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# CHAPTER 3

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## CARBON STEELS

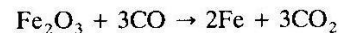
Plain-carbon steels are the most important group of engineering alloys, and accounted for 77.7 percent of the steel produced in the United States in 1988. The relatively low cost and wide range of properties of plain-carbon steels make them of prime importance as engineering materials. The applications of plain-carbon steels are innumerable. Some of the major product forms of plain-carbon steels are sheet, strip, bar, wire, tubular products, structural shapes, forgings, plate, and castings.

### 3-1 MODERN STEELMAKING PROCESSES

#### Principal Steps in the Production of Finished Steel-Mill Products

A general diagram for the production of steel from raw materials to the finished mill products is shown in Fig. 3-1. The following is a brief description of the basic steps involved in the steelmaking process.

1. *Reduction of iron compounds (chiefly iron oxides) to molten iron (pig iron).* In this process, coke (carbon) acts as a reducing agent in a blast furnace (Fig. 3-2) to produce iron containing from 3 to 4.5% C according to the following typical reaction:



Since most steel used today contains less than 1% C, the excess carbon must be removed from the pig iron to convert it to steel.

# STEELMAKING

FROM RAW MATERIALS TO FINISHED MILL PRODUCTS  
(EXCLUDING COATED PRODUCTS)

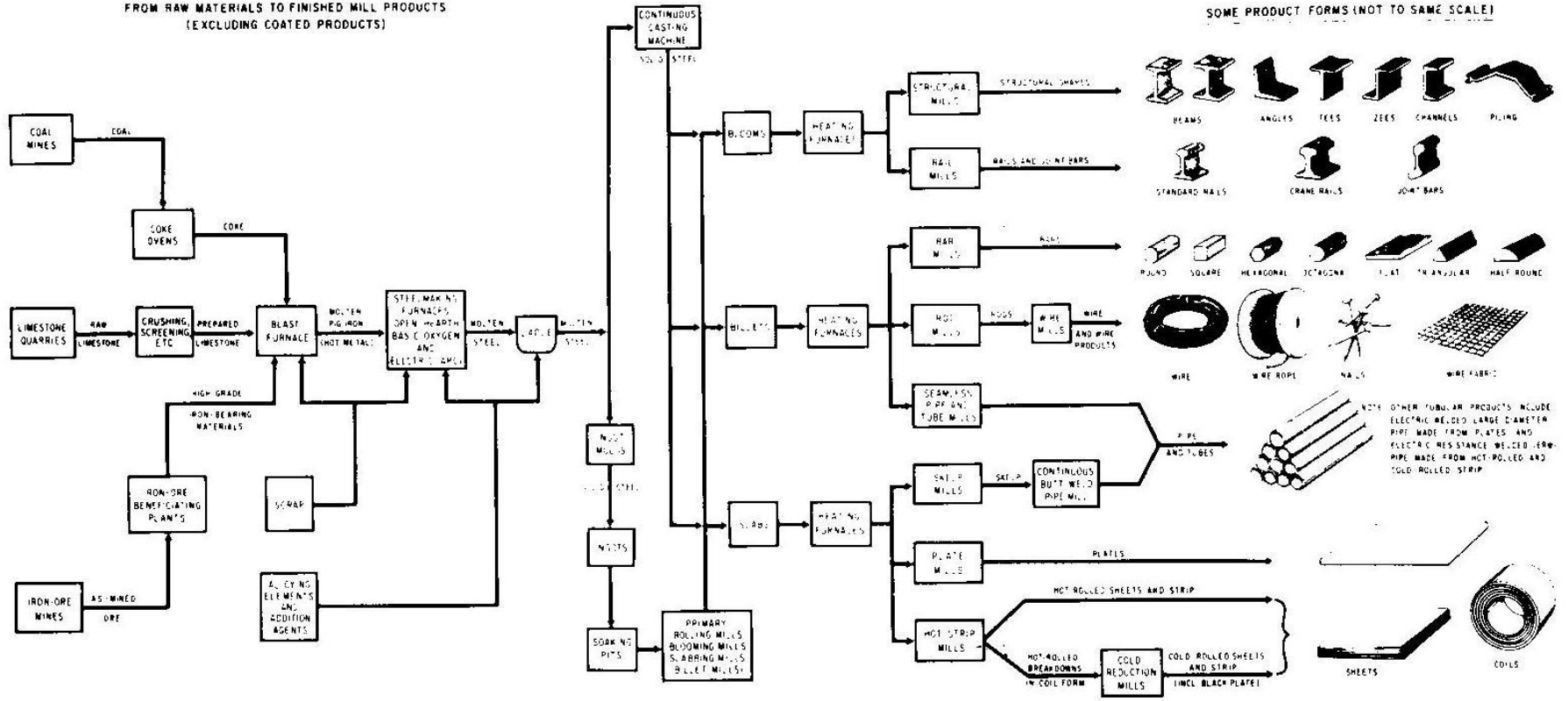
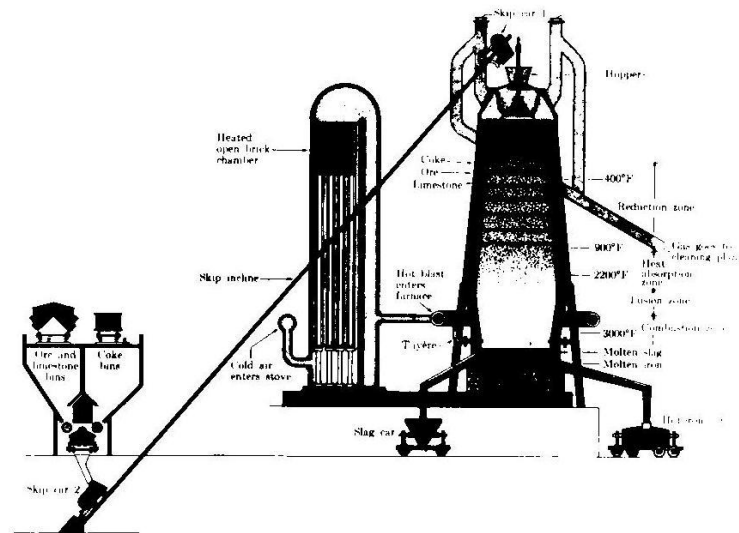


FIGURE 3-1

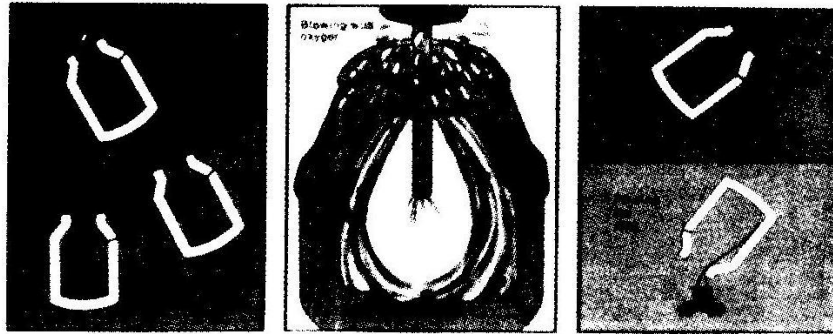
Flow diagram showing the principal process steps involved in converting raw materials into the major product forms, excluding coated products. [After H. E. McGannon (ed.), "The Making, Shaping, and Treating of Steel," 9th ed., United States Steel Corporation, Pittsburgh, 1971, p. 2.]



**FIGURE 3-2**

Cross section of the general operation of a modern blast furnace. (After A. G. Guy, "Elements of Physical Metallurgy," 2d ed., © 1959, Addison-Wesley, Reading, Mass., Fig. 2-5, p. 21.)

2. *Process steelmaking.* In furnace-process steelmaking, the excess carbon in the steel is reduced to the desired level by controlled oxidation of mixtures of pig iron and iron and/or steel scrap. The two principal furnace steelmaking processes used are (a) basic-oxygen furnace and (b) electric-arc furnace. Alloy steels are made by adding elemental or alloy manganese, chromium molybdenum, nickel, vanadium, etc., into the molten steel during or after the carbon-removal process.
3. *Casting.* After the steel has reached its desired composition, it is tapped or poured from the steelmaking furnace into a large container or *ladle*. Sometimes alloying elements or deoxidizing agents such as aluminum or ferrosilicon are added to the molten steel in the ladle to further adjust the chemical composition of the steel or to remove gaseous oxygen. The steel is then poured (*teemed*) into tall rectangular stationary ingot molds or tapped into a *tundish* (reservoir) for continuous casting of the steel.
4. *Rolling (forging).* Most ingots are reheated to a high temperature (below the melting point of the lowest-melting constituents in the steel) and held for a sufficient time so that the ingots will be homogeneously heated throughout. The reheated or soaked ingots are then hot-rolled or forged into the desired shape. Continuously cast steel can be directly cast into the semifinished shape desired.

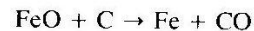


**FIGURE 3-3**  
 Steelmaking in a basic oxygen furnace. (Courtesy of Inland Steel Company.)

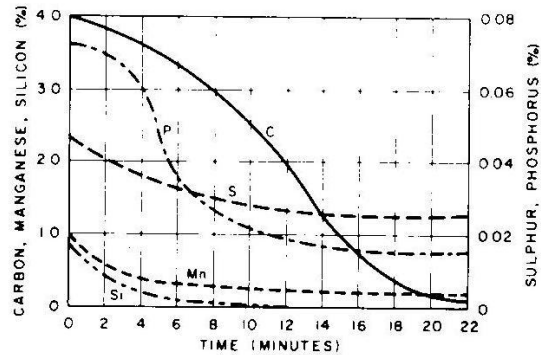
5. *Mechanical treatment.* The semifinished products are further worked by hot rolling, cold rolling, forging, extruding or drawing, etc., to produce the finished steel products such as plate, sheet, bars, tubular products, structural shapes, etc.
6. *Heat treatment.* In order to produce the finished steel product in the desired strength, it is sometimes necessary to heat-treat the steel. Heat treatment allows a certain degree of control over the structure and properties of the steel. The heat treatment of steel will be emphasized in this book since it greatly influences the structure and properties of steels.

### Steelmaking Processes

**BASIC-OXYGEN PROCESS (BOP).** In 1989 in the United States 55.9 percent of the crude steel was produced by the basic-oxygen process and 35.5 percent by the electric-arc process. In the BOP process, liquid pig iron and up to 30 percent scrap are charged into a barrel-shaped refractory-lined converter. In one type of BOP process an oxygen lance is inserted into the top of the converter (Fig. 3-3). Pure oxygen from the lance reacts with the liquid bath to form iron oxide. Carbon in the steel reacts with the iron oxide to form carbon monoxide:



Immediately after the oxygen reaction starts, slag-forming fluxes (chiefly lime) are added in controlled amounts. The reaction proceeds rapidly and requires no external flame. In about 45 min, about 200 tons of steel can be produced with a desired carbon level and low levels of impurities such as sulfur and phosphorus. Fig. 3-4 shows how the levels of carbon, manganese, silicon, sulfur, and phosphorus are reduced with time for a typical heat of steel.



**FIGURE 3-4**

Schematic representation of progress of refining in a top-blown basic-lined vessel. [After H. E. McGannon (ed.), "The Making, Shaping, and Treating of Steel," 9th ed., United States Steel Corporation, Pittsburgh, 1971, p. 494.]

In one type of variation of the top-oxygen-blowing BOP process, added stirring of the oxygen-hot metal reaction is produced by blowing a mixture of argon and nitrogen in from the bottom of the converter. In another type of BOP process (Q-BOP), oxygen is blown in from the bottom of the converter.

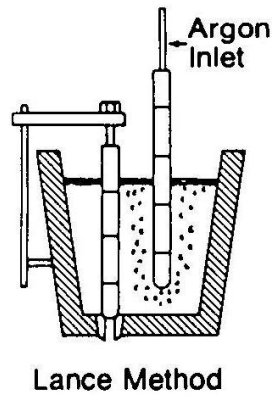
**ELECTRIC-ARC PROCESS.** In this process, adjustable electrodes are lowered to a point just above a charge of cold steel scrap. An electric arc is struck between the electrodes and the steel scrap, resulting in the melting of the steel (Fig. 3-5). Since about 1945, this process has been used increasingly for melting plain-carbon steel scrap. Since the electric-arc furnace has a relatively low capital investment cost and can remelt steel scrap, this process is used where local supplies of steel scrap are available.

The electric-arc furnace is also used for producing special alloy steels which contain an appreciable amount of easily oxidized alloying elements such as chromium, tungsten, and molybdenum. It is also used when very low sulfur



**FIGURE 3-5**

Steelmaking in an electric-arc furnace. (Courtesy of Inland Steel Company.)



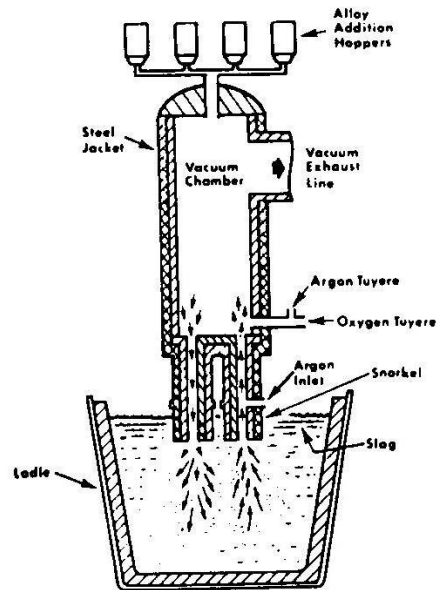
**FIGURE 3-6**  
Stirring molten steel in a ladle with an argon-gas lance. (After "Making, Shaping, and Treating of Steel," 10th ed., Association of Iron and Steel Engineers, 1985.)

and phosphorus levels are necessary in some alloy steels. Special slag covers are used to lower sulfur and phosphorus levels and give protection against oxidation of the alloying elements. Careful temperature control is also possible with this process.

**LADLE METALLURGY.** In the 1980s considerable improvements were made in producing cleaner steels with lower oxygen and sulfur contents and consequently lower inclusion contents by using *ladle metallurgy*. The improved refining processes are carried out in the liquid-steel transfer ladle into which the steel has been poured from the basic-oxygen or electric-arc furnaces. By applying these refining operations outside the steelmaking furnace, valuable steelmaking time and fluxes are saved. Also, much better control is possible inside the ladle as some refining processes, i.e., desulfurization, require a reducing atmosphere. Vacuum degassing is also possible with the steel in the ladle. Fig. 3-6 shows a schematic of a steel ladle with an argon-gas lance submerged in the molten steel for stirring.

The use of special ladle practices can achieve the following:

1. *Improved temperature control.* By using submerged heating electrodes or aluminum additions, the steel temperature can be increased to the ideal temperature for continuous casting.
2. *Composition homogenization.* By stirring the molten steel with argon gas, the chemical composition of the steel can be made more homogeneous.
3. *Improved deoxidation.* Closer control can be attained for deoxidizing the molten steel by adding just enough aluminum to remove the oxygen. Continuously cast steel must be fully deoxidized to prevent the formation of blowholes or pinholes at or close to the surface of the cast product.
4. More efficient methods can be applied to add alloying additions and to control the final chemical composition of the steel.



**FIGURE 3-7**  
Schematic of the RH-OB vacuum-degassing system for molten steel. (After "Making, Shaping, and Treating of Steel," 10th ed.: Association of Iron and Steel Engineers, 1985.)

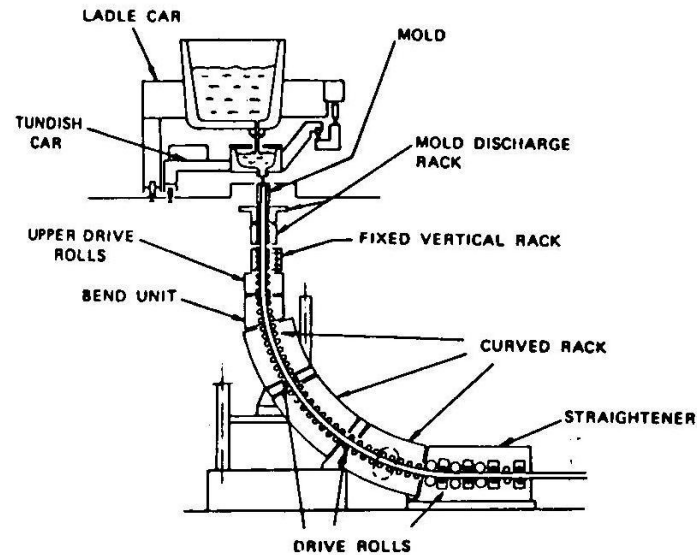
5. *Desulfurization.* By using reducing conditions with a synthetic cover slag in the ladle, sulfur contents can be reduced to very low levels and inclusions can be floated to the surface of the steel into the slag.
6. The shape of remaining sulfide and oxide inclusions can be controlled by calcium and rare earth additions.

**VACUUM DEGASSING.** Vacuum degassing in conjunction with ladle metallurgy has been introduced in the past years for the following reasons:

1. Ultralow-carbon steels with carbon contents as low as about 0.002 percent can be produced. Sheet steels with very low carbon and nitrogen levels can now be continuously annealed and still have high formability for deep drawing applications.
2. Very low hydrogen contents can be obtained to reduce hydrogen flaking and porosity.

The most widely used vacuum-degassing system in the United States in 1991 was the RH-OB (Ruhrstahl-Heraeus-oxygen-blowing) system, which is schematically shown in Fig. 3-7. In the RH-OB process two legs (or snorkels) are immersed in the molten steel in the ladle. Argon gas is introduced in the up leg to pump the metal into the RH unit for treatment. Oxygen units introduce oxygen in the RH chamber to reduce the carbon content of the molten steel to





**FIGURE 3-8**  
Section schematic of a continuous-casting machine for steel. (After "Making, Shaping, and Treating of Steel," 10th ed., Association of Iron and Steel Engineers, 1985.)

very low levels by the reaction



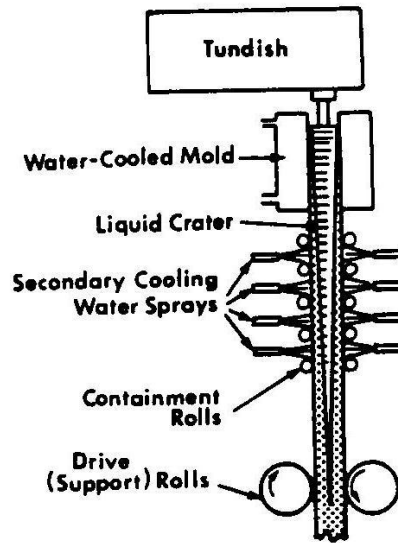
The steel is then returned in the down leg of the RH unit and recirculated. In the RH system the hydrogen content of the steel is also reduced by about half while producing the low-carbon steels.

### 3-2 INGOT CASTING

In general, most steel is produced by the basic-oxygen or electric-arc processes and is transferred in the molten state into large ladles. The steel, after being treated in the ladle, is then cast continuously into long ingots which are periodically cut into the required length or "teemed" or cast into stationary ingot molds. In 1991 about 75 percent of the steel produced in the United States was continuously cast.

#### Continuous Casting

In continuous casting, the ladle of molten steel is transported to an elevated casting platform above a casting machine (Fig. 3-8). The molten steel is discharged into a rectangular trough, called a *tundish*, which acts as a reservoir



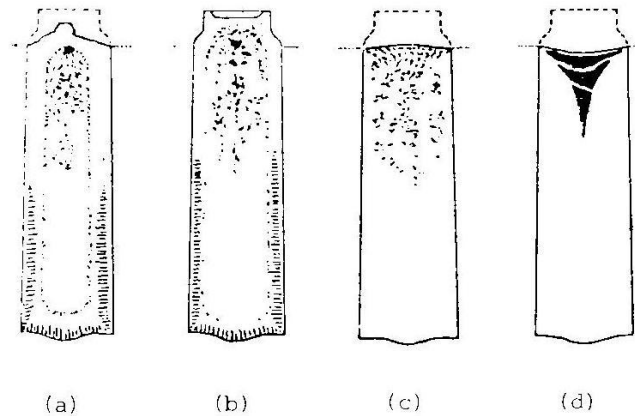
**FIGURE 3-9**  
 Details of the mold region of a continuous-casting system for steel. (After "Making, Shaping, and Treating of Steel," 10th ed., Association of Iron and Steel Engineers, 1985.)

for the steel (Fig. 3-9). From a spout in the bottom of the tundish, the molten steel is poured into a water-cooled mold with a movable bottom, which is slowly lowered. As the molten steel enters the mold, the metal at the mold surface solidifies, forming a thin skin. This skin thickens as the metal passes through the mold. The remaining metal in the center of the ingot is solidified by cold water sprayed onto the ingot as it leaves the mold. The solid metal billet is pulled by rollers so that a long continuous steel slab is produced, as shown in Fig. 3-8.

For most types of steels, the continuous-casting process is more advantageous as is evidenced by the worldwide change from the casting of individual ingots to continuous casting. Advantages of the continuous-casting process include reduced costs, improved product quality, increased yield, energy savings, and less pollution.

Metallurgical quality improvements include less variability in chemical composition of metallurgical structure. In addition to improved homogenization of carbon, sulfur, and alloying elements across the section of a continuously cast slab, there is also less variability along the length of the slab. In modern continuous casting, the surface quality of the cast slab is superior to that of a semifinished rolled shape from an individual ingot with respect to surface defects such as seams and scabs. Thus, an improved, more uniform finished product can be attained with fewer internal and surface defects.

The yield of usable steel from continuous casting is higher than with individually cast ingots since it is not necessary to crop the ends of continuously cast slabs. Scaling losses associated with ingot heating in soaking pits are also avoided with continuously cast slabs. Energy savings are achieved with continu-

**FIGURE 3-10**

Types of ingot structure. (a) Rimmed; (b) capped; (c) semikilled; (d) killed. Note the distribution of blowholes in the rimmed steel and the pipe cavity in the killed steel. [After H. E. McGannon (ed.), "The Making, Shaping, and Treating of Steel," 9th ed., United States Steel Corporation, 1971, p. 597.]

ous casting because of the elimination of the high energy costs of ingot-soaking pits and the operation of primary rolling mills. The thickness of continuously cast slabs is about half that of the individual ingots, and so much less hot rolling is required.

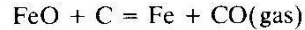
### Individual Ingot Casting

Casting of steel into individual ingot molds is still used in the United States for producing steel ingots for hot-working. In this process, a full ladle of steel is moved by overhead crane so that it can be tapped (or teemed) into individual molds standing upright on rail cars. The ingot molds are slightly tapered for easy removal after the solidification of steel (Fig. 3-10). After stripping the ingot molds, the hot ingots are transferred to soaking pits for reheating for hot rolling. About 25 percent of the steel cast in the United States today is still cast in individual ingot molds.

### 3-3 TYPES OF INGOT STRUCTURES

When steel is cast or teemed into individual stationary molds, various types of structures can be produced depending on how the steel is allowed to solidify (Fig. 3-10), while the decision as to type of ingot structure to be produced depends on the final use of the steel. During the solidification of the steel, excess gases are expelled from the metal. Oxygen in the molten steel in the form of FeO reacts with carbon in the steel to produce carbon monoxide according to

the following reaction:



Since the steel solidifies over a range of temperatures, gases evolved from the unsolidified liquid can be trapped at the solid-liquid interfaces, producing *blowholes*. The amount of oxygen dissolved in the liquid steel just before casting can be controlled by the addition of deoxidizing agents such as aluminum and ferrosilicon. Depending on the amount of gases, mainly oxygen, remaining in the liquid steel during the solidification process, the following types of ingot structures can be produced: rimmed, capped, semikilled, and killed (Fig. 3-10).

### **Rimmed Ingot Structure**

In a rimmed steel, the reaction of the dissolved oxygen and carbon to form carbon oxide gases (CO and CO<sub>2</sub>) is allowed to progress until a heavy rim of relatively pure iron free from voids is produced (Fig. 3-10*a*). The interior of the ingot contains gas porosity in the form of blowholes of various sizes and shapes. During hot rolling, these voids are welded together to produce sheet and plate with good surface quality. The rimming action lowers the carbon content of steel and causes segregation of carbon, sulfur, and phosphorus toward the center and top of the ingot. The segregation of the metalloids causes a variation in composition and mechanical properties from sheet to sheet. Rimmed steel is cheaper to produce since the top part of the ingot does not have a large pipe cavity, which means the yield is higher.

### **Capped Ingot Structure**

In capped steels, the rimming action is stopped chemically or mechanically (Fig. 3-10*b*). Chemically capped steel is poured into the mold and allowed to rim for 1 to 3 min, and then the reaction is stopped by the addition of shot aluminum or ferrosilicon to the top. In mechanical capping, a heavy cast-iron cap is used to close the top opening as soon as pouring is stopped. The gas evolution is stopped due to the increased pressure when the metal strikes the cap.

### **Semikilled Ingot Structure**

A typical semikilled ingot structure is shown in Fig. 3-10*c*. In this type of ingot, only a slight amount of gas is allowed to evolve during solidification. Only a sufficient number of blowholes are allowed to form so that the volume contraction due to solidification can be compensated for.

### **Killed Ingot Structure**

Fully killed steels evolve no gas and form a pipe cavity at the top of the ingot (Fig. 3-10*d*) since the addition of aluminum or silicon to the molten steel in the

ladle or mold stops the gas reaction. Aluminum-killed steels are widely used for cold-rolled sheet that will be used for severe forming or deep drawing and also for sheet that will be stored for long periods before being used. These steels show minimum strain aging and have a fine-grain size. (Strain aging will be discussed in Sec. 3-8.) The composition of killed steels is more uniform than rimmed steels because there is no gas reaction.

### **3-4 CLASSIFICATION OF PLAIN-CARBON STEELS**

Plain-carbon steels are classified by several different systems, depending on the type of steel and its application. There is thus no one classification system that applies to all plain-carbon steels. The two most commonly used systems are the AISI-SAE<sup>1</sup> system and the ASTM<sup>2</sup> classification.

#### **AISI-SAE Classification System for Plain-Carbon Steels**

This system is applied to hot-rolled and cold-finished bars, wire, rod, and seamless tubing, and semifinished products for forging. Since the carbon content of plain-carbon steels essentially determines their strength, this system uses the percent carbon to designate the different steels. A four-digit number is used, with the first two digits being 10 to designate a plain-carbon steel. The second two digits indicate the hundredths of percent carbon. For example, the number 1020 indicates a plain-carbon steel with 0.20 nominal percent carbon. As will be seen in the next chapter on alloy steels, this system is also used for alloy steels, with the first two digits altered to indicate other major alloying elements. Table 3-1 lists some selected grades of plain-carbon steels.

#### **ASTM System**

In the ASTM system, standards are written for various alloys to meet special requirements. In addition to establishing chemical compositions, the ASTM standard also set mechanical property levels and often specify fabrication procedures and heat treatments. Plate steels, for example, are mainly classified according to ASTM standards.

#### **Other Systems**

Special standards are often set for special products. For example, many low-carbon steel products such as tin plate and special automotive sheet are

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<sup>1</sup> AISI: American Iron and Steel Institute; SAE: Society of Automotive Engineers.

<sup>2</sup> American Society for Testing and Materials.

TABLE 3-1  
AISI-SAE carbon-steel compositions

AISI-SAE No.	% C	% Mn
1006	0.08 max.	0.25-0.40
1010	0.08-0.13	0.30-0.60
1015	0.13-0.18	0.30-0.60
1020	0.18-0.23	0.30-0.60
1025	0.22-0.28	0.30-0.60
1030	0.28-0.34	0.60-0.90
1035	0.32-0.38	0.60-0.90
1040	0.37-0.44	0.60-0.90
1045	0.43-0.50	0.60-0.90
1050	0.48-0.55	0.60-0.90
1055	0.50-0.60	0.60-0.90
1065	0.60-0.70	0.60-0.90
1070	0.65-0.75	0.60-0.90
1075	0.70-0.80	0.40-0.70
1080	0.75-0.88	0.60-0.90
1085	0.80-0.93	0.70-1.00
1090	0.85-0.98	0.60-0.90
1095	0.90-1.03	0.30-0.50

P, 0.040 max; S, 0.05 max.

produced according to special specifications, and so there is no general numbering system for these steels.

### 3-5 EFFECTS OF OTHER ELEMENTS IN PLAIN-CARBON STEELS

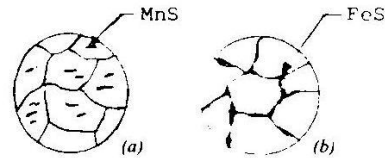
In addition to carbon, plain-carbon steels contain the following other elements:

- Manganese up to 1.0 percent
- Sulfur up to 0.05 percent
- Phosphorus up to 0.04 percent
- Silicon up to 0.30 percent

The effects of each of these elements in plain-carbon steels are summarized in the following subsections.

#### Manganese

Manganese in plain carbon steels ranges from 0.35 percent maximum in AISI 1005 steel to 1.0 percent maximum in AISI 1085 steel. Manganese combines with the sulfur present in the steel to produce manganese sulfide (MnS), which



**FIGURE 3-11**  
Schematic distribution of (a) manganese sulfide and (b) iron sulfide in plain-carbon steels.

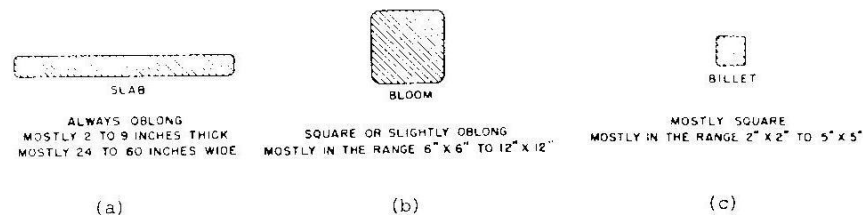


**FIGURE 3-12**  
Mixed sulfides of iron and manganese containing a few small oxide spots. (Rimmed low-carbon steel) (As published:  $1000\times$ ) (After *Metals Handbook*, 8th ed., vol. 7, American Society for Metals, 1972, p. 16.)

exists as soft gray inclusions in the steel. The MnS inclusions are scattered in the grain bodies and are elongated in the direction of working (Fig. 3-11a). Figure 3-12 shows an inclusion in a rimmed low-carbon steel which consists of mixed sulfides of iron and manganese. MnS is preferable to iron sulfide (FeS) in the steel since FeS is a brittle, low-melting compound which forms at the grain boundaries (Fig. 3-11b). Manganese also raises the yield strength of plain-carbon steels by refining the pearlite and by solid-solution strengthening of the ferrite. Manganese increases the depth of hardening during quenching from austenite, but in large amounts it also increases the tendency toward cracking and distortion during quenching.

### Sulfur

Sulfur is present up to a maximum of 0.05 percent in plain-carbon steels. It usually is combined with manganese in the steel to produce MnS inclusions, as indicated in Fig. 3-11a. However, if the sulfur combines with iron, it forms FeS, which usually occurs as a grain boundary precipitate (Fig. 3-11b). Since FeS is hard and has a low melting point, it can cause cracking during hot and cold working of the steel. Thus in order to avoid the FeS inclusions, the manganese to sulfur ratio in these steels is usually about 5:1.

**FIGURE 3-13**

Typical cross sections and dimensional characteristics of shapes of steel products after primary rolling. (a) Slab, (b) bloom, (c) billet. [After H. E. McGannon (ed.), "Making, Shaping, and Treating of Steel," 9th ed., United States Steel Corporation, Pittsburgh, 1971, p. 675.]

### Phosphorus

Phosphorus is limited to a maximum of 0.04 percent in plain-carbon steels since it forms a compound,  $\text{Fe}_3\text{P}$ , which is extremely brittle and segregates in the steel.

### Silicon

The amount of silicon in plain-carbon steels varies from about 0.1 to 0.3 percent. Silicon is used as a deoxidizer, and forms  $\text{SiO}_2$  or silicate inclusions. Otherwise, silicon has little effect on the mechanical properties of plain-carbon steels, since it dissolves in ferrite.

## 3-6 HOT AND COLD WORKING OF CARBON STEELS

### Primary Rolling

Reheated ingots are removed from the preheating furnaces (soaking pits) at about  $1370^\circ\text{C}$  and are hot-worked by primary rolling mills into slabs, billets, and/or blooms (Fig. 3-13). In the slabbing mill, the ingot is rolled into a flat slab (Fig. 3-13a), which is later further rolled into plate and sheet. In the blooming mill, the ingot is rolled into a rectangular shape called a bloom (Fig. 3-13b), which is subsequently rolled into structural shapes and rails. In the billet mill, the ingot is rolled into a smaller rectangular shape than a bloom, called a billet (Fig. 3-13c), which is later rolled into bars, rods, and seamless pipe and tube stock.

By continuously casting, slabs, billets, and blooms may be cast directly so that the primary working stage can be circumvented. Wherever economically and technically feasible, therefore, continuous casting is used, although most steel today is still cast as individual ingots. Figure 3-1 shows the steel flow



diagrams and indicates the stages by which the various steel products are processed from slabs, billets, and blooms, but in this book the emphasis will be on the processing of *sheet products* since these are economically the most important steel products.

### Hot Rolling

To produce hot-rolled flat steel strip, slabs are reheated to about 1315°C and are reduced from about 10 in in thickness to about 0.1 in by a series of reductions in a line of hot-rolling mills (Fig. 3-14). A series of roughing mills reduces the thickness of the slab to about 1 in. The slab is then rolled to a final hot-strip thickness of about 0.1 in in a series of closely spaced finishing mills, and then is coiled.

If a deep-drawing quality low-carbon killed steel is being rolled, it is important to keep the reheating temperature high-enough so that aluminum nitride (AlN) will be taken into solid solution. The temperature of the slab must also be kept high enough so that iron oxide (scale) formed on the strip surface can be removed by high-pressure water sprays at each roughing stand. If the scale is not moved, it can be detrimental to the surface of the final cold-rolled sheet.

The temperature most closely controlled during hot rolling is the temperature of the strip after it leaves the last finishing stand. The temperature of the strip is usually controlled by water sprays located between the finishing stands and the coiler.

Hot rolling is carried out above the recrystallization temperature so that the grain structure is reformed after working. The temperature of hot working must not be too high, however, or excess grain growth will occur. Hot working should be finished at a temperature slightly above the recrystallization temperature so that a fine-grain size will be obtained upon cooling below the recrystallization temperature.

The effects of hot rolling steel ingots can be summarized as follows:

1. Hot rolling breaks down the coarse columnar structure of the cast ingots.
2. Hot rolling homogenizes the dendritic segregation which occurs during casting.
3. In rimming steels, the blowholes are welded together. In all steels, porosity is healed.
4. Nonmetallic inclusions are broken up and elongated in the direction of rolling. This leads to direction properties in the rolled product. The strength is increased in the direction of rolling.
5. If the finishing temperature is closed to the recrystallization temperature, grain refinement will be obtained.

# HOT STRIP ROLLING MILL

## TYPICAL REDUCTIONS PER PASS IN FINISHING STANDS

(THIS DRAWING IS ENTIRELY SCHEMATIC AND NOT TO SCALE)

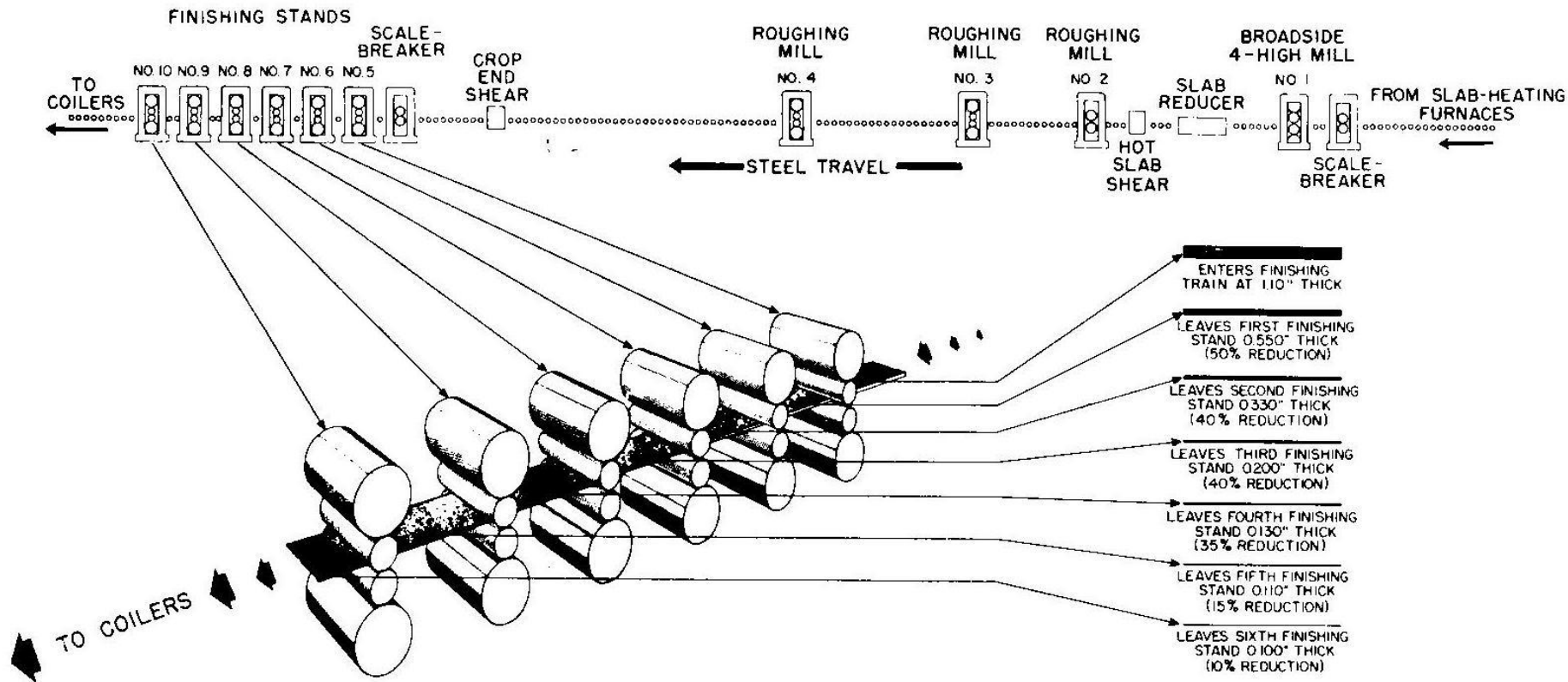
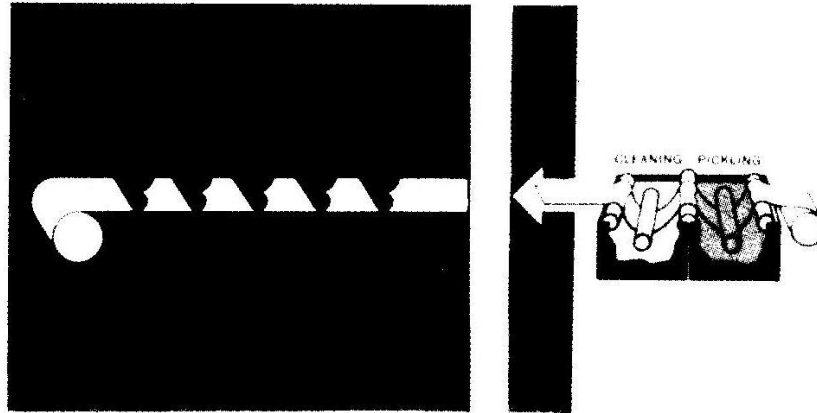


FIGURE 3-14

Typical reductions in the finished stands of a hot-strip mill equipped with four roughing stands and six finishing stands. [After H. E. McGannon (ed.), "Making, Shaping, and Treating of Steel," 9th ed., United States Steel Corporation, Pittsburgh, 1971, p. 937.]



**FIGURE 3-15**

(a) Pickling and cleaning of low-carbon sheet steel. (b) Cold-rolling of low-carbon sheet steel in multistand mill. Note that *a* and *b* are two separate batch operations and that the sheet steel is coiled up after cleaning and then uncoiled again at the start of the cold-rolling operation. (Courtesy of Inland Steel Company.)

### Pickling

Most hot-rolled strip which is to be cold-reduced is acid-cleaned, or *pickled*, to remove the scale from the hot-rolling operation (Fig. 3-15a). In this process, which is usually continuous, the strip is immersed in an acid bath (HCl or H<sub>2</sub>SO<sub>4</sub>) at approximately 82°C. The pickled strip is then rinsed with water, air-dried, oiled, and coiled.

### Cold Reduction

In order to produce cold-rolled sheet products, the pickled hot-mill strip is cold-reduced from 40 to 70 percent. A minimum amount of cold reduction is necessary to ensure recrystallization of the cold-worked sheet during subsequent annealing. Figure 3-15b shows the schematic arrangement of a multistand tandem mill for cold rolling. Modern cold-rolling mills produce cold-rolled sheet with a high-quality surface, good shape, and close gauge control.

## 3-7 NON-HEAT-TREATABLE LOW-CARBON SHEET STEEL

Low-carbon sheet steel is used in large tonnages primarily for consumer products such as automobile body stock, tin plate, and sheet steel for porcelain enameling. These mass-produced materials, which are relatively low in cost,

must have special properties, some of which are:

1. Ease of fabrication (formability and weldability)
2. Sufficient strength after fabrication
3. Attractive appearance before and after fabrication
4. Compatibility with other materials and for various coatings

In order to produce low-carbon sheet steel which meets some or all of the above requirements, the chemical composition, fabrication practices, and heat treatment procedures are varied as is necessary.

### Chemical Composition

About 80 percent of the amount of low-carbon sheet steel and strip has a composition in the following ranges:

Element	% Composition
Carbon	0.03 to 0.12
Manganese	0.20 to 0.60
Silicon	0.02 to 0.15
Phosphorus	0.04 max.
Sulfur	0.04 max.

The normal carbon content of low-carbon sheet is from 0.06 to 0.12 percent. However, for porcelain enameling, the carbon may range from 0.04 to as low as 0.002 percent. In order to achieve very-low-carbon contents, the sheet must be decarburized by a special process. For sheet steel for deep drawing, the phosphorus and sulfur contents are kept as low as possible.

### Deoxidation Practice

Low-carbon sheet steel is produced from ingots of rimmed, capped, semikilled, or killed steel. See Sec. 3-3 for the details of these types of ingot structures and their deoxidation procedures.

### Heat Treatment and Microstructure of Low-Carbon Sheet Steel

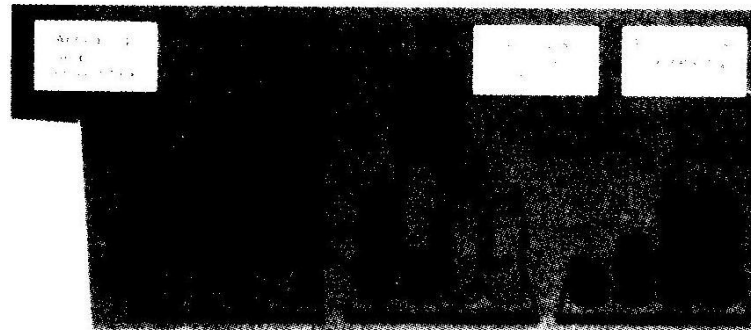
**RIMMED STEEL.** Rimmed steel is hot-rolled at as high a temperature as possible to produce a refined grain structure for subsequent cold rolling and annealing. After hot rolling, the strip is pickled and cold-rolled from about 40 to 65 percent reduction depending on the final use for the sheet. Figure 3-16 shows the structure of cold rolled (65 percent reduction) rimmed steel.

The cold-reduced coils of sheet are then softened by annealing if the steel is to be used for deep drawing or forming. The most common method of

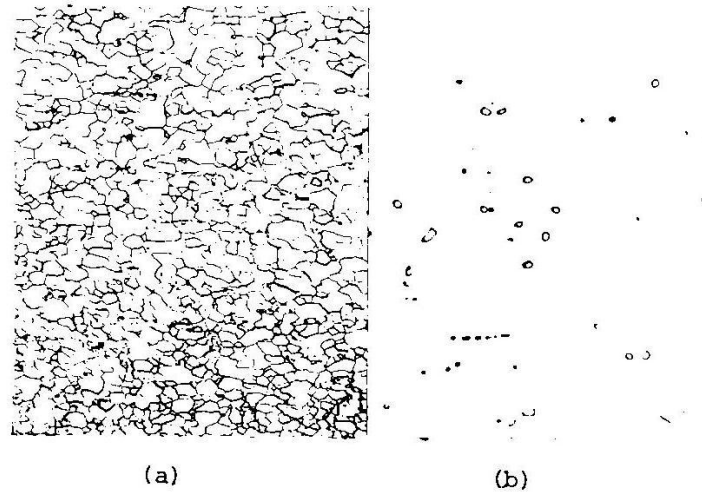


**FIGURE 3-16**  
Cold-worked structure of rimmed sheet steel (0.06% C) after 65 percent reduction. (Etch: 2% nital; 100 $\times$ .) (Courtesy of Inland Steel Company.)

annealing cold-reduced coils of sheet steel is by *box annealing* (Fig. 3-17). In this batch process, coils are stacked three or four high and placed under a cover. They are heated to the desired temperature and held for the necessary time using a special reducing atmosphere that prevents decarburizing of the surface. Rimmed sheet steel is annealed just under the  $A_1$  temperature at about 705°C for sufficient time, and then slow-cooled to about 90°C. Figure 3-18a shows the typical equiaxed recrystallized grain structure of annealed rimmed steel (0.06% C) at 100 $\times$  after box annealing at 705°C. Figure 3-18b shows some of the spheroidized iron carbides in the interior of a grain at 1000 $\times$ .



**FIGURE 3-17**  
Box-annealing sheet steel coils. (A reducing atmosphere is used to prevent decarburizing of the sheet and steel surface.) (Courtesy of Inland Steel Company.)

**FIGURE 3-18**

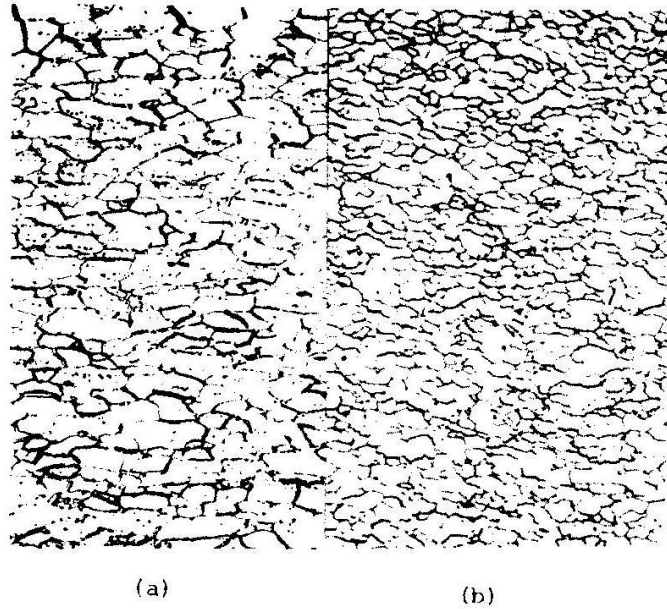
Rimmed steel sheet (0.06% C) after box annealing at 702°C. (a) Equiaxed recrystallized grain structure at 100 $\times$ . (b) Spheroidized iron carbide within a grain at 100 $\times$ . Etch: 2% nital. (Courtesy of Inland Steel Company.)

**KILLED STEEL.** Aluminum-killed steel is coiled at the end of the hot-strip mill at a temperature just below 600°C to keep the AlN in solution. During box annealing, the AlN precipitates, producing an elongated grain shape which has high formability. Since the AlN inhibits recrystallization, box-annealed aluminum-killed steels have to be annealed at higher temperatures than rimmed steels. It is common practice to anneal aluminum-killed steel at about 730°C, which is between the  $A_1$  and  $A_3$  (intracritical anneal).

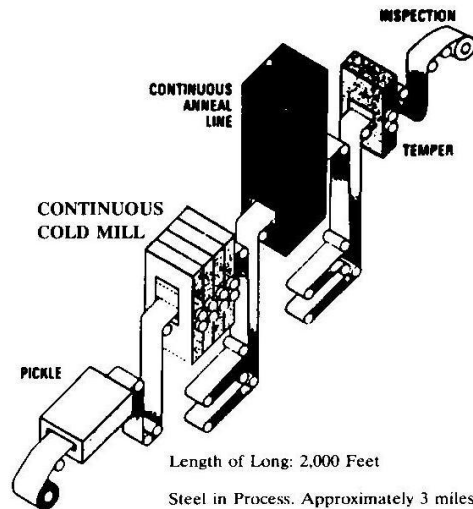
During box annealing, which involves a slow heating rate, AlN precipitates in the subboundaries of the unrecrystallized matrix. By controlling the extent of AlN precipitation at low temperatures during the recovery, polygonization, and coalescence stages, recrystallization at high temperatures results in a grain size that has an elongated grain structure (Fig. 3-19a). This elongated grain structure has a special crystallographic texture which makes it desirable for deep drawing and high formability. Rapid heating aluminum-killed steels to the annealing temperature results in a finer-grain size (Fig. 3-19b) and higher mechanical properties, while it prevents the development of the elongated structure. This difference is attributed to the prevention of the precipitation of finely dispersed AlN.

### Continuous Annealing of Low-Carbon Sheet Steels

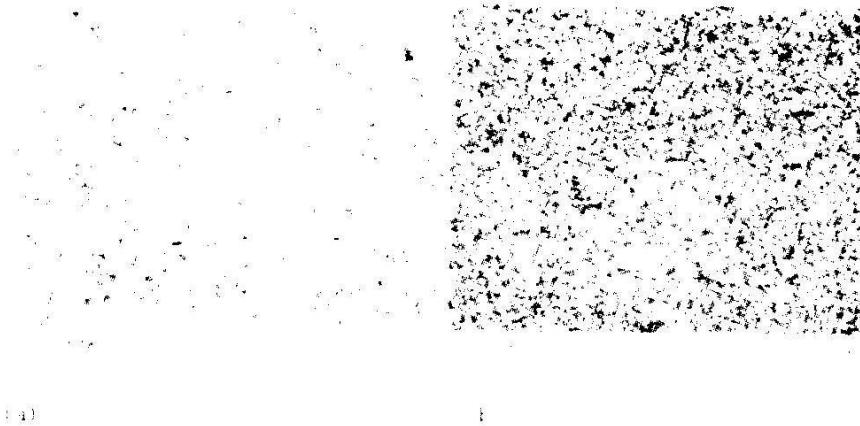
Continuous annealing with its rapid heating rate results in a finer grain size than that developed by the box-annealing process with its slow heating rate (Fig.



**FIGURE 3-19**  
 Aluminum-killed 0.06% C sheet steel after annealing at 715°C. (a) Elongated grain structure; (b) equiaxed grain structure. (Etch: 2% nital; 100 ×.) (Courtesy of Inland Steel Company.)



**FIGURE 3-19c**  
 Integrated system for pickling, cold rolling, continuous annealing, and temper rolling sheet steel continuously. (After I/N Tek. Co.)



**FIGURE 3-20**

Low-carbon capped steel (0.06% C, 0.30% Mn); cold-rolled and then (a) recrystallized by box annealing and (b) recrystallized by continuous annealing. Note the finer grain size of the continuously annealed steel. (After *Metals Handbook*, 8th ed., vol. 8, American Society for Metals, 1973, p. 228.)

3-20). Continuously annealed sheets thus have higher strengths and lower ductilities than similar box-annealed steels. Thus, the formability of box-annealed special-killed sheet steels will be higher than those that are continuously annealed.

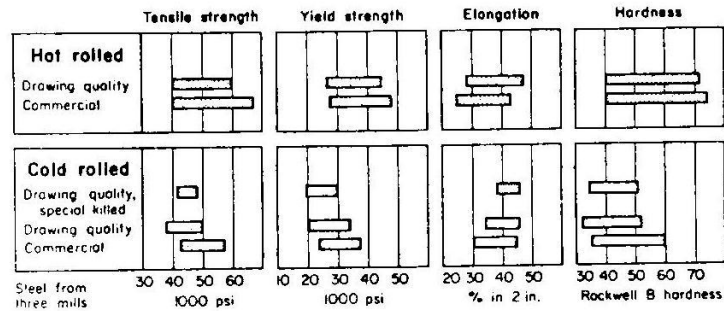
More recently, new, very low carbon ( $< 0.01\%$  C) sheet steels have been produced using the RH-OB vacuum-degassing system (Fig. 3-7). After cold rolling, this sheet steel can be continuously annealed and still have very high formability for deep drawing. Fig. 3-19c shows a schematic of an integrated-pickling, cold-rolling, continuous-annealing, and temper-rolling sheet steel system. This process of the I/N Tek Co. began operation in 1991 and has the advantage of being able to reduce the finishing time of a coil of sheet steel from about 12 days to less than 1 h. Other advantages of this process include more uniformity of strength and ductility and less surface damage.

One way to increase the strength of very low carbon ( $< 0.01\%$  C) sheet steel is to increase its phosphorus level to about 0.05 percent. If the steel is to be used for external automobile panels, it may be further strengthened by age-hardening at  $175^{\circ}\text{C}$  for 20 min at the same time the paint on the steel is being baked.

### Mechanical Properties of Low-Carbon Sheet Steels

After annealing, the cold-rolled rimmed steel is usually temper-rolled. This light (approximately 1 percent) cold-rolled reduction retards strain aging in rimmed





**FIGURE 3-21**

Typical range of mechanical properties of low-carbon steel from three mills. Hot-rolled sheet thicknesses from 0.598 to 0.135 in.; cold-rolled from 0.029 to 0.0598 in. All cold-rolled grades include a temper pass. All grades were rolled from rimmed steel except the one labeled special killed. (After *Metals Handbook*, 8th ed., vol. 1, American Society for Metals, 1961, p. 81.)

steels. The temper rolling, while decreasing the strain-aging effect in rimmed steels, increases their strength and decreases their ductility and formability. Figure 3-21 gives typical ranges for the mechanical properties of rimmed and killed low-carbon sheet steels. It is noted that the special-killed steels have lower strength and higher ductility.

### 3-8 QUENCH AGING AND STRAIN AGING OF CARBON STEELS

#### Quench Aging

Aging in low-carbon steels can be divided into two types: quench aging and strain aging. Quench aging is caused by the precipitation of carbon, nitrogen, or both from supersaturated solid solution. These solubilities of both these elements decrease sharply with decreasing temperature. The interstitial solubility of carbon in ferrite decreases from about 0.02 percent at 723°C (eutectoid temperature) to as low as  $10^{-7}$  percent at room temperature. The solubility of nitrogen also decreases rapidly with decreasing temperature to an exceedingly low value.

If low-carbon sheet steels containing about 0.1% C are rapidly cooled after annealing, the carbon and nitrogen will be retained in interstitial supersaturated solid solution. Upon subsequent aging at room temperature or slightly above it, finely dispersed precipitates of  $\epsilon$  carbide will be produced. These precipitates cause an increase in hardness and strength of the steel, as shown in Fig. 3-22.

The principal hardening agent in quench aging is carbon, since carbon steels contain much more carbon than nitrogen. This carbide precipitate, which

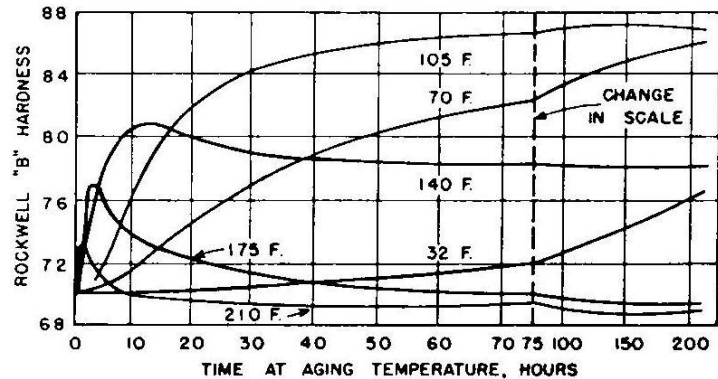


FIGURE 3-22

Hardness changes in a 0.06% C steel quenched from 720°C and aged at indicated temperatures. (After *Metals Handbook*, American Society for Metals, 1948, p. 439.)

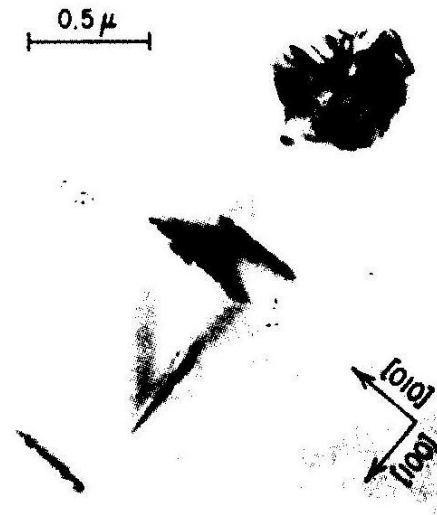
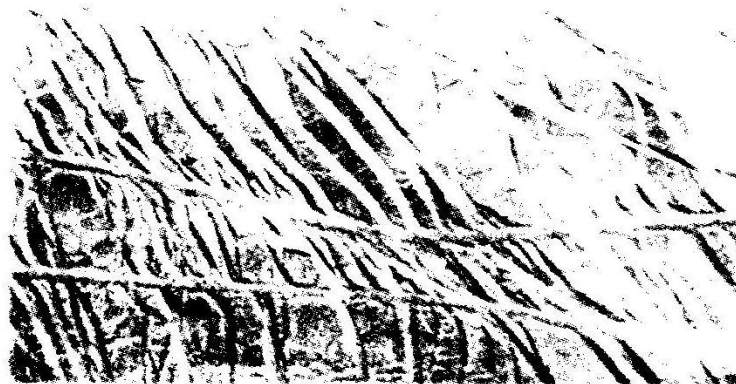


FIGURE 3-23

Metastable carbide precipitation on  $\{100\}_\alpha$  planes in an Fe-0.013% C alloy quenched from 700°C and aged 6 h at 200°C. [After H. W. Wagenblast and R. Glenn, *Metall. Trans.* (1970):2299.]

is formed on aging, has been identified as  $\epsilon$  carbide,<sup>1</sup> and is shown in Fig. 3-23 as precipitates on the  $\{100\}_\alpha$  planes in an Fe-0.013% C alloy. The maximum hardness achieved by quench aging in steel is at about room temperature. Aging at slightly elevated temperatures leads to a rapid rise in hardness (although not as high), and then to a decrease caused by *overaging* and coarsening of the

<sup>1</sup> F. W. Langer, *Met. Sci. J.* 2(1968):59.



**FIGURE 3-24**  
Stretcher strains in a sheet steel part (three-fourths actual size). (After *Metals Handbook*, 8th ed., vol. 1, American Society for Metals, 1961, p. 325.)

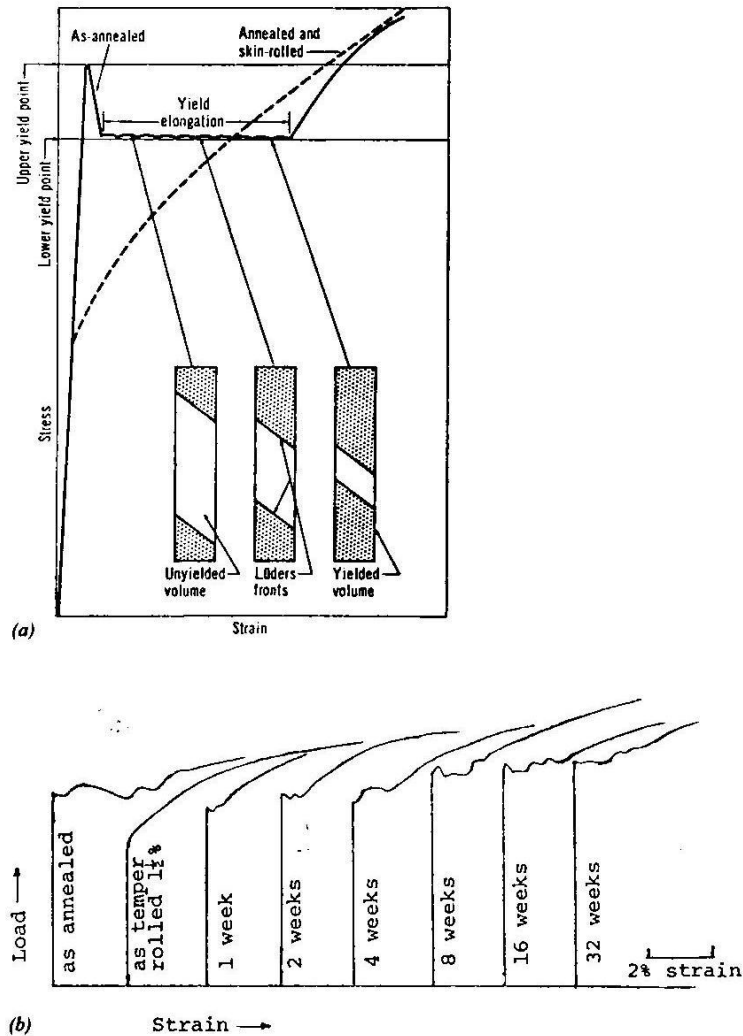
precipitates (Fig. 3-22). The maximum hardness is due to an optimum size and interparticle spacing of the carbide precipitates.

### Strain Aging

Strain aging is industrially more important for low-carbon sheet steels than quench aging, since it can cause unsightly stretcher strains during deep drawing, as shown in Fig. 3-24. Strain aging manifests itself during plastic deformation as a sharp upper yield point, which is followed by a lower-yield-point elongation (Fig. 3-25a). Cold working during the lower-yield-point elongation can lead to the formation of stretcher strains, especially during deep drawing. A small amount of cold working just after annealing can eliminate the problem.

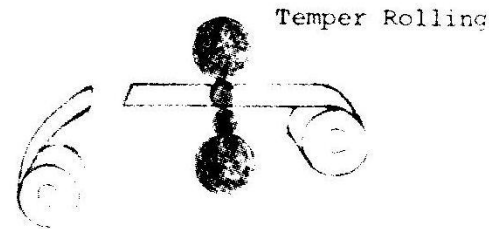
The cause of stretcher strains is the segregation of interstitial solute atoms (mainly nitrogen and carbon) to the strain fields of dislocations in the  $\alpha$ -iron lattice. When this occurs, dislocations are anchored in place. The upper yield point is attributed to the extra stress required either to tear the dislocations loose from their "atmospheres" of interstitial solute atoms or to initiate new sources of dislocations. By temper rolling 1 to 3 percent (Fig. 3-26) before deep drawing, the lower-yield-point elongation is eliminated.

If temper-rolled rimmed steel is allowed to age before deep drawing, the yield point will gradually come back (Fig. 3-25b). It is believed that the nitrogen interstitial atoms have time to diffuse back to dislocations and thus cause a new upper yield point. Aluminum-killed low-carbon sheet steels do not show this phenomenon since the nitrogen is combined with aluminum as AlN.



**FIGURE 3-25**

(a) Yield-point behavior in low-carbon steel sheet. Unless skin-rolled (dashed line), annealed sheet has definite upper and lower yield points. Once the steel yields in a sheet tensile specimen, it elongates for a period at the lower yield point. Stretcher strains (Lüders bands) develop during the yield elongation. (After D. J. Blickwede, *Met. Prog.*, vol. 95, no. 6, June 1969, p. 12.) (b) Temper rolling of annealed sheet eliminates the yield point, according to stress-strain tests. As the sheet ages, for the indicated periods, the yield point gradually returns. (After M. R. Baren and P. G. Nelson, *Met. Prog.*, December 1970, p. 98.)



Winding into coils

**FIGURE 3-26**  
Temper rolling of low-carbon sheet steel. (Courtesy of Inland Steel Company.)

### 3-9 HARDENABLE CARBON STEELS

Hardenable plain-carbon steels can be divided into the following groups according to their carbon contents: (1) low-carbon steels with 0.10 to 0.25% C, (2) medium-carbon steels with 0.25 to 0.55% C and (3) high-carbon steels with 0.55 to 1.00% C.

#### Low-Carbon Steels with 0.10 to 0.25% C

Steels in this group have increased strength and hardness and reduced cold formability compared to non-heat-treatable 0.06 to 0.10% C low-carbon steels. Although carbon steels of this type can be quenched and tempered for increased strength, it is not usually economical. For heat-treating purposes, these steels are carburized or case hardened. For carburizing applications, AISI 1016, 1018, and 1019 steels are commonly used for thin sections with AISI 1022 and 1024 steels are used for heavier sections. Typical mechanical properties of AISI 1015, 1020, and 1022 steels in the as-rolled, normalized, and annealed conditions are listed in Table 3-2.

#### Medium-Carbon Steels with 0.25 to 0.55% C

Plain-carbon steels of the medium-carbon type are usually strengthened by quenching and tempering because of their higher carbon content. These grades are normally produced as killed steels. By proper selection of quenching medium and temperature, a wide range of mechanical properties (85 to 160 ksi) can be obtained, as indicated in Table 3-2 for AISI 1030, 1040, and 1050 steels. When the section size is relatively small or if the properties required after heat treatment are not too high, oil quenching instead of water quenching is used since this treatment eliminates the cracking problem and reduces distortion.

Figure 3-27 shows the optical microstructures of AISI 1040 steel after various heat treatments.

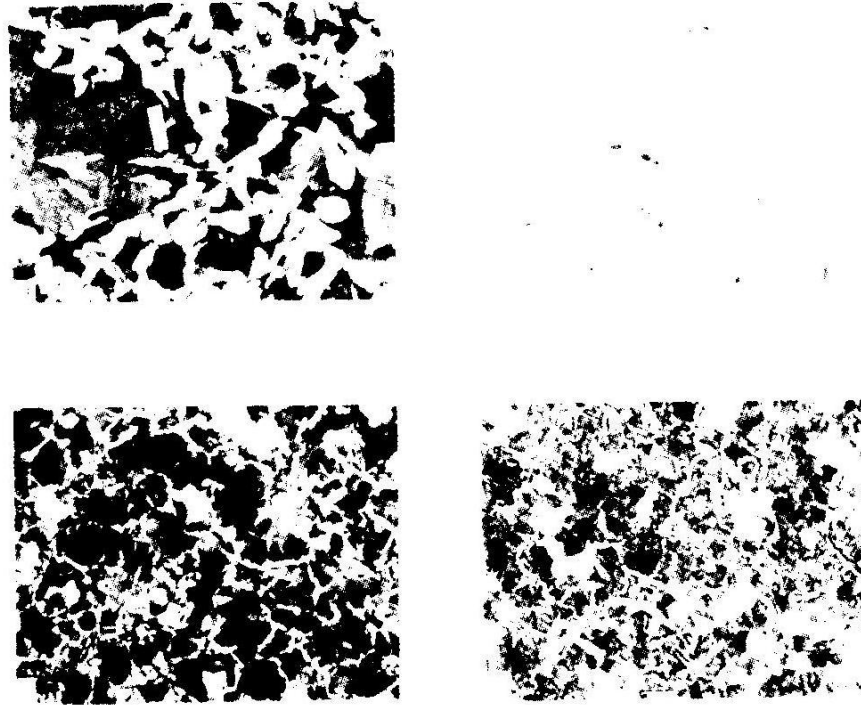
The medium-carbon steels are the most versatile of the three groups of hardenable plain-carbon steels, and are used for a wide range of applications. Many parts of automobiles are made from medium-carbon steels, such as parts for engines, transmissions, suspensions, and steering (Table 3-3).

**TABLE 3-2**  
**Mechanical properties of selected hardenable plain-carbon steels**

Hot-rolled, normalized, and annealed							
AISI No.	Treatment	Yield strength, psi	Tensile strength, psi	Elongation, %	Reduction in area, %	Hardness, Bhn	Impact strength (Izod), ft · lb
1015	As-rolled	45,500	61,000	39.0	61.0	126	81.5
	Normalized (1700°F)	47,000	61,500	37.0	69.6	121	85.2
	Annealed (1600°F)	41,250	56,000	37.0	69.7	111	84.8
1020	As-rolled	48,000	65,000	36.0	59.0	143	64.0
	Normalized (1600°F)	50,250	64,000	35.8	67.9	131	86.8
	Annealed (1600°F)	42,750	57,250	36.5	66.0	111	91.0
1022	As-rolled	52,000	73,000	35.0	67.0	149	60.0
	Normalized (1700°F)	52,000	70,000	34.0	67.5	143	86.5
	Annealed (1600°F)	46,000	65,250	35.0	63.6	137	89.0
1030	As-rolled	50,000	80,000	32.0	57.0	179	55.0
	Normalized (1700°F)	50,000	75,500	32.0	60.8	149	69.0
	Annealed (1550°F)	49,500	67,250	31.2	57.9	126	51.2
1040	As-rolled	60,000	90,000	25.0	50.0	201	36.0
	Normalized (1650°F)	54,250	85,500	28.0	54.9	170	48.0
	Annealed (1450°F)	51,250	75,250	30.2	57.2	149	32.7
1050	As-rolled	60,000	105,000	20.0	40.0	229	23.0
	Normalized (1650°F)	62,000	108,500	20.0	39.4	217	20.0
	Annealed (1450°F)	53,000	92,250	23.7	39.9	187	12.5
1060	As-rolled	70,000	118,000	17.0	34.0	241	13.0
	Normalized (1650°F)	61,000	112,500	18.0	37.2	229	9.7
	Annealed (1450°F)	54,000	90,750	22.5	38.2	179	8.3
1080	As-rolled	85,000	140,000	12.0	17.0	293	5.0
	Normalized (1650°F)	76,000	146,500	11.0	20.6	293	5.0
	Annealed (1450°F)	54,500	89,250	24.7	45.0	174	4.5
1095	As-rolled	83,000	140,000	9.0	18.0	293	3.0
	Normalized (1650°F)	72,500	147,000	9.5	13.5	293	4.0
	Annealed (1450°F)	55,000	95,250	13.0	20.6	192	2.0

TABLE 3-2 continued

Quenched and tempered						
AISI No.	Tempering temperature, °F	Tensile strength, psi	Yield strength, psi	Elongation, %	Reduction in area, %	Hardness, Bhn
1030*	400	123,000	94,000	17	47	495
	600	116,000	90,000	19	53	401
	800	106,000	84,000	23	60	302
	1000	97,000	75,000	28	65	255
	1200	85,000	64,000	32	70	207
1040*	400	130,000	96,000	16	45	514
	600	129,000	94,000	18	52	444
	800	122,000	92,000	21	57	352
	1000	113,000	86,000	23	61	269
	1200	97,000	72,000	28	68	201
1040	400	113,000	86,000	19	48	262
	600	113,000	86,000	20	53	255
	800	110,000	80,000	21	54	241
	1000	104,000	71,000	26	57	212
	1200	92,000	63,000	29	65	192
1050*	400	163,000	117,000	9	27	514
	600	158,000	115,000	13	36	444
	800	145,000	110,000	19	48	375
	1000	125,000	95,000	23	58	293
	1200	104,000	78,000	28	65	235
1050	400	—	—	—	—	—
	600	142,000	105,000	14	47	321
	800	136,000	95,000	20	50	277
	1000	127,000	84,000	23	53	262
	1200	107,000	68,000	29	60	223
1060	400	160,000	113,000	13	40	321
	600	160,000	113,000	13	40	321
	800	156,000	111,000	14	41	311
	1000	140,000	97,000	17	45	277
	1200	116,000	76,000	23	54	229
1080	400	190,000	142,000	12	35	388
	600	189,000	142,000	12	35	388
	800	187,000	138,000	13	36	375
	1000	164,000	117,000	16	40	321
	1200	129,000	87,000	21	50	255
1095*	400	216,000	152,000	10	31	601
	600	212,000	150,000	11	33	534
	800	199,000	139,000	13	35	388
	1000	165,000	110,000	15	40	293
	1200	122,000	85,000	20	47	235
1095	400	187,000	120,000	10	30	401
	600	183,000	118,000	10	30	375
	800	176,000	112,000	12	32	363
	1000	158,000	98,000	15	37	321
	1200	130,000	80,000	21	47	269



**FIGURE 3-27**

Microstructure of AISI 1040 steel after (a) normalizing, (b) annealing, (c) oil quenching, (d) oil quenching and tempering. (a) Normalized at 871°C 1 h and air-cooled; structure shows ferrite and pearlite; coarse pearlite was caused by coarsening of austenite during normalizing. (b) Normalized at 871°C 1 h and air-cooled; annealed at 691°C for 24 h; structure shows ferrite + spheroidized carbides. (c) Austenitized at 843°C for 1 h and oil quench; structure shows fine pearlite with ferrite outlining former austenitic grain boundaries. (d) Same as (c) plus tempering 4 h at 538°C; structure is similar to (c); little effect of tempering on structure. Etchant: 2% nital 400 $\times$ . (Courtesy of Republic Steel Co.)

### High-Carbon Steels with 0.55 to 1.00% C

Steels in this group are more restricted in application than the medium-carbon steels since they are more costly to make, and have poor formability and weldability. These steels have more carbon than is needed to attain maximum as-quenched hardness, and consequently, have lower ductility than the medium-carbon steels. Table 3-2 lists the mechanical properties of AISI 1060, 1080, and 1095 steels. The ultimate tensile strengths of these steels range from 90 to 216 ksi, while their elongations range from 9 to 25 percent.

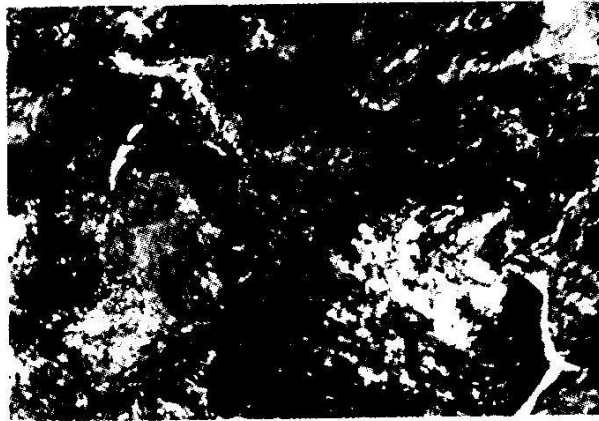


**TABLE 3-3**  
**Usage of carbon steels in automobiles**

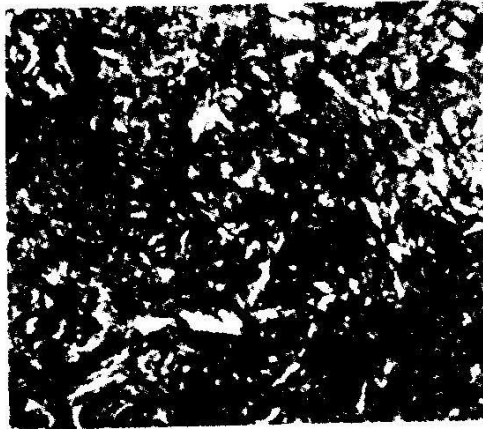
Use	Type of Steel
<b>Body</b>	
Body sheet metal	1006, 1008, SAE 950, HSLA*
<b>Suspension and steering</b>	
Struts	1040 and 1030
Pitman and idler arms	1038, 1040, and 1041
Torsion bar housing	1021
Steering knuckles	1046
Tie rod ends	1040
Ball joint studs	1041
Center link	1040
<b>Engine</b>	
Pulley	1010
Crankshaft	1046, 1049 modified, nodular cast iron
Connecting rod	1041
Piston pin	1016
Rocker arm	1040, 1010 case-hardened (stamped)
Intake valve	1041, 1547
Oil pan	1010
<b>Torque converter: flex plate</b>	
Cover, turbine and impeller shell, and valves	1020 to 1050
Overrunning clutch cam	1006 and 1010
Overrunning clutch hub	1060 modified
Impeller hub	1060
<b>Transmission</b>	
Input shaft	1024, 1045 induction hardened
Output shaft	1024, 1036, 1045 induction hardened, 4027 carburized
Kickdown and reverse bands	1040, 1050 quenched and tempered
Sun gear driving shell	1010
Planet pinion shaft	1041, 1050 induction-hardened, 8620 carburized
Clutch disks and plates	1020 to 1030

\* High-strength low-alloy steels.

Figure 3-28 shows the microstructure of an AISI 1060 steel rod which was air-cooled after hot rolling, producing a fine pearlitic structure. Figure 3-29 shows the microstructure of a 1070 steel valve-spring wire that was quenched and tempered, producing a tempered martensitic structure. In most cases the high-carbon steels are heat-treated by oil quenching and tempering. Water quenching is used for heavier sections and when cutting edges are required.

**FIGURE 3-28**

Microstructure of an AISI 1060 steel rod,  $\frac{1}{4}$  in in diameter, which was cooled from hot-rolling using a high-velocity air blast. Structure is mostly unresolved pearlite with some lamellar pearlite visible; some white areas of ferrite partly outlining the prior austenite grain boundaries. (Etch: Picral; 1000 $\times$ .) (Courtesy of United States Steel Corporation.)

**FIGURE 3-29**

Microstructure of an AISI 1070 valve-spring steel wire in the quenched and tempered condition; steel was austenitized at 871°C, oil-quenched, and tempered at 454°C; structure is mainly tempered martensite with some free ferrite, which are the white regions. (Etch: 2% nital;  $\times 1000$ .) (Courtesy of United States Steel Corporation.)

### 3-10 MICROALLOYED STEELS

In recent years, the microalloying of plain-carbon steels with small amounts (rarely exceeding about 0.1 wt%) of strong carbide- and nitride-forming elements such as Nb, Ti, and V has achieved a great improvement in their mechanical properties. The addition of small amounts of Nb, Ti, and V in conjunction with controlled rolling practices has produced low-carbon (0.05 to



**FIGURE 3-30**

Fine NbC (niobium carbide) precipitates formed in austenite during hot rolling. Small areas of retained austenite are indicated by the arrows. (Dark field illumination.) (Electron micrograph; 10,000 $\times$ .) (After A. T. Davenport, L. C. Brossard, and R. E. Miner, *J. Met.*, June 1975, p: 21.)

0.1% C) plain-carbon steels at low cost with yield stresses of 50 to 80 ksi and good toughness qualities. These improvements in mechanical properties are a result of many factors, the most important of which are

1. Refinement of the ferrite grain size by the formation of a fine-subgrain structure
2. Strain-induced precipitation of the carbides and nitrides of the strong carbide- and nitride-forming elements
3. Precipitation strengthening of the ferrite

### **Precipitation Mechanisms in Hot-Rolled Microalloyed Steels**

Before the hot-rolling operation, the steel ingots are preheated (soaked) at temperatures above 1230°C and, as a result, a significant amount of the carbonitrides are dissolved. As the temperature decreases during hot rolling, the carbonitrides become insoluble and precipitate out in the austenite during hot rolling (Fig. 3-30).

In the initial stages of hot rolling, the coarse austenite grains produced by preheating are progressively reduced in size by recrystallization induced by the deformation of each reduction. The carbonitride particles which are induced by

the deformation reduce the size of the recrystallized grains by "pinning" the grain boundaries. Second, in the final stages of hot rolling, these precipitates retard recrystallization because they prevent the substructure from changing by the processes of dislocation and subgrain boundary migration. The net effect of these processes is to progressively flatten the austenitic grains so that a "pancake" structure is produced which has a higher austenitic grain boundary area per unit volume than normally would be obtained.

Since the ferrite nucleates mainly in the austenitic grain boundaries, the increased grain boundary area will provide more nuclei for ferrite and hence lead to a finer ferrite grain size. Finally, any microalloying element left unprecipitated during hot rolling will precipitate in the ferrite either during cooling to room temperature (plate steels) or during the coiling operation (strip steels). The precipitation in the ferrite will provide additional strength to the microalloyed steels.

### Precipitation of Nb, Ti, and V Carbides and Nitrides

**M(C, N) PRECIPITATION IN AUSTENITE.** The principal compound which precipitates in microalloyed steels is the FCC-type phase (NaCl) of the general formula M(C, N). The phase precipitates in the austenite according to the following relationship:



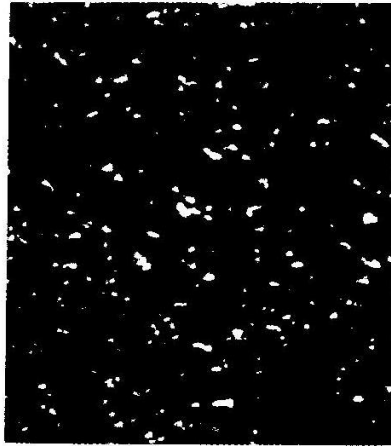
Figure 3-30 shows fine NbC particles formed in austenite when a 0.1% C–1.3% Mn–0.1% Nb steel was preheated at 1288°C, hot-rolled at 870°C, and aged 15 min at the rolling temperature.

**M(C, N) PRECIPITATES IN FERRITE.** M(C, N) precipitation can also occur in the ferrite both in the matrix and at the  $\gamma/\alpha$  interface boundaries. The following relationship has been determined for the precipitation of M(C, N) in supersaturated ferrite:

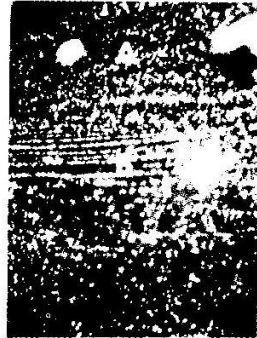


Figure 3-31 shows fine NbC particles nucleated in the ferrite in a quenched and tempered Nb low-carbon steel.

M(C, N) precipitates nucleated at the  $\gamma/\alpha$  interphase boundaries form with the same ferrite nucleation orientation as described above and lie in sheetlike arrays, the plane of which denotes the position of the interphase boundary at the time of nucleation. These interphase precipitates sometimes appear as precipitate rows (Fig. 3-32), which are formed by VC in a normalized microalloyed steel.



**FIGURE 3-31**  
Fine NbC particles nucleated in the ferrite matrix in a quenched and tempered Nb-microalloyed steel. (110,000 $\times$ .) (After A. T. Davenport, L. C. Brossard, and R. E. Miner, *J. Met.*, June 1975, p. 21.)

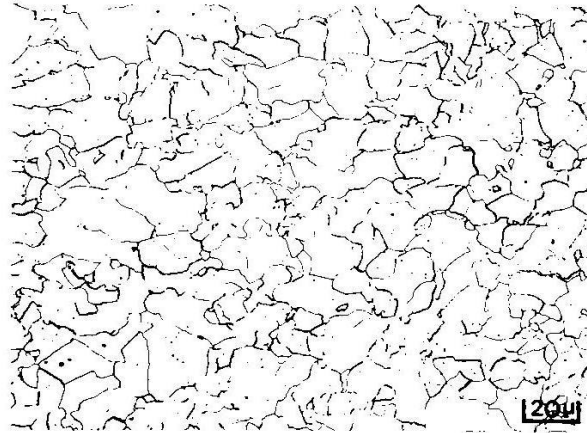


**FIGURE 3-32**  
A colony of VC particles formed by interphase precipitation in a normalized V-bearing steel. (25,000 $\times$ .) (After A. T. Davenport, L. C. Brossard, and R. E. Miner, *J. Met.*, June 1975, p. 21.)

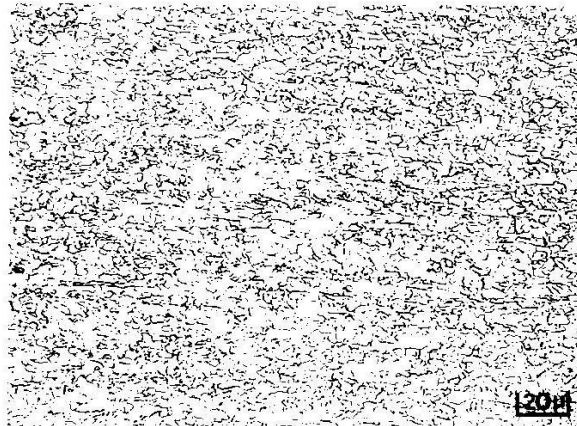
### Strengthening of Microalloyed Steels by Grain Refinement and Subgrains

Microalloyed steels are also strengthened to some degree by a fine-grain size and fine-subgrain structure. Figure 3-33 compares the grain size of 50- and 80-ksi niobium steels. Although grain size is only one factor contributing to the increased strength of microalloyed steels, there is some increase in lower yield strength due to a finer grain size, as shown in Fig. 3-34.

A far greater structural combination to increased strength, however, is due to a fine subgrain structure. Figure 3-35 shows the observed microscopic difference in substructure between the 50- and 80-ksi microalloyed steels. The highly refined substructure of the 80-ksi steel is quite noticeable. Figure 3-36 shows the incremental increase in yield strength due to the subgrain refinement,



(a)



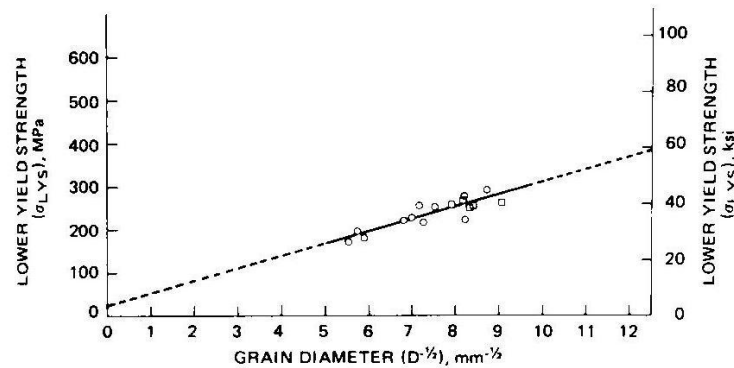
(b)

**FIGURE 3-33**

Optical microstructures of 50- and 80-ksi microalloyed niobium steels. (After P. L. Mangonon and W. E. Heitmann, *Microalloying 75*, Union Carbide Co., New York, 1977, p. 59.)

which was found to depend on the subgrain size and the volume fraction of grains with subgrains.

Thus microalloyed steels are strengthened by a combination of grain refinement, subgrain formation, and precipitation hardening. The amount of strengthening from niobium carbonitride precipitates depends upon the amount of niobium added, finishing rolling temperatures, and amount of deformation.



**FIGURE 3-34**  
Relationship between grain size and lower yield strength in AISI 1005 rimmed steel sheet. (After P. L. Mangonon and W. E. Heitmann, *Microalloying 75*, Union Carbide Co., New York, 1977, p. 59.)



**FIGURE 3-35**  
Substructure of (a) 50-ksi and (b) 80-ksi microalloyed niobium steels; electron transmission micrographs. (After P. L. Mangonon and W. E. Heitmann, *Microalloying 75*, Union Carbide Co., New York, 1977, p. 59.)

### 3-11 DUAL-PHASE STEELS

Dual-phase steels are a new class of high-strength low-alloy (HSLA) steels characterized by a microstructure consisting of a mixture of about 20 percent hard martensite particles in a soft, ductile ferrite matrix (Fig. 3-37). The term “dual phase” refers to the existence of essentially two phases, ferrite and martensite, in the microstructure even though small amounts of bainite, pearlite, and retained austenite may also be present. Dual-phase steels have relatively



(b)

FIGURE 3-35 (Continued)

high tensile strengths, continuous yielding behavior, low 0.2 percent offset yield strengths, and a higher total elongation than other high-strength low-alloy steels of similar strength.

Typical chemical compositions of dual-phase steels produced at present (1991) are listed in Table 3-4. In general, these steels have a carbon content of about 0.06 to 0.12% C which allows them to be spot-welded. Manganese in

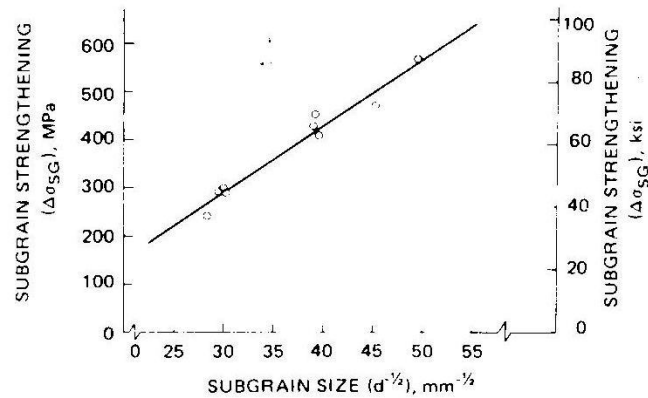


FIGURE 3-36

Regression line between subgrain size ( $d$ ) and its strengthening effect ( $\Delta\sigma_{SG}$ ) for AISI 1005 rimmed steel. (After P. L. Mangonon and W. E. Heitmann, *Microalloying 75*, Union Carbide Co., New York, 1977, p. 59.)





**FIGURE 3-37**  
 Ferrite-martensite microstructure of a dual-phase steel (0.06% C, 1.5% Mn); water-quenched from 760°C. The white phase is martensite and the dark phase ferrite.

amounts from about 0.40 to 2.5 percent ensures that martensite will form upon rapid cooling. Silicon in amounts up to 0.40 to 1.40 percent is added to increase solid solution hardening. Sometimes amounts of up to 0.6% chromium and 0.4% molybdenum are added to further ensure the formation of martensite in some cases. Small amounts of vanadium, niobium, and titanium may be added to provide precipitation hardening and/or grain-size control.

Dual-phase steels are produced by first intercritically annealing, usually in the 720 to 780°C range, by either the continuous-annealing or box-annealing processes (Fig. 3-38). The austenite-ferrite structure created by annealing is then quenched to produce a mixture of ferrite and martensite with small amounts of other phases such as bainite, pearlite, and retained austenite. Sheet steels can be cooled rapidly after continuously annealing, but with box-annealing heat times are longer and cooling rates are slower. In general, the Mn and Si contents of box-annealed steels are much higher for the same carbon content than for continuously annealed steels (Table 3-4).

**TABLE 3-4**  
**Typical dual-phase steel compositions**

Production method	Composition, wt%					
	C	Mn	Si	Cr	Mo	V
Continuous annealing, hot-rolled gage	0.11	1.43	0.61	0.12	0.08	0.06
Continuous annealing, cold-rolled gage	0.11	1.20	0.40			
Box annealing	0.12	2.10	1.40			

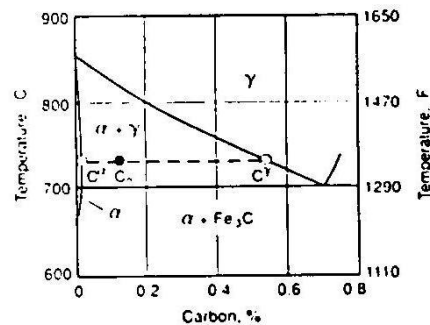


FIGURE 3-38

Phase diagram for 1.5% Mn steel showing the intercritical annealing temperature in the  $\alpha + \delta$  phase field for a dual-phase steel with 0.1% C. This point is indicated in the phase diagram at  $C_0$ .

In general, dual-phase ferrite-martensite steels do not have a yield point. The combination of high residual stresses (due to quenching) and a high mobile dislocation density in the ferrite allow plastic strain to occur easily at low plastic strains. As a result, yielding occurs at many sites in the ferrite and discontinuous yielding is suppressed.

The initial work-hardening rate of dual-phase steels is high, and this leads to high strength and good formability compared to other HSLA steels of similar strength level (Fig. 3-39a). Fig. 3-39b compares the tensile strengths and total elongations of dual-phase steels with other HSLA steels. The enhanced ductility of dual-phase steels has been attributed to many causes, including the lower carbon content of the ferrite, the plasticity of the martensite phase, and the amount of retained austenite. Of these factors, the amount of retained austenite

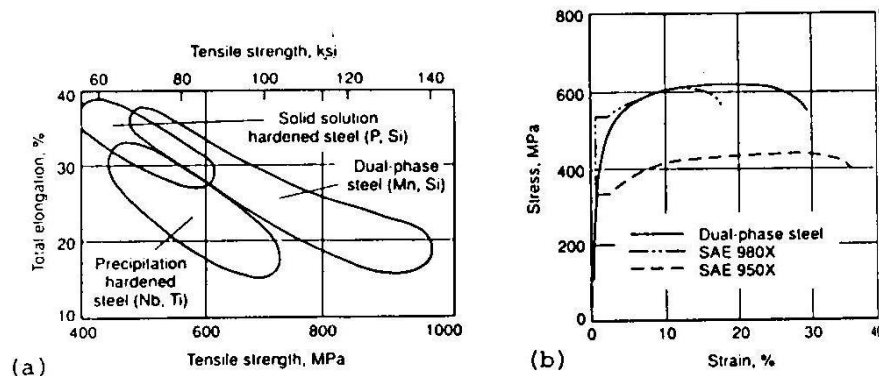


FIGURE 3-39

(a) Relation between tensile strength and total elongation for various HSLA sheet steels. (b) Stress-strain curves for the HSLA sheet steels SAE 950X and SAE 980X (with yield strengths of 340 and 550 MPa, or 50 and 80 ksi, respectively) and a dual-phase steel (with a yield strength of 550 MPa, or 80 ksi). (After "ASM International Metals Handbook," 10th ed., 1990, p. 424.)

and the way it transforms during plastic strain is believed to be the main cause of the high ductility.

In general, dual-phase steels are nonaging at room temperature and exhibit sluggish aging behavior at temperatures up to 270°C. Dual-phase steels are used in automobiles for applications requiring high strength and good formability such as bumpers and reinforcing posts.

## PROBLEMS

1. Briefly describe the following steelmaking processes: (a) basic-oxygen, (b) electric-arc.
2. What are the advantages of the basic-oxygen steelmaking process?
3. What are the advantages of the electric-arc steelmaking process?
4. What is ladle metallurgy?
5. What improvements in steel quality can be attained using ladle metallurgy?
6. Why has vacuum degassing been applied in conjunction with ladle metallurgy to produce steel?
7. Explain the operation of RH-OB process for vacuum-degassing steel.
8. What are some of the advantages of continuously casting steel instead of casting it into individual molds?
9. Describe the following types of steel ingot structures and the processes used to produce each of them: (a) rimmed, (b) capped, (c) semikilled, and (d) killed.
10. What are the advantages and disadvantages of rimmed steel ingots? Of aluminum-killed ingots?
11. How would it be possible to produce a composite ingot with a rimmed outer zone and an aluminum-killed core?
12. What is the AISI-SAE classification system for plain-carbon steels? Why can it not be used for all plain-carbon steels for all purposes?
13. Describe the effects of the following elements in plain-carbon steels: (a) manganese, (b) sulfur, (c) phosphorus, and (d) silicon.
14. Why are manganese sulfide inclusions in steel preferable to iron sulfide ones?
15. When manganese sulfide inclusions are rolled, they are elongated in the direction of rolling. What would be the disadvantage of these inclusions in rolled plate?
16. Describe the typical cross sections of (a) slabs, (b) blooms, and (c) billets.
17. Describe the effects of hot rolling on the structure of steel strip.
18. Describe the pickling process which is used for hot-rolled steel strip before it is cold-rolled.
19. What properties are desirable in non-heat-treatable low-carbon sheet steel?
20. What is the chemical composition of about 80 percent of the non-heat-treatable low-carbon sheet steel?
21. Describe the box-annealing process. What are its advantages and disadvantages?
22. What is the effect of AlN in the recrystallization of low-carbon sheet steels?
23. Describe the type of structure of killed low-carbon sheet steels which have especially high formability.

24. How does the grain structure of low-carbon sheet steel which has been continuously annealed differ from that which has been box-annealed?
25. How can highly formable continuously annealed steels be produced?
26. How can low-carbon ( $< 0.01\%$  C) highly formable sheet steels which are to be used for outside auto panels be strengthened after being formed?
27. What causes the quench-aging effect in low-carbon sheet steel?
28. Describe the strain-aging phenomenon in low-carbon sheet steels.
29. How can strain aging be avoided in rimmed low-carbon sheet steels?
30. Why is strain aging not encountered in killed low-carbon sheet steels?
31. Describe the three major groups of hardenable plain-carbon steels and some of their applications.
32. What are microalloyed steels? What are the principal elements that are added to produce microalloyed steels?
33. Describe the precipitation mechanisms which strengthen microalloyed steels.
34. Describe how microalloyed steels are strengthened by grain refinement and subgrain structure.
35. What processing factors affect the amount of strengthening obtained in microalloyed steels?
36. In the rolling of sheet, plate, and strip in modern steel mills, deformation takes place mainly in the longitudinal direction. During this operation, manganese sulfides are deformed plastically into longitudinal stringers.
  - (a) What difference in strength with respect to the longitudinal, transverse, and thickness directions would be expected?
  - (b) Cerium and calcium additions modify the sulfide inclusions to isolated globules with decreased plasticity. How would the strength properties of plate or sheet be changed in the different directions? [See T. M. Banks and T. Gladman, *Met. Tech.* 6(1979):81.]
37. What is a dual-phase steel?
38. What are some characteristics of dual-phase steels?
39. Why are small amount of V, Nb, and Ti sometimes added to dual-phase steels?
40. What is the manganese content of typical dual-phase steels as high as 1.5 to 2.1 percent?
41. Why is discontinuous yielding suppressed in dual-phase steels?
42. Why do dual-phase steels have a combination of high strength and high ductility?