PLASTIC DEFORMATION

AND

STRESS-STRAIN CURVES

Background Unit: Plastic Deformation and Stress-Strain Curves

Introduction

      In the last unit we studied the elastic response of materials to externally applied loads. All the loads applied were well below the elastic limit of the materials so no permanent deformation occurred in the sample.
      In this unit we will continue our study of the effects of externally applied forces and will apply loads large enough to cause permanent deformation and eventually fracture .

Objectives

After studying this unit and completing the lab assignment you should be able to perform the following tasks:

1. Write definitions for the following terms, including SI and English units when appropriate.
   a. Pascal
   b. offset yield strength
   c. ultimate tensile strength
   d. plastic strain
   e. hardness
2. Given specific dimensions and load-elongation data from a metal tensile test, calculate stresses and strains, plot an appropriate stress-strain curve, and determine the yield strength (by the 0.2% offset method when appropriate or by the sudden change in slope of the stress-strain curve when appropriate), the elastic modulus, and the ultimate tensile strength.
3. Given the dimensions of a tensile test specimen before and after testing calculate the percent elongation and the percent reduction in area.
4. With the assistance of a classmate, run a tensile test on a metal sample obtaining load and elongation data.

Plastic Deformation

      After a material has reached its elastic limit, or yielded, further straining will result in permanent deformation. After yielding not all of the strain will be recovered when the load is removed. Plastic deformation is defined as permanent, non-recoverable deformation. Plastic deformation is not linear with applied stress.
      Recall if a material experiences only elastic deformation, when the stress is removed the elastic strain will be recovered. If a material is loaded beyond its yield point it experiences both elastic and plastic strain. After yielding the rate of straining is no longer linear as the applied stress increases. When the stress is removed, only the elastic strain is recovered; the plastic strain is permanent.
      Elastic deformation occurs as the interatomic bonds stretch, but the atoms retain their original nearest neighbors and they "spring back" to their original positions when the load is removed. Clearly in order to have permanent deformation there must be permanent movement in the interatomic structure of the material. Although some of the atoms move away from their original nearest neighbors not all of the interatomic bonds

are broken (this is evident because we can achieve permanent deformation without fracture of the material). The mechanism for permanent deformation is called slip. Slip occurs when planes of densely packed atoms slide over one another: individual bonds are broken and reformed with new atoms in a step-wise fashion until the desired deformation is achieved.

Stress-Strain Curves

Again we will use stress-strain curves to investigate the mechanical behavior of materials. Recall most of the properties aren't dependent on the specimen size, and the elastic modulus is the same whether we use a tensile test or a compression test to find it. Since

$$\text{strain} = \varepsilon = \frac{L - L_o}{L_o}$$

the strain will be positive for tensile testing. A tensile stress will also be positive and

$$\text{stress} = \sigma = \frac{F}{A_o}$$

And during the initial deformation of the material when the strain is elastic, the stress and strain are related linearly by the elastic modulus.

Stress-strain curves for metals come in several basic types (Fig. 1). The linear portion of the stress-strain curve indicates elastic, or recoverable, deformation. The non-linear portion indicates plastic deformation. Plastic strain is defined as permanent, non-recoverable deformation. Curve A is for a metal which broke while still showing linearly elastic behavior. Curve B is the most common type of stress-strain curve, i.e. a gradual deviation from linear behavior as plastic flow (yielding) begins. Curve C shows the behavior of some steels, i.e. a sudden deviation from elastic behavior at the yield point, a sharp, easily identified yield point. (The solid lines on the stress-strain curves indicate real data, the dashed lines indicate a "best guess" or interpolation between known data points.)
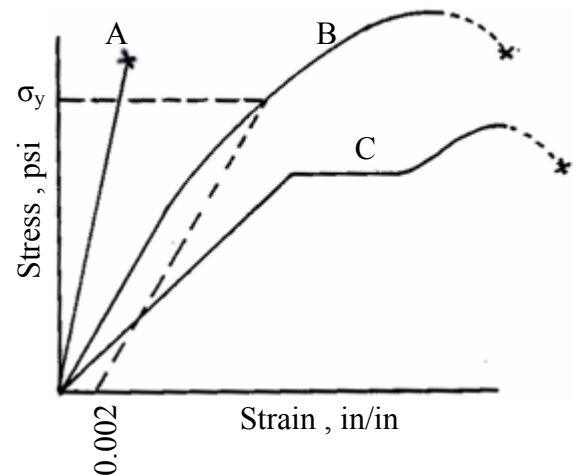

Figure 1

Recall that the elastic modulus is defined by the relation:

$$\sigma = E\varepsilon$$

so by rearranging this equation we can write:

$$E = \frac{\sigma}{\varepsilon}$$

This equation is valid only for the elastic portion of the curve, that is, the linear region of the stress-strain curve. We can easily calculate the elastic modulus of a material by calculating the slope of the straight-line portion of the stress- strain curve.

Regardless of how much total strain a specimen experiences the elastic strain is always recovered when the load is removed.

total strain = elastic strain + plastic strain

$$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{plastic}$$

The recovery (or "unload") curve that is produced when the load is removed from a specimen is parallel to E. The amount of strain recovered during the unloading process is the elastic strain; the amount of strain that remains in the specimen after unloading is the plastic strain (Fig. 2)

The yield strength, or yield point, is defined as the stress at onset of plastic deformation. The material used to generate curve A in Fig. 1 did not exhibit plastic deformation before rupture. Curve C in Fig. 1 shows an easily identifiable, sharp yield point. Materials showing behavior like that in curve B of Fig. 1 have a gradual onset of yielding though, so the yield point is arbitrarily defined as the stress at which an offset line, paralleling the linear part of the stress-strain curve, but starting from a strain offset of 0.002 (or 0.2%), intersects the stress strain curve. The offset yield strength is the stress associated with a small, allowable amount of permanent deformation; the 0.2% offset yield strength is the stress associated with 0.2% plastic strain.
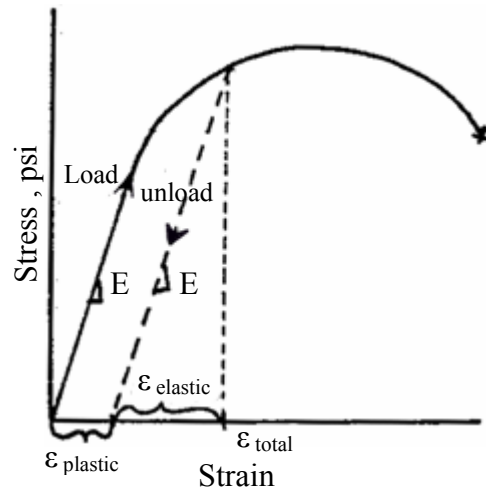

Figure 2

An important measurement that must be made when evaluating load- elongation data is the specimen gage length. The gage length is the length of the specimen over which the elongation is measured. With large amounts of deformation the strain will change if the gage length is changed.

Another important property determined from the stress-strain curve is the maximum stress reached. This is often called the ultimate tensile strength (σ_{UTS} or UTS) or sometimes just tensile strength. The UTS is calculated:

$$UTS = \frac{F_{max}}{A_o}$$

where: F_{max} = maximum applied load

            A_o = original cross-sectional area

The breaking strength is defined as the load at rupture (breaking) divided by the original cross-sectional area.

$$breaking\ strength = \frac{F_{break}}{A_o}$$

where: F_{break} = load at rupture

A stress-strain curve with the yield strength, ultimate tensile strength and breaking strength indicated is shown in Fig. 3.
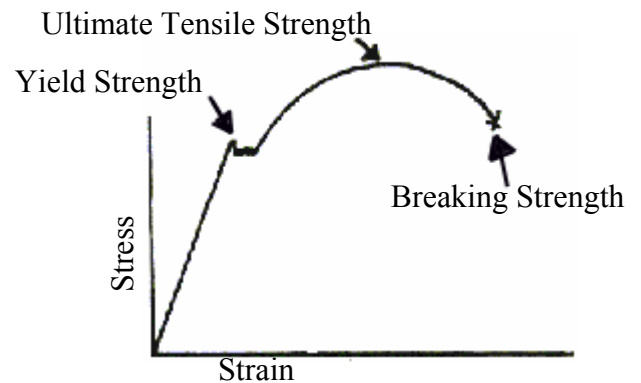

Figure 3

True Stress

The breaking strength is often less than the ultimate tensile strength and may even be less than the yield strength. That is sometimes troubling because it does not seem possible that it would require less energy to finally rupture the specimen than it does to cause the initial yielding. In fact the stress required to actually break the specimen is greater than any other stress the specimen experiences. Recall the stress-strain curves that we are constructing are based on the original specimen dimensions, but the specimen is actually changing dimensions as the test proceeds. After yielding, permanent deformation occurs and the specimen's cross-sectional area is decreasing. With further loading the deformation becomes exaggerated in a localized area and a "neck" forms in the specimen. After necking occurs the specimen experiences a much greater stress in the region of the neck, and the actual load required to cause an increase in stress decreases. The data in the region of the stress-strain curve beyond the UTS are meaningless because after necking the cross-sectional area is changing dramatically and the strain is localized in the necked region and is not occurring over the entire gage length. As the load decreases after the UTS the stress calculated using the original cross- sectional area (the engineering stress) also decreases and the stress-strain curve starts to fall with increasing strain; the true stress, the load divided by the actual cross-sectional area, continues to increase. We define the true stress for our specimen as the load divided by the smallest cross sectional area in the necked region. Clearly the stress varies with specimen dimension throughout the necked region but we define true stress with respect to the smallest area since that plane of the specimen experiences the largest stress.

At rupture the true breaking strength is:

$$\sigma_{\text{true break}} = \frac{F_{\text{break}}}{A_{\text{rupture}}}$$

where: A_{rupture} = specimen cross section at the smallest area of the necked region where the specimen broke

Hardness

Hardness is defined as resistance to penetration. A material's hardness can be measured by using a standard indenter with a standard load. There are several different systems with different types of indenters using different loads. Two common measures of hardness are the Rockwell and Brinell scales.

Rockwell hardness is measured by applying a particular load to an indenter, either a diamond brale (conical point) or a steel ball, and measuring the depth of penetration. A Rockwell hardness tester is used to apply the loaded indenter to the sample. The sample is locally permanently deformed by the indenter, and the Rockwell hardness number is related to the depth of that permanent indentation. The most common Rockwell scales are the "B" and "C" scales. The Rockwell B scale uses a 1/16th in. diameter steel ball indenter and a 100 kg load. The Rockwell C scale uses a diamond brale indenter and a 150 kg load. The hardness numbers are read directly from the hardness tester and are written as R_B_?_ or R_C_?_. These scales were arbitrarily determined, so the units are arbitrary also.

The Brinell hardness test is very similar to the Rockwell test but the indenter, a steel ball, is larger and the applied load is larger (1000 or 3000 kg) .The Brinell hardness number (BHN) of a sample is determined by measuring the diameter of the permanent indentation in the sample and comparing that to a BHN chart. The units of the BHN are kgf/mm^2, where kgf stands for kilogram as a force, as opposed to kg which is the symbol for kilogram as a mass.

Because hardness is a measure of how easily a material can be permanently deformed, we can correlate hardness with metal strength; in general, the harder the metal, the higher the ultimate tensile strength we expect for that specimen. Hardness- UTS conversion charts for steel have been prepared so that by measuring a steel specimen's hardness we can predict its UTS. (Appendix B)

Ductility

Two measures of metal ductility, percent elongation and percent reduction in area, can also be determined from the tensile test. The percent elongation is the overall fractional length increase as determined by measuring the sample length after testing:

$$\text{percent elongation} = \% \text{ El} = \frac{L_{br} - L_o}{L_o} \times 100\%$$

where: L_{br} = length between gage marks on the broken specimen

L_o = original length between gage marks

Just as with strain, the percent elongation is dependent upon the specimen's original gage length.

The percent reduction in area is the decrease in the cross-sectional area of the specimen as measured after testing.

$$\text{percent elongation} = \% \text{ R in A} = \frac{A_o - A_{br}}{A_o} \times 100 \%$$

where: A_{br} = cross-sectional area at break

A_o = original cross-sectional area

Bibliography

1. Wood Handbook. U.S. Department of Agriculture Handbook No.72, Government Printing Office (Washington, D.C.).
2. ASTM Standard D9, "Standard Definitions of Terms Relating to Timber."
3. ASTM Standard D143, "Standard Methods of Testing Small Clear Specimens of Timber."
4. ASTM Standard A370, "Mechanical Testing of Steel Products."
5. George E. Dieter, Jr., Mechanical Metallurgy, Ch. 9, "The Tension Test," McGraw-Hill Book Co., Inc., New York, 1961.

Acknowledgement

Laboratory Unit: Plastic Deformation and Stress-Strain Curves

In this unit you will learn to use the universal testing machines (UTMs) and mechanical extensometers to determine stress-strain curves in tension. The data obtained will be used to calculate all the usual quantities found when metal alloys are tensile tested.

Tensile Tests of Metal Alloys

The most important mechanical properties of metals and alloys are determined by the tensile test. A standard sample is tested by pulling on it until the sample breaks. The standard sample has a diameter of 0.505 in. (making the cross-sectional area 0.200 in^2) and a gage length of 2.000 in. Often load- elongation data are recorded only during the initial part of the test, however it is possible to generate an entire stress-strain curve utilizing a few more obtainable data points. The maximum load and breaking load reached during the test are also recorded so the ultimate tensile strength and breaking strength can be calculated. The gage length after breaking and the diameter at the break are also measured and recorded so the percent elongation and percent reduction in area can be calculated.

Materials and Equipment

1. Standard 0.505 in. diameter tensile test specimens (Fig. 4) of steel and aluminum.
Your steel specimen is in the "as-received" condition. There are a number of standard heat treatments applied to steel (you will study these later in this course) to change the strength and ductility. Annealing steel means heating it to a high temperature (= 1600 ^{o}F) , holding it for a short time, and allowing it to
furnace cool to a low temperature. This is a very slow cooling process and results in a very soft, ductile steel. Normalizing steel is similar to annealing it, but after the specimen is heated to the high temperature and held it is removed from the furnace for cooling. The specimen is not exposed to the room temperature air, but remains packed in a material that ensures a slow cooling rate. The normalized cooling rate is not as slow as the annealed cooling rate; a normalized specimen is cooled faster than an annealed one. Commercial practice often is to furnace cool the steel part of the way then allow it to air cool the rest of the way which results in material with properties between annealed and normalized. You should compare your experimental data to that set of literature values (annealed or normalized) that is closest to your data (Appendix C).
Your aluminum sample has also been heat treated. Your instructor will discuss the exact alloy and heat treatment and indicate which literature data should be used for comparison (Appendix C).

2. Universal testing machine set up for tensile testing.
3. Dial gage extensometer and electronic extensometer.
4. Steel rules, caliper, micrometer, gage mark jig, hammer, alcohol, paper towels.
5. Rockwell hardness tester.

Testing procedure

1. Measure the hardness of your steel specimen. Use the hardness-UTS conversion chart to predict the specimen's ultimate tensile strength.
2. Put 2 inch gage marks on the specimen. Check its diameter to see that it is within tolerance (0.500 ± 0.010 in.). From the predicted UTS determine the maximum load your specimen will tolerate.
3. Zero the machine by setting the machine to the low range and using the low range zero adjust to bring the UTM's large dial pointer to zero. Set the machine to the middle range and adjust the middle range zero; set the machine to the high range and adjust the high range zero. Return the range selector to the middle range. Set the follower pointer to zero.
4. The specimen is installed in the UTM by screwing it into the large knurled gripping nuts. Make sure the gripping nuts or the retaining nuts on the both end of the loading bars are tight. Clean the gage section of the specimen with alcohol.
5. Attach the extensometer to the specimen, Fig. 5 (your instructor will demonstrate the proper way to handle the extensometer) .The extensometer does not need to be mounted coincident with the gage marks. You will use two kinds of extensometers, a dial gage and an electronic type. For the dial gage extensometer each small mark on the extensometer dial gage represents an elongation of 0.0001 inches. There are 100 marks per revolution of the dial so each complete revolution of the pointer indicates an elongation of 0.01 inches. Rotate the dial gage so that the needle points to zero. Your data will be load and elongation.

For the electronic extensometer make sure it is affixed so it will collect data both on the load and strain scales. Note that the graph generated (your data) will be load vs. magnified strain.
6. Start With the middle range of the UTM. Note that you can switch from lower ranges to higher ranges without unloading the specimen, but never sWitch from a higher Figure 5 range to a lower range without first removing the load from the specimen.
7. Load the sample slowly and carefully (you shouldn't need to open the load valve beyond "15"). For the dial gage extensometer record the load and elongation values at every 500 lb. increment of load. When the dial gage pointer is moving too fast to read accurately or when the load on the UTM starts to decrease (indicating you have passed the UTS), close the load valve for a moment and remove the extensometer.

Figure 5

When using the electronic extensometer make sure the drum is turning and the pen is moving. When the pen reaches the end of the paper close the load valve for a moment and remove the extensometer.
8. Resume loading without the extensometer until the sample breaks. Record the maximum load reached during the test and the breaking load. Measure the length of the broken specimen between the gage marks and the diame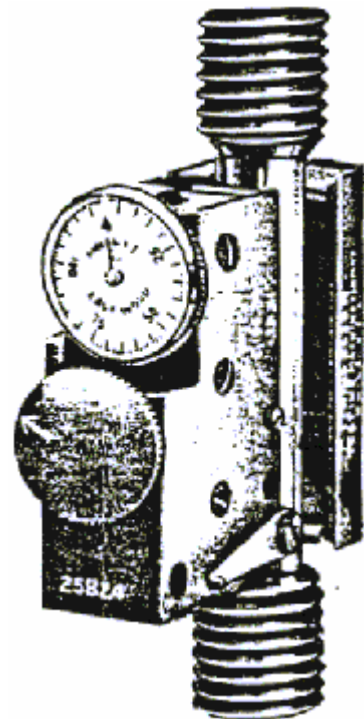ter of the specimen at the break.