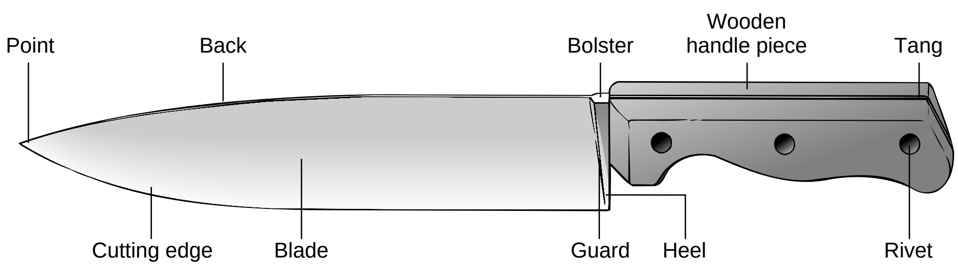

Section 16.1

Knives and Steel

A dull knife is useless in the kitchen—you might as well tear a tomato or a loaf of crusty bread apart by hand. But sharpening a knife isn't always easy because some knives take edges better than others. While there are many knives that simply won't stay sharp, a few wonderful knives never seem to dull. Though they are all made of steel, there is clearly something different about their blades.

Knives have always been one of the greatest tests of a steel maker's skill, from the days when swordmaking was an art to the present era of science and technology. A knife's blade must be tough and flexible, while its cutting edge must be hard but not brittle. Giving steel these properties requires great control over its composition and processing. To understand a knife blade, you must understand its steel.

Questions to Think About: *Why are some knife blades softer and more flexible than others? Why are some knives more corrosion resistant than others? Why does a knife blade spring back when you bend it a little but deform permanently when you bend it further? Why do some knife blades bend or stretch before they break while others simply shatter?*

Experiments to Do: *Take a new steel paper clip and carefully unbend one of its ends, making sure that you notice just how stiff the wire is. Now rebend that end and straighten it repeatedly. Do you notice any change in the stiffness of the metal? Eventually a crack will develop at the edge of the wire and the wire will break into two pieces. Cracking is typical for hard objects such as rocks. Has the steel in the paper clip become harder than it was originally? If so, what has happened inside the steel to cause this change?*

Stresses and Strains, Bends and Breaks

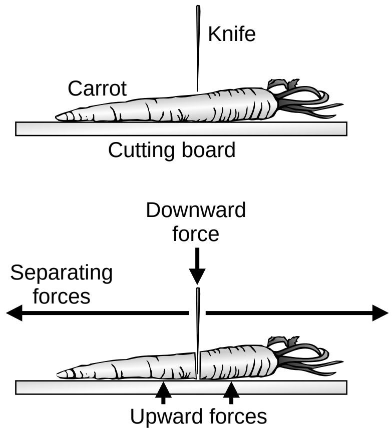

Fig. 16.1.1 - When you push down on a knife to cut a carrot, the cutting board pushes up. Overall, the vertical forces on the carrot, including its weight, cancel completely. But the ramp-like surfaces of the knife blade create large horizontal forces on the two halves of the carrot and these forces divide the carrot.

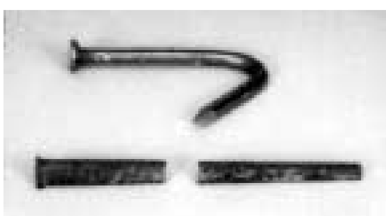

Fig. 16.1.2 - Soft steel containing little carbon bends easily while hard, carbon-rich steel breaks instead of bending.

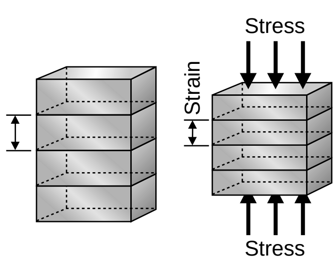

Fig. 16.1.3 - Steel is compressed when it experiences an inward stress. Stress is equal to the inward force exerted on each unit of surface area. This stress causes a strain in the steel. This strain is equal to the fractional change in the steel's length—its change in length divided by its original length.

Knives are simple tools that we use to cut things into pieces. They are essentially wedges that use mechanical advantage to convert small forward forces into large separating forces. When you push down on the blade of a knife as you cut a carrot (Fig. 16.1.1), its cutting edge penetrates the carrot while the two inclined surfaces of the blade exert huge horizontal forces on the two halves of the carrot. One half accelerates to the left while the other half accelerates to the right and the carrot divides neatly in half.

But while the mechanical action of cutting is simple, the physical structure of the knife is not. The secret to its ability to cut through the carrot lies in the properties of its blade. This blade is almost certainly made of steel, so the story of how a knife works is really the story of how steel works.

Steel is not a specific material but rather a whole range of iron-based metals. These metals differ from one another in their specific chemical compositions and in how they have been processed. The variety of steels is so broad that it's difficult to encompass them all in a single definition. However *steels* are generally mixtures of iron and other elements that contain no more than 2.06% carbon by weight. A mixture with more carbon than this is usually called *cast iron*. It's an unfortunate historical accident that cast irons actually contain more carbon and less elemental iron than many steels.

Carbon content is important in distinguishing steel from cast iron because it affects the hardness, brittleness, and other characteristics of these metals (Fig. 16.1.2). **Hardness** is a measure of a material's resistance to penetration, deformation, abrasion, and wear. **Brittleness** is the tendency for a material to fracture while it's being deformed. A good knife blade should be hard but not brittle; distorting very little as you push it through the carrot but resisting fracture even if you use the knife to open a metal can.

Controlling the hardness, brittleness, and other characteristics of steel is a complicated task that involves all aspects of steel production. These characteristics can even vary within a single steel object—the cutting edge of a good knife blade is actually harder than the rest of the blade. To understand how these characteristics are controlled, we'll first look at how materials respond to outside forces and then examine the microscopic basis for steel's properties. What we learn in the process will apply not only to steel, but also to many other materials.

When you push gently on a solid object, that object distorts by an amount proportional to the force you exert on it. This relationship is simply Hooke's law, which we first encountered in the section on spring scales. If the object is a steel block resting on the floor and you're stepping on it, then its tiny distortion is proportional to your weight. By measuring how much your weight distorts this block, you can learn something about the steel from which it's made.

But the distortion is also related to the block's dimensions. The broader its surface, the more your weight is spread out and the less the block distorts. Since we are trying to learn about the steel rather than the block, we divide your weight by the surface area of the block to obtain the stress on the steel (Fig. 16.1.3). **Stress** is the amount of force exerted on each unit of a block's surface area and is the measure of how much the steel is being squeezed.

However, the distortion also depends on the block's height. Each centimeter of metal shrinks a little bit so that a tall block shrinks more than a short block. Again, we are more interested in the steel than the block, so we divide the change in height by the original height of the block to obtain the strain in the steel (Fig. 16.1.3). **Strain** is the change in length per unit of a block's length and is a measure of how much the steel responds to being squeezed.

Hooke's law relates the stress on the steel to the strain that results:

$$\text{strain} = \frac{\text{stress}}{\text{Young's modulus}}, \qquad (16.1.1)$$

where *Young's modulus* is a measure of how difficult it is to compress the steel. Strain is just a number and has no dimensions, while stress and Young's modulus are both pressures and are measured in pascals (Pa).

Young's modulus is related to the interatomic forces that hold a material together. The atoms in a solid exert attractive and repulsive forces on one another and these forces only balance when the atoms have the proper separations. If you push the atoms closer together or pull them farther apart, the forces no longer balance and they oppose your action. The stiffer the interatomic forces, the larger Young's modulus and the less the material shrinks as you squeeze it.

Because the interatomic forces in steel are primarily between iron atoms, it has roughly the same Young's modulus as iron: about 195 GPa (195 gigapascals or 195,000,000,000 Pa). This large value makes steel extremely difficult to compress. A 1 m cube of steel would lose somewhat less than a micron of height while supporting a city bus. A similar cube of lead would shrink 14 times more while a cube of tungsten would shrink only half as much.

Although we arrived at Eq. 16.1.1 while thinking about squeezing, this equation also applies to situations where the steel is exposed to gentle tension. In that case, the stress is negative (pulling apart rather than squeezing together) and the strain that results is also negative (stretching rather than compressing). Whether you squeeze or stretch steel, you are still measuring the stiffness of the interatomic forces and arrive at the same value for Young's modulus. Young's modulus is usually measured with **tensile stress** (stretching) rather then with **compressive stress** (squeezing) because compression can cause a thin piece of material to buckle while tension pulls it straight and true.

But compression and tension aren't the only stresses a steel block can experience. If you push the bottom of the block to the left and the top of the block to the right, the metal experiences **shear stress** (Fig. 16.1.4). This stress bends the block and causes shear strain in the metal. **Shear strain** is the angle of the bend caused by a shear stress. As long as the forces involved are relatively small, the shear strain is proportional to the shear stress,

$$\text{shear strain} = \frac{\text{shear stress}}{\text{shear modulus}}, \qquad (16.1.2)$$

where the *shear modulus* is a measure of how difficult it is to bend the metal.

Stress and strain help to characterize a particular steel. The crucial test for a knife is how it responds to stress. Because all steels have similar Young's and shear moduluses, it's hard to tell them apart with gentle stresses. The real differences between steels only appear when the stresses become large and Eqs. 16.1.1 and 16.1.2 stop being valid. That's when the steels begin to bend and break and when the good knives begin to distinguish themselves from the poor ones.

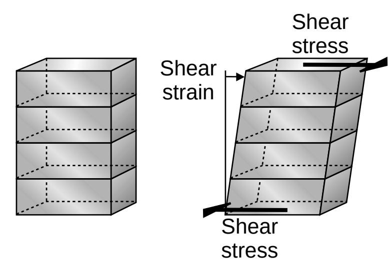

Fig. 16.1.4 - A material bends when it experiences shear stress. Shear stress is equal to the sideways force exerted on each unit of surface area and causes a shear strain in the material. The shear strain is equal to angle of the bend.

CHECK YOUR UNDERSTANDING #1: Holding Up Under Stress
Which is experiencing the greater stress: a single brick supporting a 100 kg post or two bricks, side by side, supporting a 200 kg beam?

Plastic Deformation and Crystalline Materials

A spring has an elastic limit beyond which it stops obeying Hooke's law and bends permanently. A gentle force distorts the spring elastically and it bounces back while a strong force deforms it forever. The same holds true for a piece of

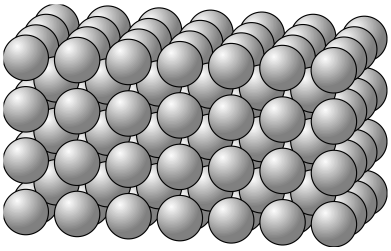

Fig. 16.1.5 - In ferrite, iron atoms are arranged in a body-centered cubic lattice. This lattice is built out of eight-atom cubes (2 by 2 by 2 atoms) with an additional atom located in the center of each cube.

steel. As long as the stress is small, steel undergoes **elastic deformation**—it distorts temporarily while stressed, according to Eqs. 16.1.1 and 16.1.2, and then returns to its original shape. However when the stress is large, steel undergoes **plastic deformation**—its atoms rearrange and it deforms permanently.

Steels differ considerably when it comes to plastic deformation. They all start off responding elastically to small stresses but gradually shift over to plastic deformation as the stresses increase. Just how much stress a particular steel can tolerate before it begins plastic deformation is its **yield strength** and is an important measure of that steel's load-bearing capacity. A weak steel yields easily to a modest stress while a strong steel responds elastically to all but enormous stresses. The cutting edge of a knife must tolerate severe stresses without yielding so that it doesn't become dull.

To see how plastic deformation occurs in a knife blade, we must examine the microscopic structure of steel. But since steel has a rather complicated structure, let's start with pure iron instead. Like most metals, iron is a crystalline solid. It may not have the pretty natural facets typical of some minerals but it does have an orderly arrangement of atoms. At room temperature, iron forms ferrite crystals. *Ferrite* is a ferromagnetic material in which the iron atoms are arranged in a body-centered cubic lattice (Fig. 16.1.5).

As you can see by looking at this lattice, it has smooth surfaces between sheets of atoms. When it experiences enough shear stress, this lattice can undergo a phenomenon called **slip**, in which sheets of atoms slide across one another. Slip is the most common mechanism for plastic deformation. When you squeeze, stretch, or bend a piece of pure iron so that it yields, you are probably causing slip. As the sheets slide across one another, the crystals change shape just like a stack of cards does when you push the top card to one side. The atoms lose track of their original positions and the iron doesn't return to its original shape when you stop pushing on it.

Slip occurs fairly easily in iron because the bonds that hold it together are relatively non-directional. Its **metallic bonds** are formed by a general sharing of electrons between countless atoms. This sharing lowers both the kinetic and potential energies of the electrons and causes the atoms to cling to one another. Because these metallic bonds are rather insensitive to the relative positions of its atoms, iron crystals are quite susceptible to slip.

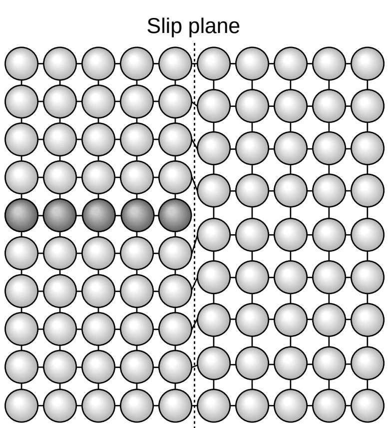

Fig. 16.1.6 - Dislocations occur when a sheet of atoms ends abruptly, part way through a crystal. In this top view of an imperfect crystal, the darkened sheet of atoms on the left ends suddenly and the sheets on the right are stretched to compensate. Slip occurs relatively easily along the slip plane. Thermal energy allows dislocations to move about in many materials, further softening those materials.

But there are other factors that affect when and where slip occurs. These factors appear because real metals are never perfect crystals. Nature tends to introduce randomness wherever possible so that even the purest crystals contain a few random mistakes. Typical iron crystals are filled with imperfections.

One common defect in iron is a **dislocation**, a sheet of atoms that ends abruptly in the middle of the crystal (Fig. 16.1.6). In a perfect crystal, a whole sheet of atoms must slip at once. But a dislocation breaks up the uniformity of the crystal and allows the sheet to slip gradually, one row of atoms at a time. A crystal containing a dislocation has an unusually low yield strength along the *slip plane*, the sheet of atoms perpendicular to the end of the dislocation.

While dislocations weaken iron by easing slip, there are other imperfections that strengthen iron by preventing slip. One such imperfection is iron's **polycrystalline** structure—rather than being a single crystal, iron is normally composed of many individual crystallites that meet one another at random angles. These individual crystallites are called **grains** and the boundary layers of atoms between grains are called **grain boundaries**.

Grains and the grain boundaries strengthen iron. Within each grain, slip only occurs between particular sheets of atoms and along specific directions. Since the grains are randomly oriented, they aren't all able to slip along the same direction. They must coordinate their slips along many directions to allow the piece of iron to yield along one direction, a process that can only occur when the iron is experiencing enormous stress. As a result, iron with lots of tiny grains has a higher yield strength than iron with only a few large grains.

The sizes and shapes of the grains depend on how the iron has been handled and processed. Because the atoms in a grain boundary don't fit into the crystallites they connect, they have relatively high potential energies and create a surface tension around each grain. **Surface tension** appears whenever a surface has extra potential energy and it acts to make that surface as small as possible. Like a soap froth that tries to minimize the surface area of its soap bubbles, the iron tries to minimize the surface area of its grain boundaries (Fig. 16.1.7). But the iron atoms can only rearrange while the iron is hot. **Annealing** iron—heating it to high temperature and then cooling it slowly—allows its larger grains to grow by consuming the smaller grains. Annealing is the principal method for softening iron, steel, and most other metals.

In contrast, deforming iron at low temperatures breaks up its grains and makes it harder. Like most metals, iron can be **work hardened** by pounding, rolling, folding, and twisting it. Wrought iron is a good example of work hardening, a technique that has been used for millennia to strengthen metals.

But annealing and work hardening have consequences beyond their effects on yield strength. Instead of yielding to stress, work hardened iron may fracture into pieces. This catastrophe is called **brittle fracture** because the metal doesn't yield before it breaks. Brittle fracture occurs in metals that are so hard that sheets of atoms separate completely rather than sliding across one another. Overworked iron may also suffer from **metal fatigue**, in which the metal tears as cracks work their way inward from surface defects.

Annealed iron yields before it breaks. In fact, it's **ductile**, meaning that it can be stretched quite a bit during plastic deformation. The main reason that the annealed iron breaks at all is that it gets thinner as it stretches and usually develops a narrow neck. Stretching work hardens the neck and the high stress there eventually pulls the atoms apart. Because the iron yields before it breaks, this type of breakage is called **ductile fracture**. The peak stress that the iron can withstand before such fracture occurs is its **tensile strength**.

Plastic deformation and ductility are actually quite useful in a knife. When the stress on the knife is too great for the blade to handle elastically, you would rather have it bend than break. A metal's ductility increases with temperature because thermal energy allows dislocations and other defects to move through crystals so that slip can occur between many different sheets of atoms. In a cold metal, those defects are immobile and slip is reduced. Because of its low ductility, cold iron is much more susceptible to brittle fracture than hot iron. (For some interesting examples of brittle fracture in cold metal, see ❒s.)

Moreover, plastic deformation requires energy. When you push on an iron knife and it bends in the direction of your push, you are doing work on the blade and the blade absorbs energy. A metal's ability to absorb energy during deformation is called **toughness**. Toughness is extremely important in car bodies, swords, and armor, all of which dent during collisions to absorb energy. If they shattered instead of yielding, they wouldn't be nearly as useful. Glass car windows and eyeglass lenses are dangerous precisely because they don't exhibit plastic deformation. In contrast, plastic windows and eyeglass lenses are much safer because they're able to dent and absorb energy without shattering.

CHECK YOUR UNDERSTANDING #2: Softness and Strength

Pure annealed copper is so soft that you can bend thick rods of it with your hands. Nonetheless, ancient coppersmiths managed to hammer pure copper into useful tools and weapons. What gave these tools and weapons their strength?

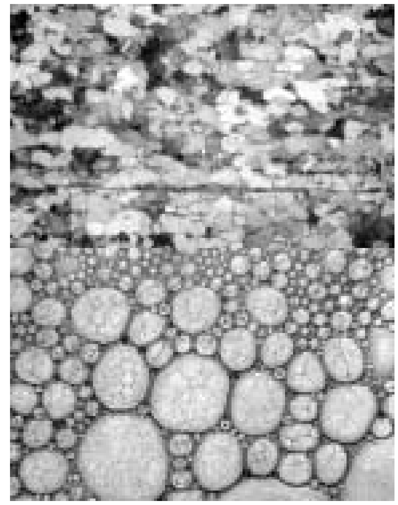

Fig. 16.1.7 - A piece of steel is composed of many tiny crystals (top). These crystals are jumbled together in an arrangement that resembles soap bubble froth (bottom). Surface tension acts to minimize the surface areas of both the metal grains and the bubble froth, so that both have similar features.

❒ When the Titanic struck an iceberg and sunk on April 14, 1912, it was thought that the iceberg had torn a long hole in its steel hull. However recent explorations of the wreck have found that the real culprit was probably brittle fracture. Instead of denting when it collided with the ice at 41 km/h, the ship's cold steel hull appears to have shattered.

❒ When the Purity Distilling Company's 30 m tall molasses tank burst in Boston's North End on January 15, 1919, it released 2.2 million gallons of molasses in a wave that destroyed several city blocks and killed 21 people and dozens of horses. The noontime disaster was initially attributed to an explosion but an official investigation found that the tank's brittle steel had fractured in the 4° C (40° F) winter weather. Purity, a subsidiary of United States Industrial Alcohol Company, paid $1,000,000 in damages. Ironically, the accident occurred one day before ratification of the 18th Amendment to the U.S. Constitution, prohibiting the sale of alcoholic beverages.

Steel

Adding carbon to iron produces steel, an *alloy* or metallic mixture that is far tougher and harder than pure iron. But different amounts of carbon produce different types of steel. Moreover, the ways in which this material is processed mechanically and thermally can dramatically change its character.

The first small amount of carbon added to iron dissolves in the iron to form a solid solution. It may seem strange for a solid to have something dissolved in it, but there is no rule that says a solvent must be liquid. Solution occurs whenever energy and entropy (randomness) make it favorable for one material to divide into atoms, molecules, or ions and become dispersed throughout a second material. Whether it's liquid or solid, iron can dissolve a small amount of carbon.

The iron remains in its ferrite form and the dissolved carbon atoms arrange themselves randomly in the *interstitial spaces* between iron atoms. Ferrite can dissolve up to 0.01% carbon by weight at room temperature and is somewhat harder than pure iron. The carbon atoms introduce local distortions in the ferrite crystals so that sheets of atoms can't slide as easily across one another. Since the dissolved carbon reduces slip, it increases the yield strength of the steel.

Only hydrogen, nitrogen, and carbon atoms are small enough to fit in between the iron atoms and cause *interstitial solution hardening* of the steel. However, there are a number of other atoms that harden iron and steel by substituting for iron atoms in ferrite crystals. These atoms also distort the crystals, impeding slip and increasing the yield strength of the steel. Phosphorus, silicon, manganese, chromium, and nickel atoms are often added to steel to cause this *substitutional solution hardening*.

When the carbon fraction in ferrite exceeds 0.01%, it can't all remain dissolved in the ferrite at room temperature. A new material appears in the steel: iron carbide (Fe_3C). Iron carbide is an extremely hard and brittle crystalline material, also called *cementite*. The presence of tiny cementite crystals dispersed throughout the ferrite impedes slip and increases the steel's yield strength. Strengthening of this sort is called *dispersion hardening*.

The arrangement of ferrite and cementite particles in the steel depends on the amount of carbon in the mixture and on the thermal and mechanical histories of the steel. When it's cooled slowly from high temperatures, steel consists of a material called *pearlite*, which is alternating layers of ferrite and cementite and has a carbon content of about 0.8% by weight. If the steel has less than 0.8% carbon, it forms some extra ferrite and consists of pearlite interspersed with ferrite. If it has more than 0.8% carbon, it forms some extra cementite and consists of pearlite interspersed with cementite.

However good knives use characteristics of steel that don't appear until steel is subject to more sophisticated heat treatments. The microscopic structure of steel changes remarkably as it's heated and cooled. Above 723 °C, iron forms austenite crystals. *Austenite* is a nonmagnetic material in which the iron atoms are arranged in a face-centered cubic lattice (Fig. 16.1.8).

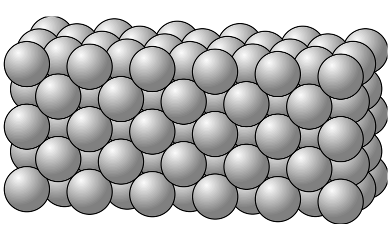

Fig. 16.1.8 - Above 723 °C, the atoms in solid iron are arranged in a face-centered cubic lattice. This lattice is built out of eight-atom cubes (2 by 2 by 2 atoms) with an additional atom located in the center of every face of that cube.

Austenite can dissolve more carbon than ferrite; up to 0.8% by weight at 723 °C and up to 2.06% at 1148 °C. The latter figure sets the upper limit for what is considered steel. As you slowly heat steel above 723 °C, its ferrite, pearlite, and cementite all convert into austenite—a structural change called a *solid-to-solid phase transition*. When you cool the steel back down slowly, the reverse phase transition occurs and the austenite turns into ferrite, pearlite, and cementite.

But even more remarkable effects occur during rapid cooling. If the austenite is suddenly cooled to about 600–650 °C and kept there, it transforms into *fine pearlite*—pearlite with extremely thin layers. To form pearlite, carbon atoms must diffuse through the iron. At lower temperatures, they can't travel the long distances needed to form thickly layered *coarse pearlite*, so they form fine pearlite instead. Fine pearlite doesn't undergo slip as easily as coarse pearlite so it has a higher yield strength.

Austenite that is suddenly cooled to about 260–400 °C and kept there doesn't form pearlite at all. The carbon atoms diffuse such short distances that they form tiny nodules of cementite. These nodules are arranged between sheets of ferrite in a layered material called *bainite*. Bainitic steel has a higher yield strength than fine pearlite.

Austenite that is suddenly cooled below about 200 °C forms an entirely new material. At 200 °C, there is so little thermal energy around that carbon atoms don't diffuse through the iron at all, so cementite, pearlite, and bainite can't form. Instead, the austenite tries to turn into ferrite without first getting rid of all its dissolved carbon. What forms is *martensite*, a distorted ferrite that is stretched in one direction.

Since ferrite can't have more than about 0.01% carbon in it by weight, martensite is essentially ferrite with way too much dissolved carbon. A solution containing more dissolved material than is stable at the current temperature is said to be **supersaturated**. The dissolved material will eventually come out of solution but it may take quite a long time. Martensite is a supersaturated solution of carbon in ferrite that lasts almost forever at room temperature. Because martensite is very resistant to slip, steel containing it has an extremely high yield strength and hardness. However martensite also makes the steel brittle by preventing it from undergoing plastic deformation. Steel containing martensite isn't as tough as steel containing bainite or fine pearlite.

Clearly sudden cooling or **quenching** of austenitic steel produces a harder material than slow cooling. The faster you cool the austenite and the colder you take it in that first step, the harder the steel becomes. Unfortunately, red-hot carbon steel must be plunged into water to cool it quickly enough to form martensite. The steel contracts during this harsh treatment and traps stresses that weaken the metal. To relieve these internal stresses, quenched steel is often **tempered** by reheating it just enough to let some of the stresses resolve themselves. The hotter and longer this tempering process, the more stress is relieved but the softer the steel becomes.

Quenching carbon steel in water is dramatic, with steam billowing up from the hot metal, but only a thin surface layer cools quickly enough to harden properly. To ease the formation of martensite and reduce the cooling rate needed to harden steel, it's often alloyed with other elements. Such alloy steels harden easily and deeply when quenched unspectacularly in oils or air and are important in knives and other tools. Some alloy steels also undergo *precipitation hardening*, in which small crystals of various compounds precipitate out of solution in the steel as it cools and strengthen the metal. Titanium carbide, niobium carbide, and vanadium nitride frequently appear in precipitation-hardened steel.

Part of a knife maker's skill comes in choosing just the right steel and just the right thermal processing to bring out that steel's best characteristics in the blade and its cutting edge. Knife blades require particularly careful heat treatment. A blade that retains too much stress will be hard but brittle while one that has been tempered at too high a temperature will dull easily.

In a fine knife, the cutting edge may be hardened more than the body of the blade by adjusting both the chemical composition of the edge and its heat treatment. Flames and laser beams are often used to reheat the edge and to add more carbon to the steel there. The result is a knife with the toughness of fine pearlite or bainite in its body and the hardness of carefully tempered martensite in its cutting edge. You can occasionally see evidence for this special treatment in the color and appearance of the blade. (Joining different materials to perform a task that neither could do alone is common in modern construction, see ❐.)

❐ A mixture of steel and concrete supports many buildings. These two materials enjoy a symbiotic relationship. Steel has enormous tensile strength but bends easily when compressed. Concrete can withstand immense compressive stress but fractures easily when stretched. However they can be combining into a composite material that has the tensile strength of steel and the compressive strength of concrete. Prestressing the pair by stretching the steel while the concrete is drying further improves the performance of the composite.

CHECK YOUR UNDERSTANDING #3: Hot Tips

Quality drill bits are usually made from a high carbon steel called tool steel (0.8% to 1.1% carbon). Each bit is shaped and hardened so that its tip can bore holes in most metals, including softer steels. When drilling in steel, you should lubricate the tip with a cutting oil so that sliding friction doesn't overheat it. What will happen to the tip if it becomes too hot?

Stainless Steel Blades

One last feature of steel that's important in knife blades is corrosion resistance. Because carbon steel is susceptible to rust, knife blades are usually made of stainless steel. This corrosion resistant material is formed by replacing at least 4% of steel's iron atoms with chromium atoms. Most stainless steels contain more than 11% chromium by weight and some contain nickel as well. Nickel enhances the steel's corrosion resistance and also makes it more ductile.

But not all forms of stainless steel are appropriate for knives. Alloying the steel with chromium and nickel affects more than just its chemical properties. The crystalline structures of these alloys depend on the precise mixtures of the various elements and on their thermal histories. Perhaps the most remarkable effect of adding chromium and nickel to the steel is that these elements can make austenite stable at room temperature.

The most common stainless steel is called *18–8 stainless* and contains roughly 18% chromium and 8% nickel. It consists exclusively of nonmagnetic austenite grains. Since 18–8 stainless can't form cementite or martensite, it can't be hardened by thermal processing. In fact, overheating it can spoil its corrosion resistance (see ❐). The only way to harden 18–8 stainless steel is to work harden it. Because it's difficult to make a good knife edge by work hardening, 18–8 stainless is a poor choice for knives. However 18–8 stainless is inexpensive, ductile, and easy to work with so it's often used in cafeteria grade cutlery. The next time a dull knife bends while you're cutting your food, you'll know that it's probably made from soft, austenitic stainless steel.

❐ Austenitic stainless steels like 18–8 are susceptible to subtle damage when they're overheated. At temperatures between about 500° C (932° F) and 800° C (1472° F), the chromium and carbon in the steel can precipitate out at the grain boundaries as chromium carbide. This process depletes the grain edges of chromium and leaves them extremely vulnerable to corrosion. Corrosion at the grain edges cuts the grains right out of the metal so that the metal falls apart. That's why a badly overheated stainless pot is never the same again.

There are two ways to harden stainless steels: martensite formation and precipitation hardening. *Martensitic stainless steels* contain little or no nickel and moderate amounts of carbon. With too little nickel to stabilize austenite, martensitic stainless steels crystallize like normal steels and are magnetic. Quenching hot martensitic stainless steel produces tiny martensite crystals and hardens the metal.

Precipitation hardening stainless steels contain alloying elements that form hard precipitate crystals within the steel during quenching. Titanium, niobium, aluminum, copper, and molybdenum dissolve in the steel when it's hot but form tiny precipitate crystals within the steel as it cools. These crystals make the stainless steel hard.

High quality knives and cutlery are generally made of martensitic or precipitation hardening stainless steels. These metals are tough, keep their edges well, and are hard to bend. But knives and utensils made from these steels require careful heat treatment during manufacture, so they are considerably more expensive than common cafeteria dinnerware.

CHECK YOUR UNDERSTANDING #4: Steel vs. Steel

With some care, you can cut a cheap stainless steel knife with a good stainless steel knife. How is that possible?

How Steel Is Made

Steel is produced on enormous scales using techniques that have become almost as high-tech as those involved in the semiconductor industry. The days of dirty, grimy steel mills are over because modern high quality steels require exceptional chemical purity.

Steel is generally made in two steps: iron ore is converted into pig iron and pig iron is converted into steel. These two steps were once quite separate and followed by many further independent processing steps. However modern steel mills convert iron ore into finished steel in an uninterrupted manner.

Iron ores are essentially iron oxides (Fe_2O_3, Fe_3O_4, FeO) so something must remove the oxygen atoms to convert iron ore into iron. That something is carbon. When iron oxide and carbon are heated together, the carbon reacts with the oxygen to form carbon monoxide and carbon dioxide. These two gases escape and leave behind *pig iron*, a mixture of iron and carbon.

The carbon needed for this process is obtained by heating coal to high temperatures. The coal cracks chemically and releases compounds such as acetylene, light oil, coal tar, and ammonia, all of which are collected for use outside the steel mill. What remains is nearly pure carbon, a material called *coke*.

But both the iron ore and the coke contain rocks and other undesirable materials that would contaminate the pig iron. To remove these contaminants, the iron ore and coke are mixed with *lime* (CaO) obtained from limestone ($CaCO_3$). The lime acts as a liquid *flux* at high temperature, floating on top of the molten pig iron and dissolving many of the undesirable materials.

The mixture of iron ore, coke, and lime is converted into pig iron in a blast furnace. The coke burns in a stream of air, providing the intense heat needed to initiate and sustain the chemical reactions between carbon and iron oxide. The lime flux carries away most of the unwanted materials as slag, which can then be used to make concrete.

Until about 1856, this was all the processing that iron received. In fact, most iron ore was converted to iron at relatively low temperatures so that it never melted at all. Carbon and carbon monoxide diffused through the iron ore and reacted with the oxygen atoms, thereby converting solid iron oxide into solid iron. This iron was then hammered into shape as wrought iron (Fig. 16.1.9). It contained various amounts of carbon and lots of slag.

Good techniques for melting pig iron and removing carbon and slag from it to make steel appeared in the last century and a half. The Bessemer converter, the open-hearth process, and the basic oxygen process all remove excess carbon and other impurities by burning them out of the pig iron. The basic oxygen process

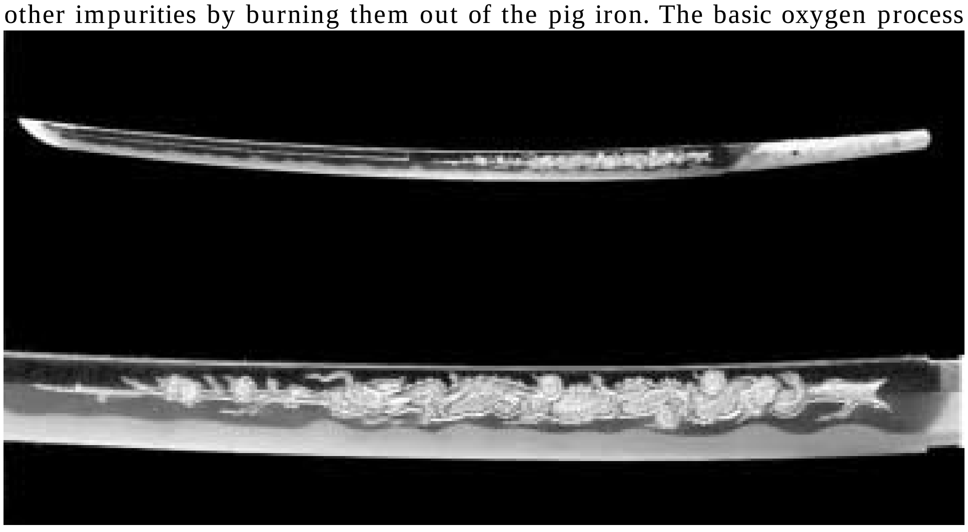

Fig. 16.1.9 - The blade of a Samurai sword was made of several different steels, hammered together so that the hard, razor-sharp cutting edge was supported by a tough durable body. Lumps of carbon steels were made from black iron ore (Fe_3O_4) in charcoal-fired furnaces. The sword smith carefully selected portions of those lumps for carbon content and gradually assembled the materials needed to craft the blade. The lumps were then heated, pounded, folded, and assembled into a blade whose carbon content was low near the center but high on the surface. A paste that covered all but its cutting-edge then protected the blade. The sword smith heated the blade to the right color of incandescence and plunged it into water. The hardened edge was then carefully ground to the razor sharpness of the finished sword.

now dominates the steel industry. It uses a water-cooled pipe or “lance” to inject pure oxygen gas into a vessel of liquid pig iron. The impurities burn away, leaving behind almost pure iron. Even oxygen and other gases are often removed from the iron by vacuum pumps. The conversion from pig iron to steel takes roughly 30 minutes and is monitored by disposable sensors that are plunged into the liquid metal to examine its composition.

To make the appropriate steel, alloying elements are added to the liquid iron and the resulting material descends out of the bottom of the converter through a series of containers. In a continuous casting machine, the steel is formed into a red-hot solid bar that descends from a mold. This bar is bent until it’s horizontal and it then enters a series of rolling machines. These machines shape the steel into anything from beams to sheet metal. The whole procedure is so smoothly orchestrated that the steel making never stops. The mill just keeps on making more steel and it keeps flowing out to the finishing equipment. Even changes in the steel’s composition are handled without interrupting the flow.

The finishing equipment rolls the steel into various shapes, gradually changing its dimensions with enormous pressures and high temperatures. While steel is occasionally worked with as a liquid, it’s generally much easier to handle as a hot solid.

While the work hardened steel that emerges from these rolling machines is fine for construction, it must be softened before it can be molded into car body panels or cooking pots. Softening is done by annealing the steel in huge ovens. At the opposite extreme is spring steel, which is reheated and quench hardened so that it snaps back to its original shape after being deformed.

Many tools, including locks and wrenches, need a hard surface layer on a softer core. The hard surface makes the tool impenetrable while the softer core allows it to withstand energetic blows. This layered arrangement can be made by *case hardening* the tool—exposing its heated surface to extra carbon. The carbon atoms diffuse into the surface and increase its hardenability. Once it has been heat treated, a case hardened tool is extremely difficult to break.

CHECK YOUR UNDERSTANDING #5: Going Up in Smoke

Pig iron contains roughly 4% carbon by weight. If a basic oxygen converter is initially charged with 250 metric tons (250,000 kg) of pig iron, how much carbon must be burned away to make steel?