Chapter 10
Materials and Materials Testing

Objectives
After studying this chapter, you will be able to:

- Identify the classes of materials.
- Define the terms ferrous and nonferrous.
- List various types of nonferrous metals and alloys and how they are used.
- Summarize those properties that influence the selection of materials.
- Explain the different types of hardness testing.

Technical Terms

- alloying elements
- antimony
- bismuth
- Brinell hardness test
- brittleness
- bronze
- compressive strength
- ductility
- elastic limit
- elasticity
- fatigue strength
- flex strength
- hardness
- impact strength
- materials
- plasticity
- properties
- Rockwell hardness test
- shear strength
- shore scleroscope hardness test
- strain
- strength
- stress
- tensile strength
- torsion strength
- zinc
Knowledge of various metal materials and their properties is useful for sheet metal workers. Most workers will never be asked to purchase or test the materials needed for a job, but understanding how these materials are created, and knowing their strengths and weaknesses, results in a more knowledgeable worker.

Materials

Materials are physical substances used in production or manufacturing. Materials can be raw, semifinished, or finished. Sheet metal is a finished material. It is produced from raw materials like iron and carbon that are mined and processed into steel. This semifinished material is then processed further into the finished material: sheet metal.

Materials are generally classified based on their properties and characteristics. A basic classification method divides materials into metals and nonmetals. Metals are further divided into ferrous (contains iron) and nonferrous (no iron) categories. Nonmetals can be further classified into polymer, ceramic, and composite categories, Figure 10-1.

Ferrous Metals and Alloys

Ferrous metals contain iron and are magnetic. Iron and steel are the most common ferrous metals. They are an economical material. They are widely used in machinery, construction, and other applications where the ability to carry a load is important.

Pure iron (ferrite) is a relatively soft element. In order to be useful, it is alloyed with other elements. Cast iron contains 2–4 percent carbon, 1–6 percent silicon, and traces of manganese. Types of cast iron include white cast iron and gray iron. Cast iron properties vary, depending on the form of the carbon within the iron. Wrought iron contains less than 0.25 percent carbon and is malleable and tough. Steel is a general term used to describe alloys in which iron is the base metal and carbon is the most important added element. Steel is usually classified as either plain carbon steel or alloy steel.

Plain carbon steel is made up of iron, carbon, and trace amounts of alloying elements. The carbon content in plain carbon steel does not exceed 1.7 percent. The higher the carbon content, the harder and stronger the steel. The alloying elements in plain carbon steel are limited to manganese, silicon, copper, and traces of other elements. The properties of the steel depend on carbon content and heat treatment.

Plain carbon steel is divided into three groups: low-carbon steel, medium-carbon steel, and high-carbon steels. Low-carbon steel, or mild steel, contains a maximum of 0.30 percent carbon. It has less strength and hardness and so is easier to machine and work. Low-carbon steel is used to make galvanized sheets, storage tanks, and is used in bridge, ship, and building parts. It is inexpensive to produce and purchase.

Medium-carbon steel contains between 0.30 and 0.60 percent carbon. Heat treating increases its hardness and strength. It is versatile and is used in a variety of applications. Common uses for medium-carbon steel include automobile parts, forgings, and high-strength castings. It is more expensive than low-carbon steel.

High-carbon steel contains between 0.60 and 1.0 percent carbon. With heat treating, it becomes very strong and very hard. However, it is also brittle. It is generally used where high strength is needed, such as lawn mower blades, knives, railroad rails, hand tools, and dies. Alloy steel is carbon steel that contains 1–4 percent alloying elements. These alloying elements are added for several reasons:

- To improve mechanical properties.
- To improve resistance to corrosion and oxidization.
- To improve hardenability of the steel.

The table in Figure 10-2 lists the effect of alloying elements on steel.

Like plain carbon steel, alloy steel is also divided into groups: low-alloy steel and high-alloy steel. Low-alloy steel contains less than 10 percent alloying elements. The amount of alloy is sufficient to change the steel properties. High-alloy steel contains more than 10 percent alloying elements. Stainless steel and tool steel are two types of high-alloy steel.

Stainless steel resists oxidation and corrosion when correctly heat treated and finished. It is also easy to clean. Stainless steel sheets are used to make industrial kitchen equipment such as sinks, food preparation surfaces, and...
range hoods. They are also used to make hospital equipment. Stainless steel is a widely used material in the sheet metal industry.

High-speed steel is one type of tool steel. It is used in cutting tools found on lathes and milling machines.

Nonferrous Metals and Alloys
Nonferrous metals and alloys contain no iron. Nonferrous metals include copper, zinc, tin, antimony, lead, and aluminum. Nonferrous alloys using those metals as a base element include brass, bronze, and aluminum alloys. Copper is ductile and malleable. It is an excellent conductor of heat and electricity. It also resists corrosion so it is often used as roofing material. Alloys of copper include brass and bronze.

Brass is an alloy of copper and zinc. Small percentages of tin, lead, and other metals are also found in some types of brass. The amount of zinc in brass determines its color, Figure 10-3. Tensile strength varies, according to composition and treatment. Brass is easily polished to a bright finish that is useful in decorative applications.

Zinc is brittle at room temperature, but malleable and ductile between 212°F (100°C) and 300°F (149°C). It is commonly used as a coating to prevent corrosion. Steel sheets are dipped in liquid zinc, resulting in galvanized steel sheets. These are used in car bodies to reduce corrosion resulting from road salt. Zinc is also used for eaves, gutters, and roofs because it is light and easy to handle. Tin is ductile and malleable but has low tensile strength. It can easily be drawn into wire at 212°F (100°C) and rolled into very thin sheets. Tin is used as a protective coating for iron and copper because it resists corrosion.

Antimony is a hard, brittle metal that resembles tin. It is an elementary substance that resembles metal in its appearance and physical properties, but is chemically related to the class of nonmetallic substances. It is commonly mixed with lead in battery plates, and is used in manufacturing semiconductors, paint, and flameproofing compounds.

Lead is the heaviest of the common metals. It melts at 621°F (327°C) and is soft enough to be cut with a knife. Lead is also malleable, ductile, and has low tensile strength. Compared with other metals, it is not a good conductor of heat or electricity. It is used to alloy with other metals for bearings and solders. Lead has largely been replaced in the plumbing industry.

Bismuth has two remarkable properties: its specific gravity decreases under pressure and it expands on cooling. The melting point is about 520°F (271°C). Bismuth is often alloyed with antimony to fill molds completely after solidification.

- **Phosphorus**: Prevents sticking in light-gage sheets, slightly strengthens low-carbon steel, improves machineability in some steels.
- **Sulfur**: Improves machineability in some steels but is generally regarded as a contaminant.
- **Manganese**: Increases hardness and strength, although too much can create brittleness and hardness that makes cutting difficult. Has a neutralizing effect on sulfur.
- **Nickel**: Increases both strength and toughness.
- **Aluminum**: Improves strength of ingots and castings.
- **Vanadium**: Improves susceptibility to fatigue and to shock. Improves ductility, tensile strength, and elasticity.
- **Molybdenum**: Deepens hardening, counteracts tendency to brittleness, improves corrosion-resistance in stainless steel, forms abrasion-resisting particles.

**Brass Composition**

<table>
<thead>
<tr>
<th>Brass color</th>
<th>Amount of zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>5 percent</td>
</tr>
<tr>
<td>Bronze</td>
<td>10 percent</td>
</tr>
<tr>
<td>Light orange</td>
<td>15 percent</td>
</tr>
<tr>
<td>Greenish yellow</td>
<td>20 percent</td>
</tr>
<tr>
<td>Yellow</td>
<td>30 percent</td>
</tr>
<tr>
<td>Yellowish white</td>
<td>60 percent</td>
</tr>
</tbody>
</table>

**Bronze Composition**

<table>
<thead>
<tr>
<th>Treatment Method/Use</th>
<th>Amount of Tin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold-rolled into wire</td>
<td>1–6 percent</td>
</tr>
<tr>
<td>Art bronze</td>
<td>3–10 percent</td>
</tr>
<tr>
<td>Worked at red heat</td>
<td>6–15 percent</td>
</tr>
<tr>
<td>Machine parts</td>
<td>9–20 percent</td>
</tr>
<tr>
<td>Bell bronze</td>
<td>20–30 percent</td>
</tr>
</tbody>
</table>

**Zinc**: A nonferrous metal used to galvanize iron and steel against corrosion.

**Antimony**: A hard, brittle nonferrous metal that resembles tin.

**Bismuth**: A nonferrous metal whose specific gravity decreases under pressure and expands on cooling.
Aluminum is lightweight but can be made extremely strong through the use of alloying elements or heat treatment. Common aluminum alloying elements include copper, silicon, magnesium, nickel, iron, zinc, and manganese. Aluminum is corrosion resistant, attractive, malleable, ductile, and a good conductor of heat and electricity. Thermal expansion of aluminum is slightly more than twice that of steel and cast iron. Aluminum alloy castings are made in sand molds, permanent metal molds, or pressure die-casting molds. Permanent molds are practical only when a large number of identical castings are needed. The minimum number that will justify the production of a metal mold, or die, varies greatly with the nature of the casting.

Aluminum is often rolled into sheets to be stamped, punched, or shaped into many projects. Sheet aluminum is also used for siding on houses and commercial buildings. It can be used for various purposes and a number of thicknesses are available.

Babbit metal is an antifriction alloy of tin, antimony, and copper. It was invented in 1839 by Isaac Babbitt, a Boston goldsmith. At that time, it was used in steam engines. Today, Babbit metal is used as bearing material in automobile crankshafts and axles, and in marine applications. The alloy is made of a combination of hard crystals and softer alloys, which allows it to conform to bearing shafts.

White metal is a term often applied to various alloys containing mainly zinc and tin, or zinc, tin, and lead. White metal is used for bearings.

Miscellaneous Metals
Monel metal is an alloy of copper and nickel and a small percentage of iron. Its melting point is 2480°F (1361°C), and it may be forged from 165°F (74°C) to 1100°F (593°C). An important use of monel metal is in ship propellers.

Muntz metal is an alloy containing 60 percent copper and 40 percent tin. It is used when a hard sheet brass is desirable.

Tantung® is a trade name for a series of alloys that have great hardness, strength, and toughness, and resistance to wear, heat, impact, corrosion, and erosion, even at extremely high temperatures. These alloys are composed chiefly of cobalt, chromium, and tungsten, with either tantalum or columbium carbide and other components added.

Material Selection

Materials are selected for use in products based on their properties, cost, source, and environmental impact. The most important of these considerations is the properties of the materials.

The material chosen must have the properties needed for the product. For example, steel is strong, tough, and elastic. These properties make it useful in the construction of bridges, buildings, and certain types of machines. These properties can also be manipulated through the use of alloying elements and heat treatment. Steel is made even more desirable because its cost is reasonable and it is easy to obtain.

Properties

Sheet metals are made from various metals, including iron, aluminum, steel, and copper. Each material has properties that define its character or behavior under various conditions. Knowing the properties of all types of metals helps in selecting the right type of sheet metal for a particular job. In some instances, sheet metal sections are part of a larger project. Knowing the properties of the sheet metal and how it interacts with the other materials is important.

Materials have three basic properties: mechanical, physical, and chemical. Mechanical properties determine the ability of a material to resist or carry mechanical stresses or forces. Physical properties are the characteristics of a material as it interacts with various forms of energy (light, heat, electricity, and magnetism). Chemical properties are the characteristics of a material as it reacts with its environment, such as gases, liquids, and solids.

In sheet metal work, engineers are most concerned with a material’s mechanical properties. These properties include strength, hardness, elasticity, plasticity, ductility, brittleness, and toughness.

Strength

Strength is the ability of a material to resist stress. Stress is the result of a force or load applied to a material. For example, steel beams used to frame a building are under stress simply from their own weight. Those beams require incredible strength to stay in place and not collapse under that weight. All metals need strength to withstand the stresses encountered in different applications. If material is to be useable and practical, it requires some type of strength to withstand the stress it will encounter. Some types of forces and stresses are shown in Figure 10-5. Refer back to this figure as you read the following paragraphs.

Tensile strength is a material’s ability to resist a pulling force. This force is tensile stress. Imagine a rope hammock. It is attached tightly to either end of the frame to keep it taut. The tensile force pulls against the tensile strength of rope used in the hammock.

Compressive strength resists the force created by materials pressing together or compacting. Compressive force is created by opposite forces pushing against each other.

Flex strength is the ability to withstand tensile and compressive forces. When a material is flexed, it experiences tension on one side and compression on the opposite side.

Shear strength is a material’s ability to resist sliding action. The sliding action or force is parallel to the resisting area. Shear force is usually not as strong in most materials as tensile or compressive force. A related strength is torsion strength, the ability to resist a rotating force.
Impact strength is a material's ability to withstand a sudden shock or load. When a rock hits the windshield of a car, the impact strength of the windshield will be tested. If it is strong enough, the rock will not shatter the windshield. However, if the rock is too large or heavy, it will fracture the windshield.

Fatigue strength is the ability to withstand repeated stress. Fatigue stress is cyclic, occurring over and over. Bending a metal rod back and forth repeatedly at the same point is an example of fatigue stress. Eventually, the rod will break.

**Hardness**

Hardness is the ability of a material to resist penetration or scratching by another material. It is one of the most important properties of metal as it relates directly to several other properties. Knowing the hardness of a material also indicates the strength, brittleness, and ductility of that material. Hardness is measured using several methods that will be explained later in this chapter.

**Elasticity and Plasticity**

Elasticity is the ability of a material to return to its original shape after a load is removed. For example, a rubber band returns to its original shape after it is stretched. The elastic limit is the maximum load this material can hold without being permanently deformed.

Plasticity is the ability of a material to be permanently deformed without breaking. Nearly all metals have this property. It is a useful property for materials that are forged or extruded.

**Ductility and Brittleness**

Ductility applies to material that can be drawn out, stretched, twisted, or bent when cold, without breaking. Ductile materials are flexible and include iron, nickel, and lead.

Material that breaks easily, with a somewhat smooth fracture is called brittle. Brittleness usually increases as material becomes harder.

**Toughness**

Toughness is a property related to strength and ductility. Tough materials have the ability to absorb shock and to be deformed without breaking.

**Material Testing**

Materials are tested to determine what properties they possess and to what degree. This information is then used when choosing materials for a specific application. The materials chosen must be able to support the expected load. For example, bridge-building materials need completely different properties than materials used for gutters. Safety is the most important reason material testing is done.

Testing is conducted using a material sample. The results of testing are assumed to apply to all material from which the sample is taken. In other words, the test results from a bolt taken from a group of 500 bolts will apply to all the bolts in that group.

Testing can be destructive or nondestructive. In destructive testing, the test piece is destroyed and is no longer usable. In nondestructive testing the test piece is not destroyed and can, therefore, be used in a finished product.

**Stress and Strain**

Recall that stress is defined as a naturally occurring force or load working against the material. Stress is measured as force per unit area, such as pounds per square inch or newton per square meter. This stress causes the tested material to deform. The deformation is known as strain and causes elongation, compression, or distortion of the material.
Tensile Strength and Ductility

Tensile strength and ductility are both measured by applying a pulling force to a sample. The tensile strength machine has a set of jaws. The material sample is placed in the machine and then pulled apart by the jaws until the material breaks. The machine also provides a profile, outlining how the material reacted to the force being applied. Tensile strength is measured by the elongation of the material. Ductility is also tested using a tensile test and is measured by the elongation of the material and the reduction in cross-sectional area.

**Toughness**

Toughness is measured using an impact test. Impact tests are designed to test the ability of a notched sample to absorb sudden force. A striker is mounted on the end of a pendulum. When it is released, it breaks the sample. The height of the swinging pendulum after it breaks the sample is the amount of energy absorbed by the sample piece.

**Hardness**

Hardness is measured using one of a variety of hardness tests. Hardness can be determined using a scratch test, an indentation test, or a rebound test.

In a scratch test, a sharp file is drawn slowly and firmly across the surface of the sample material. If the file does not bite into the surface, it is considered file hard. If the file cuts quickly and easily into the surface, the material is soft. There are several obvious disadvantages to this test. There are differences in the files used for testing. There are differences in the way operators conduct the test. The hardness cannot be recorded as numerical data. The advantages include that the test is inexpensive, rapid, and nondestructive. A skilled inspector may be able to use the test to discard unsatisfactory pieces.

The **shore scleroscope hardness test** is a type of rebound test. A small diamond-pointed hammer is dropped from a predetermined height onto the surface of the test piece. The rebound height of the hammer is measured and this number translates to a scale. The corresponding number on the scale is the scleroscope hardness number. Softer material has greater deformation and less energy available for rebound.

Indentation testing methods are the most commonly used method. In these tests, an indenter of a known force is pressed into the material. The depth or area of the resulting indentation is measured and given a hardness value. Values differ based on which test is used.

There are four different hardness tests:
- Rockwell.
- Brinell.
- Knoop.
- Vickers.

Each test has its own scale and these scales do not correlate with each other. So, a five on a Rockwell test is not the same as a five on a Knoop test. However, all values increase as hardness increases.

The **Rockwell hardness test** uses either a hardened steel ball or a diamond-tipped cone as the indenter. A minor load is applied first and then a major load. The minor load produces an initial indentation. The dial is then set at zero, and the major load is applied for a set time interval. Hardness numbers are read directly from the indicating dial. A Rockwell hardness tester is shown in Figure 10-7.
Rockwell tests are considered nondestructive because the indentations are so small they do not affect the integrity of the test piece. Rockwell tests are rapid and accurate. In the higher hardness range, it is considered more accurate than the Brinell test.

The Brinell hardness test applies a predetermined load onto a hardened steel ball that then presses into the material under that load for a short time interval (not less than 15 seconds). See Figure 10-8. The diameter of the indentation is measured in two directions and averaged. This average is converted to a Brinell hardness number using a chart or a formula. Generally, the softer the metal, the larger the indentation, and the lower the Brinell hardness number. The Brinell test is considered destructive under some conditions.

The Knoop hardness test is a microhardness test. It is used to test the hardness of very brittle or thin materials that can have only a small indentation made for testing purposes. It is considered a destructive test. Precautions that must be observed when conducting this test make it impractical in many situations.

Rockwell tests are nondestructive because the indentations are so small they do not affect the integrity of the test piece. Rockwell tests are rapid and accurate. In the higher hardness range, it is considered more accurate than the Brinell test.

The Brinell hardness test applies a predetermined load onto a hardened steel ball that then presses into the material under that load for a short time interval (not less than 15 seconds). See Figure 10-8. The diameter of the indentation is measured in two directions and averaged. This average is converted to a Brinell hardness number using a chart or a formula. Generally, the softer the metal, the larger the indentation, and the lower the Brinell hardness number. The Brinell test is considered destructive under some conditions.

The Vickers hardness test is done in the same way as the Brinell test, but using a differently shaped indenter. The impression left by the Vickers indenter is clearer than that left by the Brinell indenter.

Relationship between Mechanical Properties and Hardness

All mechanical properties are directly affected by hardness.
- Toughness increases as hardness decreases. In contrast, toughness decreases as plasticity and ductility decrease.
- Plasticity increases as hardness decreases. When hardness of a metal becomes great enough, the metal ruptures before plastic deformation takes place.
- Ductility decreases as hardness increases. Decrease in ductility can make fabrication of a metal more difficult.
- Tensile strength increases as hardness increases.

Effects of Temperature

All mechanical properties are affected by temperature. As temperature increases, tensile strength and hardness decrease. As temperature increases, plasticity and deformation also increase. The effects of temperature on the mechanical properties of metals are numerous and complicated. A thorough study of the heat treatment of metals, however, is beyond the scope of this book.

Summary

Materials are physical substances used in production or manufacturing. They can be raw, semifinished, or finished. All materials are generally classified based on their properties and characteristics. A basic division of materials is metals and nonmetals. Metals include nonferrous (contains no iron) and ferrous (iron, steel) categories. Nonmetals include polymers, ceramics, and composites.
Materials are selected for use based on several considerations, the most important of these being the properties of the materials. Properties of a material define its character or behavior under various conditions. Mechanical properties are the most important to consider in metal working. Desirable properties include strength, hardness, elasticity, plasticity, ductility, and toughness. An undesirable property of metal is brittleness. Material testing is necessary to determine the ability of a material to handle a particular job. The metals chosen for use in a project must be durable, dependable, and safe. Included in materials testing are tests for elasticity and plasticity, hardness, ductility, toughness, and tensile strength. Temperature also has an effect on metal.

Internet Resources
Instron
www.instron.us/wa/home/default_en.aspx
MatWeb
www.matweb.com/search/MaterialGroupSearch.aspx

Outside Activities
1. Collect a variety of materials from around your classroom or school. Break into small groups and categorize each material as either a metal, polymer, ceramic, or composite. Further classify the materials within their groups, using Figure 10-1 as a guide.
2. Imagine that you must choose the proper material to make the supporting structure of a bridge. Write a short explanation of what materials you would choose and why. Explain what strengths your bridge would need in order to withstand the forces it would experience.
3. Observe as your instructor demonstrates the use of a hardness testing machine. Make a list of dos and don’ts to follow when using this machine. Review the user’s manual for additional information on operating and caring for the hardness testing machine.

Review Questions
Write your answers in the spaces provided.

1. True or False. Materials are classified based on their properties.

Match each of the following material subcategories with the correct materials family.

2. Ceramic matrix materials such as concrete.
   A. Metals.
   B. Polymers.
   C. Ceramics.
   D. Composites.

3. Nonferrous materials such as copper and copper alloys.
   A. Metals.
   B. Polymers.
   C. Ceramics.
   D. Composites.

4. Natural materials such as glass and diamond.
   A. Metals.
   B. Polymers.
   C. Ceramics.
   D. Composites.

5. Synthetic materials such as plastics and glues.
   A. Metals.
   B. Polymers.
   C. Ceramics.
   D. Composites.

6. Define the terms ferrous metal and nonferrous metal.

7. Plain carbon steel contains iron, carbon, and trace amounts of _____ elements.
   A. fusion
   B. matrix
   C. compounded
   D. alloying

8. List three reasons that alloying elements are added to alloy steel.

9. The _____ of a material determine its character and the way in which it behaves under certain conditions.
10. Name the three basic properties of materials. __________________________________________________________
____________________________________________________________________________________________________
____________________________________________________________________________________________________
____________________________________________________________________________________________________

Match each of the following definitions with the correct term.

11. The ability to resist pulling force. 11. __________________________

12. The ability to withstand tensile and compressive forces. 12. __________________________

13. The ability to withstand sudden shock or load. 13. __________________________

14. The ability to withstand repeated stress. 14. __________________________

15. The ability to withstand a rotating force. 15. __________________________

16. What type of load is depicted in the following drawing? __________________________

17. The _____ is the maximum load a material can hold without being permanently deformed. 17. __________________________

18. The ability of material to resist penetration or scratching by another material is called ____. 18. __________________________

A. elasticity
B. hardness
C. plasticity
D. flex strength

19. True or False? All hardness tests use the same rating scale. 19. __________________________

20. The _____ hardness test applies a single load onto a steel ball for a specific length of time. 20. __________________________