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Understanding Materials

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By Petros J. Katsioloudis

Before selecting a material for different applications, it is essential to understand the characteristics of the material.

Almost everything people have ever done has involved materials (Jacobs & Kilduff, 1985). Historical evidence indicates that "engineered materials" have been available and utilized for the benefit of humankind since the Neolithic period, beginning about 10,000 BC (Thornton, 1985). Some of these materials have been in existence for thousands of years. Perhaps this is best expressed by the following passage from the first book of the Old Testament:

> And they said one to another, Go to, let us make brick, and burn them thoroughly. And they had brick for stone, and slime had they for mortar (Genesis XI, 3).

At first, materials consisted of wood, stone, ceramic clays, and meteoric metals and ores, simply shaped into useful objects. Later, copper metallurgy was developed in Asia Minor, followed by the Iron Age promoted by the Romans for their military and civil needs (Thornton, 1985). From the Roman times to today, materials have undergone continuing evolution, with considerable improvement. Today's engineered materials are commonly divided into categories based on their physical and chemical characteristics. Included in those categories are: (a) metals, (b) ceramics, (c) polymers, and (d) composites.

Metals

Most of us are familiar with metals in a general way because of exposure to them through day-to-day use. Metals can usually be distinguished from other categories by some of their more obvious traits, such as reflectivity of light, thermal conductivity, electrical conductivity, hardness, toughness, and modulus of elasticity. Metals are large collections of millions of crystals composed of different types of atoms held together (Jacobs & Kilduff, 1985).

Ceramics

The term "ceramic" is derived from the Greek word "keramos," which literally means earth. Ceramics are defined as hard, brittle compounds of metallic and nonmetallic elements that have high melting temperatures and are chemically inert (Helsel & Liu, 2008). The advantages of ceramics over other materials are noticeable. These include high melting temperatures, high hardness, high modulus of elasticity, high compressive strength, and low electrical and thermal conductivity.

Polymers

"Poly" means many, and "mer" stands for monomer or unit (Helsel & Liu, 2008). The process of linking monomers together is known as polymerization, where polymers are being produced or plastics created that have properties different from the corresponding monomers. For industrial applications, there are two basic types of plastics; thermoplastics and thermosets. The main difference between the two types is that thermoplastics are polymers that soften when heated and regain their form when cooled, where thermosets can pass through only one heat cycle.

Composites

By definition, a composite is a material consisting of two or more integrated materials (Jacobs & Kilduff, 1985). One of the first composites was created several thousand years ago when our ancestors mixed clay and straw together to make bricks (Duvall and Hills, 2008). The main reason we create composites is to rectify weakness possessed by each constituent when it exists alone; composites are designed to serve special applications and meet certain criteria. Some of the most familiar composites include fiberglass and plywood.

Atomic Structure of Materials

An atom is the smallest particle of an element that possesses the physical and chemical properties of that element (Helsel & Liu, 2008). The average diameter of an atom is only about 10^{-10} of a meter (Jacobs & Kilduff, 1985) and it takes more than 106 atoms edge-to-edge to make the thickness of this page. Atoms consist of a nucleus and surrounding orbits that contain electrons. The nucleus is the densest part of the atom and consists of neutrons and protons. A proton is a particle of matter that carries a positive electrical charge equivalent to the negative charge of the electron. Depending on the amount of electrons existing on the outside shell of an atom, we can determine the physical stage of the material and whether it is gas, liquid, or solid. For example if we have only a few electrons on the valence shell (outside shell) we will most likely have a material in a solid stage, since the existing energy will be divided among the few electrons. With more electrons present, the constant energy is divided by a larger number, and therefore the bonding energy between the electrons is weaker, which means we will have a material in a liquid or gas stage.

Physical and Chemical Properties

Each material has unique physical properties that distinguish it from others (Duvall and Hills, 2008). The four main physical properties used to classify metals are: weight, color, conductivity (electrical and thermal), and reaction of the material when exposed to heat. When comparing two different metals such as aluminum and lead, the difference between the materials is noticeable; for example, lead is denser and has a tighter molecular structure than aluminum. The color of the metal is also a good indicator for some metals. The bright color of gold and platinum, for example, differs from the color found in stainless steel.

Materials Testing

Before selecting a material for different applications, it is essential to understand the characteristics of the material. One way to identify material properties is by testing. Different types of materials testing include Rockwell and Brinell hardness testing, compression testing, shear testing, modulus of elasticity, and tensile testing. As a part of the materials process course offered at Old Dominion University, most types of materials testing are being conducted using the Vega Universal Testing Machine. A brief description of the tests and procedures follows.

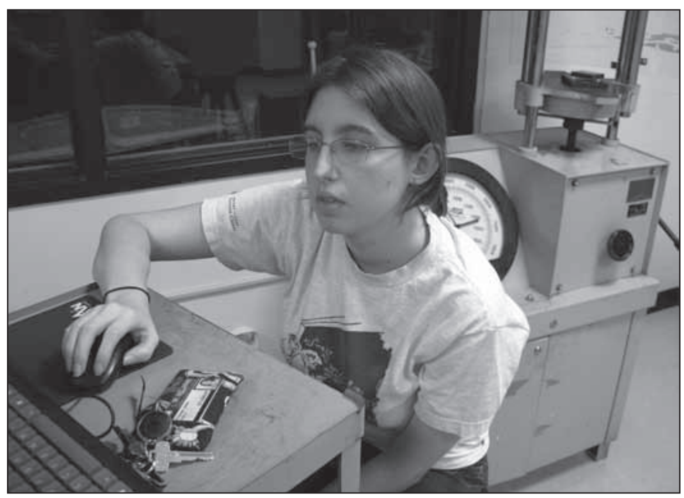

Figure 1. Knowing something about the properties of materials enables students to design products in an intelligent manner that maximizes the use of materials and learning experience. A universal testing machine plays an important role in testing the properties of materials and assisting the student in learning about materials.

Tensile Testing

A testing machine used for a tensile test must be able to apply a tension load and measure the load and elongation of that piece. The tensile tester is most commonly a universal testing machine, which is used to pull the specimen in tension until it breaks. A tensile test is performed to determine the following mechanical properties: (a) ultimate tensile strength, (b) modulus of elasticity, (c) ductility, (d) proportional limit, (e) yield strength, and (f) fracture strength (Degarmo & Kohser, 1984).

Ductility is a measure of a material's ability to deform plastically without fracture. The two most common methods of ductility measurement are: (a) percent elongation, determined by setting a gauge length (usually 2") on a specimen prior to loading and (b) after tensile failure, measuring the final distance of these gauge marks (Vega Enterprises Inc, 1975). A percent elongation value is then calculated.

$$\text{Elongation (\%)} = \frac{\text{Final Length} - \text{Original Length}}{\text{Original Length}} * 100$$

Percent area reduction is calculated by putting the two ends of the fractured specimen together and measuring the diameter at the break. Calculate the area at the break at this point of fracture. This final area is then compared with the original area of the specimen, and a percent reduction in area is then calculated.

$$\text{\% Reduction in Area} = \frac{\text{Original Area} - \text{Final Area}}{\text{Original Area}} * 100$$

Ultimate Tensile Strength or tensile strength is the maximum tensile load divided by the original specimen cross sectional area. It is one of the most important properties determined by tensile testing.

$$\text{Ultimate Tensile Strength (psi)} = \frac{\text{Maximum Load (lbs)}}{\text{Original Area (in}^2\text{)}}$$

Procedure:

a) Measure and record the original diameter of the specimen(s) and record on your data sheet. Calculate the original cross-sectional area.

b) Using the center punch, carefully mark the gauge length on the specimen.

c) Place the specimen in the anvil of the center punch, making sure that the specimen is centered. Strike the arm lightly to ensure that the marks do not go too deep.

d) Select the proper grips for specimens and the Universal testing machine. Specimens must be threaded into the grips at at least two diameters (for the 3/8" tensile specimens used on the Universal testing machine this would be .3/4") to prevent thread stripping.

e) Apply the load slowly.

f) Observe the specimen, record the maximum load, and continue loading until failure is reached. Record the breaking load, which must be observed from the load dial at the instant of fracture.

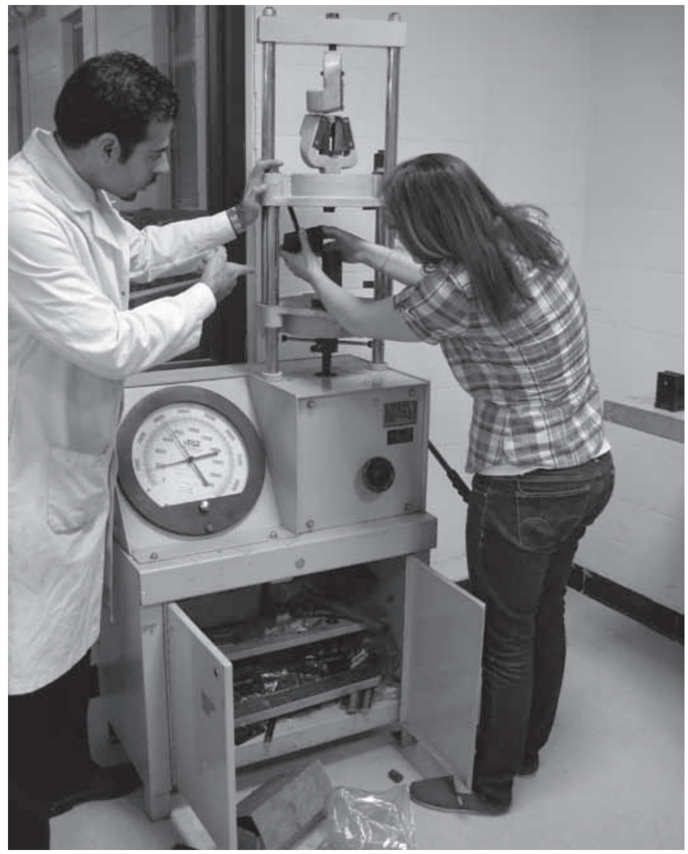

Figure 2. The instructor and student are getting the equipment ready for testing the tensile strength of a materials specimen. Standard-sized materials are used for testing, enabling the student to analyze data that is collected. Credit: Author.

Compression Testing

A compression test is the opposite of a tension test, with respect to loading direction. It is often confirmed that materials behave the same in tension and compression, and that is true for most ductile materials. However, there are some materials that are very weak in tension and extremely strong in compression (Degarmo & Kohser, 1984). Concrete, wood, and cast iron are materials that are mostly tested in compression.

Using the Universal testing machine, a compression test is most commonly performed. The compression space is the lower portion of the machine. Prior to the yield point, tension and compression results are similar. The major difference with the compression test as compared to the tensile test is that the specimen compresses or the area increases after the yield point is reached. For some ductile materials, the specimen will compress until a flat slug is reached (Degarmo & Kohser, 1984). Brittle materials will fail suddenly after their ultimate strength is exceeded. These brittle materials have much greater compression strength than tensile strength. That is why these materials are mostly tested in compression. A compression test is performed to determine the following mechanical properties: (a) ultimate compressive strength (brittle materials), (b) modulus of elasticity, (c) proportion limit, and (d) yield strength (Degarmo & Kohser, 1984). Ultimate compressive strength is the maximum compressive load divided by the original specimen cross sectional area.

$$\text{Ultimate Compressive Strength} = \frac{\text{Maximum Load (lbs)}}{\text{Original Area (in}^2\text{)}}$$

Procedure:

a) Attach compression test plates in the lower platen on the Universal testing machine.
b) Place the raising block on the lower compression plate.
c) Using the dial calipers, measure the diameter of the gray cast-iron specimen.
d) Place the gray cast-iron specimen on the raising block. Make sure that the specimen is centered on the machine. Gradually apply the load and observe the specimen. Record the maximum load that the specimen resists. Continue to apply the load and observe until the specimen fails.
e) Calculate the area of the specimen. Use this area and the maximum load to calculate the compressive strength.

Figure 3. Here the student is getting the equipment ready for a compression test of a material. Brittle materials will fail suddenly after their ultimate strength is exceeded. These brittle materials have much greater compression strength than tensile strength. That is why these materials are mostly tested in compression. Credit: Author.

Modulus of Elasticity

Another important mechanical property to study is the modulus of elasticity. From a tensile test, if we plot the stress versus strain curve, we find a straight-line portion of the curve at lower values of stress and strain. This linear portion of the curve represents the elastic portion of the material's response to a mechanical load. The material in this linear portion obeys *Hook's Law,* which states that stress is proportional to strain. The proportionality constant is known as *Young's Modulus* or the modulus of elasticity (Degarmo & Kohser, 1984).

The practical application of the modulus of elasticity is that, for similar designs with different materials under identical loading and cross sectional area but having different values of modulus of elasticity, the materials will demonstrate different stiffness. Stiffer materials will deflect less than materials having lower values of stiffness. The modulus of elasticity values will give a relative measure of stiffness for different engineering materials. For example, we may compare the modulus of elasticity for steel and aluminum, the steel having a modulus of 30,000,000 psi and aluminum 10,000,000 psi (Vega Enterprises Inc, 1975). These relative values and their implied stiffness would indicate that the aluminum would defect approximately three times that of the steel for the same mechanical loading.

The values for the modulus of elasticity remain nearly constant regardless of the processing methods or heat-treating methods. Carbon content and alloying methods for steel have negligible effects on the modulus of elasticity values for steel. This laboratory activity is designed to demonstrate the correlation between textbook values for the modulus of elasticity and the practical effects of stiffness.

Procedure:

a) Attach the center loading cylinder under the upper platen in the compression section of the Universal testing machine.
b) Mount the transverse bar on the lower platen and place the steel support cylinders for 12-inch centers.
c) Place one of the test bars on the lower support cylinders and position the gauge block under the center of the bar.
d) Slowly apply the load until the bar defects just enough to contact the gauge block. As you apply the load, slowly move this gauge block until interference is detected.
e) Record the load at the point of interference.
f) Rotate the bar 180 degrees and repeat the procedure. Average the values and record.

Shear Strength

Applications such as rivets, crank pins, and wooden blocks are subject to shearing forces. Shear stress results when two parallel forces act in opposite directions that tend to produce a sliding of one part with respect to the other part of the body (Degarmo & Kohser, 1984). Fasteners such as bolts, rivets, and pins are some practical objects subjected to shear stress. Additionally, cutting actions such as punches produce shear stress.

Shear testing results are not as precise as tension and compression testing because of the additional introduction of friction and bending forces in the testing process. Shear tests on flat stock are often done in single or double shear, whereas round stock is mostly tested in double shear. In double shear tests, the applicable area is twice the area of the cross sections.

Procedure as described in the testing machine's lab manual:

a) Attach one hardened plate to the upper platen in the compression space on the universal testing machine, and place the other hardened plate on the lower platen.
b) Measure and record the diameter of each of the shear specimens.
c) Insert the specimen in the appropriate holes in the shear test fixture. Do not center the specimen in the shear test fixture, but allow one end to slightly project a short distance to allow for a second test of the specimen.
d) Before testing, mark the position of the punch relative to the holder to allow for observation of bending during the shear testing.
e) Position the shear testing fixture between the hardened steel plates on the universal testing machine.
f) Gradually apply the load and observe the maximum load reached and any bending present at this maximum load. After the specimen has failed, continue loading until the sheared slug has passed into the relieved area in the lower portion of the shear testing fixture.
g) Remove the shear fixture from the universal testing machine (UTM).
h) Remove the sheared slug from the fixture by sliding the center plate sideways.
i) Perform a second shear test on the remaining portion of the shear specimen. Repeat this process for the other shear specimen.
j) Record the appropriate data and calculate the required information.

Figure 4. Getting the equipment ready for shear testing. Shear testing results are not as precise as tension and compression testing because of the additional introduction of friction and bending forces in the testing process. Fasteners such as bolts, rivets, and screws are typically associated with shear stresses. Credit: Author.

Brinell Hardness Test

There are several methods used to determine hardness. Rockwell and Brinell are two of the most common forms of hardness testing (Degarmo & Kohser, 1984). Rockwell hardness testing is generally used on harder steels and samples where the Brinell hardness test leaves too large an impression on the specimen to be practical (Degarmo & Kohser, 1984).

The Brinell testing machine is relatively simple. The large indenter averages out load variations in the specimen, and it can be used on relatively rough surfaces. However, it does leave rather large indentations in the test specimens. The large Brinell indenter will not make a significant impression in hard materials, so the test is not useful beyond the Rockwell C-60 range. The thickness of the specimen being tested should be about 10 times the depth of the indentation for best accuracy. This prevents the test from being conducted on thin materials. In practice, good values may be obtained if there is no visible effect on the back of the specimen.

A close correlation between the Rockwell and Brinell hardness numbers has been developed for steel, and conversion charts are available for changing from one to the other. A close correlation has been found to exist between the Brinell number and the tensile strength of steel. This is extremely important, for a fast hardness test may often be used in place of a tensile strength test.

Procedure:

a) Place the indenter in position under the upper platen of the universal testing machine.
b) Place a hardened block or pad on the lower platen. Select a specimen of adequate thickness and with a flat smooth face; position it under the indenter.
c) Adjust the machine to bring the penetrator nearly into contact with the specimen.
d) Carefully adjust the gauge pointer to zero.
e) Gradually apply the load until 3000 kg is reached, taking care not to exceed.
f) Hold at that load for 15 seconds, and release the load.
g) Remove the specimen and read the specimen diameter with a Brinell microscope or a suitable magnifying reader with a scale graduated in millimeters.
h) Measure the diameter in two directions at right angles to each other, and record them in a table.
i) Calculate the average diameter of the two readings and look up and record the BHN corresponding to these diameters.
j) Use Brinell values table to determine the Brinell number for a given diameter depression that was created using a 3000 kg load.
k) For very soft materials or materials that create a depression with a diameter of 3 5.9 mm, use a 500 kg load (1020 pounds) and table 9-2 for the Brinell numbers.

Rockwell Hardness Test

The majority of Rockwell hardness systems use a direct readout machine determining the hardness number based upon the depth of penetration of either a diamond point or a steel ball (Degarmo & Kohser, 1984). If the penetration is deep, it indicates a material having a low Rockwell hardness number. However, if the penetration is low, it indicates a material having a high Rockwell hardness number.

The Rockwell hardness number is based upon the difference in the depth to which a penetrator is driven by a definite light or "minor" load and a definite heavy or "major" load. The ball penetrators are chucks that are made to hold 1/16" or 1/8" diameter hardened steel balls. Also available are 1/4" and 1/2" ball penetrators for the testing of softer materials. There are two types of anvils that are used on the Rockwell hardness testers. The flat faceplate models are used for flat specimens. The "V" type anvils hold round specimens firmly. Test blocks or calibration blocks are flat steel or brass blocks, that have been tested and marked with the scale and Rockwell number. They should be used to check the accuracy and calibration of the tester frequently.

Procedure:

a) Flat specimens should be clean, smooth, and free from scale.
b) The shape should be such that the specimen rests firmly on the anvil. Cylindrical specimens should be clean, smooth, and free from scale.
c) Use the correction chart for corrective addition to Rockwell numbers for cylindrical specimens.
d) Using the "B" Scale: Use a 1/16" diameter steel ball penetrator. Major load: 100 Kg, Minor load: 10 Kg. Use for copper alloys, soft steels, aluminum alloys, and malleable iron. Do not use on hardened steel. Using the "E" Scale: Use a 1/8" diameter steel ball penetrator.
e) Major load: 100 kg; Minor load: 10 kg. Use for cast iron, aluminum, magnesium alloys, and bearing materials. Do not use on hardened steel.

Impact Testing

Impact is defined as the resistance of a material to rapidly applied loads. Toughness is a property, which is capacity of a material to resist fracture when subjected to impact (Degarmo & Kohser, 1984). Two basic types of impact testing have evolved: (1) bending, which includes Charpy and Izod tests, and (2) tension impact tests (Degarmo & Kohser, 1984). Bending tests are most common, and they use notched specimens that are supported as beams. In the Charpy impact test, the specimen is supported as a simple beam with the load applied at the center. In the Izod test, the specimen is supported as a cantilever beam. Using notched specimens, the specimen is fractured at the notch. Stress is concentrated, and even soft materials fail as brittle fractures. Bending tests allow the ranking of various materials and their resistance to impact loading. Additionally, temperature may be varied to evaluate impact fracture resistance as a function of temperature. Both Charpy and Izod impact testing utilize a swinging pendulum to apply the load.

The tensile impact test avoids many of the pitfalls of the notched Charpy and Izod bending tests. The behavior of ductile materials can be studied without the use of notched specimens. Pendulum, drop-weights, and flywheels can be used to apply the tensile impact load.

Procedure:

a) Setting the Pointer:
   - Before you start a test, check the "zero" of the pointer. The impact tester is calibrated for friction and wind loss; therefore, it should read zero after a free swing. The following procedure should be used to check the zero:
     - Raise the safety latch and place the operating lever in the latch position.
     - By hand, lift the pendulum counterclockwise until the latch clicks. The first click is the lower release position. Further raising the pendulum places it in the upper release position.
     - Insert the dowel, designed to prevent accidental application of the brake, into the hole in the head of the machine.
     - Set the pointer to the maximum value of the range for your test. Ranges and pendulum positions are illustrated on the dial. Make sure that no one is in the path of the pendulum.
     - Move the control lever to the release position. When the pendulum has started to swing back, remove the dowel and push the control lever to the brake position. If the pointer reads zero, you are ready for your test. If not, loosen the screw that holds the pusher arm, turn the arm to produce a zero reading, and tighten the screw.
     - Repeat until the free swing reads zero.

Summary

As we look at the new inventions and innovations in the technology of materials, we can see that, through the years, they are becoming more technologically complex. We see examples such as the space shuttle panels, where ceramic composites are applied to the surface of the spacecraft to absorb and release high amounts of heat. However, the main goal of composites—to generate materials with unique characteristics to be utilized on special applications—remains the same, and their importance to industry will remain vital.

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