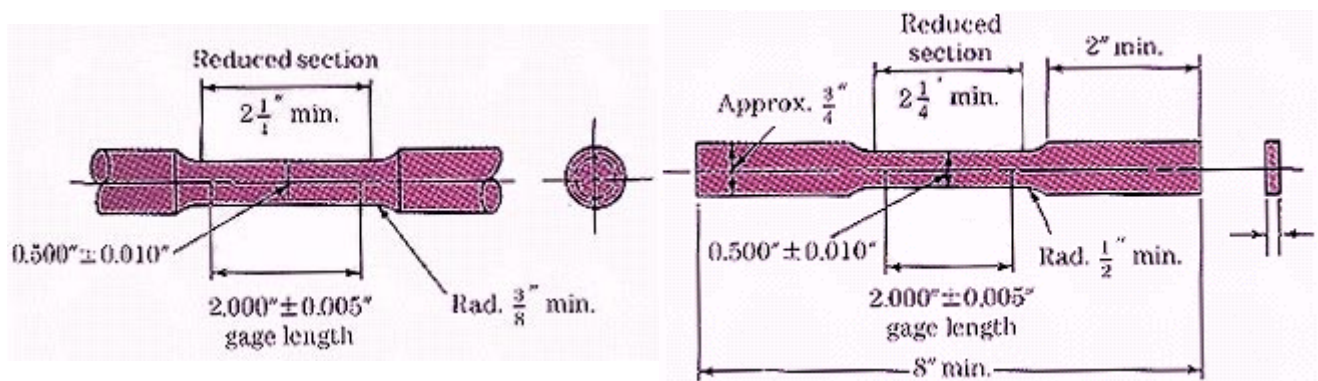
0.1" Range, 0.5" Gage Length Strain Gage Extensometer, Instron Model 2620-826

0 - 1" Micrometer

8500 Series *Instron* Servohydraulic Universal Testing Machine - 50,000 Pound Capacity

0.1" Range, 0.5" Gage Length Strain Gage Extensometer, Instron Model 2620-826

## Test Specimen



ASTM E8M Standard Specimen

*Ref: figure 5.21 (a), (b), Pg. 203, Foundations of Materials Science and Engineering*

## Lab Procedure

**Note: The following procedure addresses only running the Instron servohydraulic testing machine and does not address data acquisition.**

1. Measure and record the initial dimensions of the tensile test specimen; also record the gage length of the extensometer.
2. Conduct a preliminary check of the Instron machine: water valve should be open and all hydraulic lines should be secure and free of leaks.
3. Turn on the Instron Electronics (electronics only). Monitor the electronic control panel; system will run an initialization and self-test.

4. Conduct Calibrations for the Load and Strain Controllers:

Load: Check that no load is being applied to the Load Cell then Press Set-Up on the Load Controller, Select Cal., Select Cal., Select Auto, Select GO. Green light next to Load Set-Up will flash quickly until the calibration is complete.

Strain: Install the pin in the Extensometer, which places the Extensometer at its zero position.

Press Set-Up on the Strain Controller, Select Cal., Select Cal., Select Auto, Select GO. Green light next to Strain Set-Up will flash quickly until the calibration is complete.

5. Set Limits (to protect the Equipment and the Users):

### **Position Controller:**

Press Limits Max., Set Value, Set Action to Stop, Select ON (Light will come on).

Press Limits Min., Set Value, Set Action to Stop, Select ON (Light will come on).

### **Load Controller:**

Press Limits Max., Set Value, Set Action to Stop, Select ON (Light will come on).

Press Limits Min., Set Value, Set Action to Stop, Select ON (Light will come on).

6. Set Displays:



Choose Display 1 for Load Controller (Display 1 will show applied Load).

Choose Display 2 for Strain Controller (Display 2 will show Extensometer Displacement).

7. Set Waveform (for Position Controller!):

Press Waveform on Position Controller. Select Ramps Loading, Select S-Ramp, Set Max. Position, Set Rate.

8. Turn on Instron Hydraulics: Press Hydraulics Button (Check that pump output is 3000 psi).

9. Turn on Instron Actuator: Press Actuator Stand-By, Press Actuator Low, Press Actuator High.

10. Install Test Specimen:

Using Manual Control, set the grips at a convenient position for loading the specimen. Clamp the Specimen tightly into position. In Position Control, press "Set Point" on lower Instron control panel and adjust the position so that the load is 0 kN. Be Careful; make sure that you're in Position Control, not Load Control!

11. Install the Extensometer:

Securely attach the Extensometer, with a Gage Length extender installed if available, to the specimen within the gage length region using springs or rubber bands (reset limits if necessary). Expansion of the extensometer range can be achieved by compressing the arms and recalibrating the strain controller in the initial installed position.

12. If one of the Limits is accidentally tripped:

Select "Function" on the lower panel of the Instron terminal. Press the button below "Stop-Active"; should change to "Stop-Reset". Press the Flashing Limit button on the Strain Controller (red light will flash if tripped).

Press the button below "on/off" on the lower panel (red light should go off). Press the button below "on/off" on the lower panel (red light should come on).

13. Record the Initial Strain and Load values.

14. Start the Test by Pressing START on the Instron Control Panel.

15. Monitor the Load and Strain data output; when the strain rate increases significantly, the yield strength has been exceeded.

16. After Specimen Rupture occurs: A limit will be tripped and the Instron will stop.

18. Carefully remove the Extensometer and the Test Specimen.

19. Measure the Final Dimensions of the Test Specimen: Width and Thickness near Rupture.

20. To Quit Testing, Select Actuator Low, Select Actuator Stand-By, Select Hydraulics OFF.

## Lab Requirements

Each lab section will be given a standard cylindrical tensile test specimen composed of either a mild steel or a low-grade aluminum alloy.

1. Determine and document the following: both the original and final dimensions of the test specimen, the gage length of the extensometer, the loading rate, the Date, the Time, the person(s) who collected the data and a reference to the filename and filetype under which the data is stored. The data itself does not need to be presented, but a listing of the parameters with data contained in the computer file should be included.
2. Conduct a standard tensile test collecting Load, Displacement and Strain (Extensometer) data; make sure that the file into which the data is stored in is unique and be careful not to overwrite the previous test's data file. Each student needs to obtain a disk-copy of the data file.

3. Prior to leaving the lab session:
  - a. Measure and record the final dimensions of the test specimen focusing on the final diameter at the constricted rupture.
  - b. Visually examine the fracture surfaces of the specimen and briefly describe the salient features.
  
4. Open the data file in a graphing or spreadsheet program (Deltagraph, Kaliedagraph, Excel, Lotus 123, etc.) checking that the Load, Displacement and Strain (Extensometer) data columns are intact. Then, develop the following columns in addition to the data columns (Note: when the Extensometer data reaches the instrument's limit, switch over to the Displacement data for computing Engineering Strain):
  - Engineering Stress
  - Engineering Strain
  - True Stress
  - True Strain
  
5. Develop and present the following Plots:
  - Load versus Displacement for the entire displacement range.
  - Engineering Stress versus Engineering Strain for strain values from 0 to 0.006.
  - Engineering Stress versus Engineering Strain for the entire strain range tested.
  - True Stress versus True Strain for the entire strain range tested.
  
6. Determine the following for the specimen tested noting the proper units for each: 0.2% Offset Yield Strength, Ultimate Strength, Rupture Strength, Modulus of Elasticity, Modulus of Toughness, Modulus of Resilience, Percent Elongation, Percent Reduction in Area, Tangent Modulus at  $\sigma = 250$  MPa and the Secant Modulus at  $\sigma = 250$  MPa.
  
7. Based on two suitable data points well separated from each other in the plastic region, calculate the Strength Constant and Strain Hardening Coefficient for the tested material.
  
8. The usual dividing line between ductile and brittle behavior is about 5 percent elongation. Materials having less than 5 percent elongation at rupture are said to be brittle. Was the test specimen brittle or ductile according to this definition? Did the sample exhibit strain-hardening behavior? Did you observe necking of the sample? Briefly explain and describe.
  
9. Briefly comment on the values obtained for the Elastic Modulus, Yield Strength, Ultimate Strength and Toughness of the test specimen as compared to values of various comparable materials found in the literature. Is the test material comparatively strong? Is it stiff? Is it tough?
  
10. Briefly discuss the differences between the Engineering Stress versus Engineering Strain and the True Stress versus True Strain Diagrams for the test specimen. Briefly explain why the two plots are different. When is the use of Engineering Stress versus Engineering Strain invalid?

## Homework

1. Briefly explain how the 0.2% Offset Yield Strength is determined.
2. Why is Yield Strength generally used as a practical measure of the limit of elastic action?
3. Sketch the expected tensile stress versus strain curves for the following:
  - a. A ductile metal with significant plastic deformation prior to rupture.
  - b. A high-strength metal with minimal ductility.
  - c. A glass sample.
4. What is the difference between Engineering Stress and True Stress?
5. What is the difference between Toughness and Resilience?

6. When are the Tangent and/or Secant Modulus generally used?
7. What is Strain Hardening and why do ductile materials Strain Harden?
8. Why is Load versus Displacement data generally converted to Stress versus Strain data?
9. What problems do you foresee if a Universal Testing Machine is misaligned when a Tensile Test is conducted?
10. Briefly describe the physical phenomenon that generally occurs when a ductile tensile test sample reaches its' ultimate strength.