Third Edition

MANUFACTURING AND MACHINE TOOL OPERATIONS

Herman W. Pollack

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Preface to the Third Edition

Since the second edition was published, the computer has evolved as the dominant method for controlling machining operations. Thus, the approach to and the philosophy of machining have changed dramatically.

The fundamental principles of fabricating materials have become more important as advances in machining techniques have evolved. The need to understand these fundamentals is critical to the understanding of computer-controlled machining.

Programming is now a major force in the machine tool industry. Jigs, fixtures, and tool design have had to adapt to these changes. The adaptation of numerical control and computer numerical control to production methods will require the designer to understand the contents of this text.

The third edition is divided into three parts: nonmachining; machining; computer control. Essentially, each of these three parts stands alone.

This text is intended for use in a freshman course in Manufacturing Processes in a post high-school two-year curriculum. A concurrent college-level course in mathematics is recommended. Basic trigonometry is essential in sections two and three. If this book is used in the freshman year, its contents will provide a strong background for courses in Machine Design, Kinematics, Mechanisms, Tool and Fixture Design, Robotics, Production Systems, and so on. As background for N.C. and C.N.C., it is important that students understand the capabilities and limitations of machine tools and cutting tool technology.

The sections on C.N.C. have been expanded. It should be understood that the entire machining industry has developed very rapidly so that acronyms such as computer-integrated manufacturing (C.I.M.) and computer-integrated flexible manufacturing (C.I.F.M.) are fast becoming "household words" in the machine trade industry.

Since programming has not yet been standardized, the section on C.N.C. programming is actually a study in "computer mathematics."

The author is of the opinion that the best way to understand the "modern" machine tools is to understand the operation of earlier editions of these tools. He therefore elected to include these tools and their operations even though they are not of current vintage.

Once again, it is my privilege to acknowledge those people who had input into the development of the edition, people such as Ed Moura (Prentice-Hall) and Eileen O'Sullivan (Prentice-Hall) for their dedication to excellence. In addition, I wish to thank Mrs. Regina Westeris, who typed the revision, was patient, and made the changes that I requested. Finally, for the moral and spiritual support of my daughter Betté, which was invaluable to the completion of this edition.

Herman W. Pollack

Preface to the Second Edition

The revision of this text resulted from a radical change in the concepts of machining that developed since the publication of the first edition in 1968. During the interim period, numerical control and computer numerical control emerged as the major development in the machining industry. The shift in emphasis to tape and computer-controlled machine tools changes the entire approach and philosophy to machining processes. The changes that have taken place over the past five years are staggering. These changes are continuing at the same pace!

The fact remains that the fundamental principles of fabricating materials become more important than ever before. A thorough knowledge of cutting tool materials, clearances, rakes, cutting speeds and feeds, and so on, are essential to successful NC and CNC machining.

Programming has emerged as a major requirement for the designer. The approach to tolerances, jig and fixture design has changed radically. In the near future the machine tool companies will standardize the language of these machines, and once again the designer will need to update his knowledge.

With the above in mind, the author has rearranged the material in the first edition, updated other information, deleted obsolete materials, and expanded NC.

Once again, I wish to acknowledge those people who have had a constructive effect upon this, the revised edition: people such as William C. Hammen, John P. Corbin, and Russell F. Jerd. To my wife, Ruth, who in spite of everything, continues to give the impression that the many hours that I spend in isolation in my study is tolerable. If it has had a negative effect on her, I have not noticed it. In addition, Mrs. Regina Westeris, my secretary, has expended her usual effort in the preparation of this revision. Finally, I wish to thank Mike Melody (Prentice-Hall) for his effort and faith, and Arthur Lizza, Jr. (Prentice-Hall) for his dedication to excellence.

Herman W. Pollack

Preface to the First Edition

This book is intended as a text to be used by students in technical institutes, junior colleges and similar institutions which offer a course in manufacturing processes or machine tool operations. Almost the entire first half of this text is largely descriptive in nature and may be used by high school graduates who have completed one year of algebra. The second half of the text is more heavily mathematical. It correlates theory with practice supported with many mathematical examples.

It is intended that this text be used in a freshman course in manufacturing processes of a two-year curriculum. A concurrent college level mathematics course is recommended. The value of using this text in the freshman year is that the materials included are intended to give the student a strong background for such second year courses as Machine Design, Kinematics, Mechanisms, Tool and Fixture Design, etc.

If used in the second year in a course in Manufacturing Processes, the text material is presented so that whole blocks of chapters may be dovetailed with other second year courses.

The general purpose machine tools are discussed in some detail in an attempt to present the fundamental principles inherent in all machine tool operations. It is hoped that many of the mechanisms which make up a machine tool will be studied since they are fundamental to the design of mechanisms and machines used in automated processes. Thus the theory of gears applies to the machining of gear teeth, as well as to their use in gear trains in automated machinery. It is important that the student understand the limitations and capabilities of machine tools. New designs must be capable of being built. It is not enough to merely design mechanisms.

Many of the latest machining processes are included in this text. In many instances enough material is presented to whet the student's appetite. It should be obvious that almost every topic in this text may be expanded into a full text in its own right. The author uses the technique of requiring each student to select a topic for further library study and to expand and report on this topic to the class. However, the processes are included in this text in sufficient depth to make them meaningful.

The author owes much to his family for their patience throughout the preparation of the manuscript. Special recognition and thanks are extended to Professor Charles Toole for his review and criticism. The author also wishes to thank Irving J. Levinson (Dean of Instruction, Oakland Community College) and Stanley Brodský (Chairman, Physical Sciences Division, N.Y.C. Community College) for their review of the final draft of the manuscript. I also wish to thank and give credit to my former secretary, Miss Gertrude Ruby, for her beyond-the-call-of-duty efforts during the early preparation of the manuscript and to my present secretary, Mrs. Regina Westeris, who continued the effort so effectively. Finally the author wishes to thank Mr. Anthony Caruso (Prentice-Hall) for an excellent job in the preparation of this text and to Mr. Matthew I. Fox (Prentice-Hall) for his guidance throughout the entire project.

Herman W. Pollack

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1

Manufacture of Iron and Steel

1.1 PRODUCTION OF IRON AND STEEL

Figure 1.1 shows the processing of iron into iron and steel. The raw materials are fed into the blast furnace, where they are heated to form the melt. The oxygen compounds are burned in the presence of coke, which is mainly carbon. The oxygen is burned off and replaced with carbon from the coke. This forms cast iron. A secondary process removes the carbon, which results in the production of steel.

1.2 THE BLAST FURNACE

The blast furnace (Fig. 1.2) dates back to about the fourteenth century. It is a large steel cylinder about 30 ft in diameter set on top of a brick foundation. This shell is lined with heat-resistant fire brick and has four major regions: the hearth, the bosh, the stack, and the top.

The *hearth* is the container that holds the molten metal and molten slag. Since the specific gravity of the molten slag is less than the specific gravity of molten metal, the slag will float to the top of the melt. When it is time to remove the slag, the *slag door* is opened and the molten slag runs off into waiting slag cars. The slag cars carry it away for disposal. The *tap hole* at the lower part of the hearth is opened and the metal is allowed to run off into large *ladles*. These transport the molten metal to large storage tanks, called *mixers*, or to *molds* where the metal is poured and allowed to solidify into *pigs*.

Just above the hearth are the *combustion* and *fusion* zones. The two zones are called the *bosh*. This is where the temperatures required to melt the *charge* are generated. The temperatures reach about 3000°F generated by a continuous hot-air blast, which generates the oxygen necessary for combustion. The air enters the combustion chamber at about 30 psi through openings in the side of the furnace called *tuyers*. During this process the iron picks up carbon from the coke and silicon from the slag.

At the top of the bosh is the *stack*. It comprises the heat *absorption* and *reduction* zones. At the bottom of the *absorption zone* the temperatures are about 2200°F. The temperature decreases so that at the top of the reduction zone the temperature is about 400°F. It should be understood that there is no distinct dividing line between the various zones. The temperature decrease is continuous. The heat absorption zone's main function is to preheat the charge so that the melting process is continuous once the charge reaches the fusion zone. The reduction zone also preheats the charge. However, its main function is to burn out oxygen.

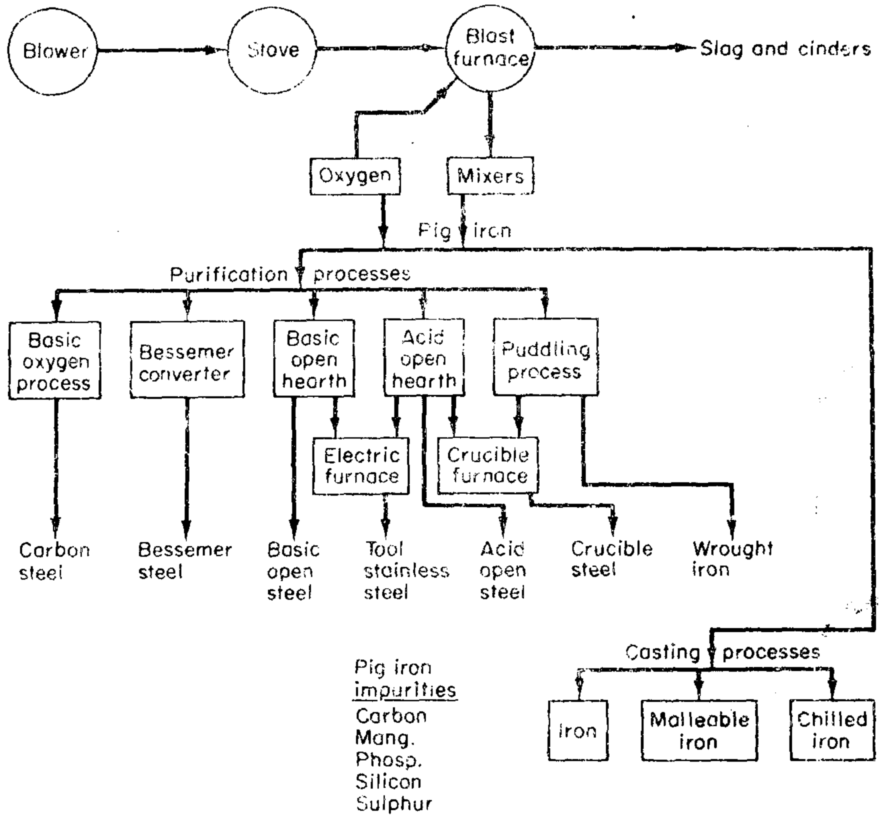

FIGURE 1.1 Flowchart. (Blast furnace charge: iron ore, coke, limestone scrap.)

The *top* of the blast furnace houses two inverted cone-shaped bells. These ensure an even distribution of the charge. Ducts spaced around the top of the furnace carry off the gaseous products of combustion.

The furnace is filled with successive layers of iron ore, scrap steel, coke, and limestone. As the coke burns, aided by air forced into the furnace, the ore melts and collects in the hearth. As the melting proceeds, the entire mass settles and thus makes room for the addition of charges at the top. As the process takes place, the limestone forms a slag of impurities.

1.3 THE CHARGE

The *charge* in the blast furnace is made up of four materials: *iron ore, scrap coke, scrap steel,* and *limestone*.

Iron ore exists as an aggregate of iron-bearing minerals. These aggregates of iron are called ***hematite***.

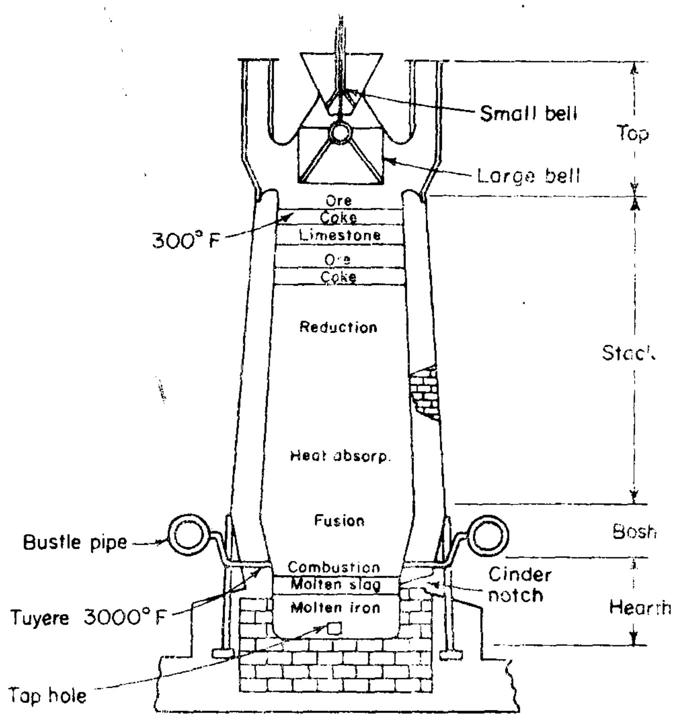

FIGURE 1.2 Blast furnace

limonite, and *magnetite*. Hematite contains about 70% iron. It takes about 1.6 tons of iron ore, 0.65 ton of coke, 0.2 ton of limestone, 0.05 ton of scrap iron and steel, and about 4 tons of air to produce 1 ton of pig iron.

Impurities are determined through analysis. They may be silicon, sulfur, phosphorus, manganese, calcium, titanium, aluminum, and magnesium. Once analysis has been completed, the ore is graded and mixed to achieve the desired balance. The amount of silicon, phosphorus, and sulfur present will determine the purification process to be used in the manufacture of steel.

The second component of the charge is *coke*. It is made from coal. Its functions are to reduce the ore and melt the iron. During the process, the iron picks up carbon from the coke and impurities from the ore. The amount of carbon picked up from the coke is more than is needed in the production of steel. Nevertheless, it becomes part of the pig iron used in the production of steel. It is the control of this carbon during the subsequent process that determines the properties of the steel produced.

Coke is produced from bituminous coal using a distillation process. When the impurities are driven off, the coke is produced. It should be noted that the coke must be dust free, not overly combustible, and strong, since it must support the charge. There are two methods for making coke: the beehive process and the recuperative process.

The *beehive* is started after it is loaded with coal. The gases are ignited and burned until the fuel assumes a semifused state. A spray of water over the hot mass causes it to contract and break into irregular pieces.

The *recuperative* process heats the coal until the gases are driven off. The gases are piped away, the ingredients extracted. The gases are piped back into the oven and used for heating purposes. The process is completed when the coal fuses and develops a large crack. The mass is packed into cars, taken to a quenching house, sprayed, sifted, and stored.

Scrap steel is used to control the grade of the cast iron produced. Two types of scrap steel are used: *home scrap*, produced in the steel mill, and *purchased scrap*, purchased outside. All scrap is graded according to the furnace in which it is used. The blast furnace uses 8% scrap in its charge.

Limestone (calcium carbonate) is the fourth ingredient. It takes about 800 lb of limestone to produce 1 ton of pig iron. Because most of the impurities in the charge will not melt at the operating temperature of a blast furnace, it becomes necessary to fuse them with a material that can be removed. That material is limestone. It combines with the impurities to form a slag which can easily be removed.

Pig iron is the end product of the blast furnace. Pig iron may be stored in large tanks in the molten state; or it may be poured into molds, allowed to solidify into pigs, and then stored. It is about 90% iron combined with impurities: about 4% carbon, 1.25% silicon, 1 to 2.5% manganese, 0.04% sulfur, and 0.06 to 3.0% phosphorus.

The secondary refining processes produce steel. The pig iron is further refined so that the desired types and amounts of impurities are added to produce steels that will possess the characteristics needed for a wide range of applications.

There are processes in existence which accept directly the products from the blast furnace and process them into steel. The three processes are (1) the kiln retort, (2) the batch, and (3) the fluidized-bed process.

The *kiln process* uses a long, rotating circular kiln lined with refractory brick. It is charged with high-grade ore pellets which move through a 2° sloping rotating cylinder. It is fired with natural gas. The material drops through chutes into a rotating cooling kiln, where the iron is cooled to about 150° F. The charge is then ready for processing.

The *retort process* uses parallel retorts which contain fixed beds of high-grade ore. The fuel is processed natural gas. As it passes into the retorts, it reduces the iron ore to the desired impurities.

A third process is the *fluidized-bed process*. It uses the partial combination of air and natural gas (one process uses hydrogen) to reduce the iron ore. The material is pressed into briquettes for further processing.

1.4 THE CUPOLA

The *cupola* (Fig. 1.3) is essentially a smaller version of the blast furnace. Its purpose is to melt pig iron so that it may be poured into controlled cavity shapes. It provides molten iron for the casting processes shown on the right side of Fig. 1.1. The end product of the cupola may be cast iron, chilled iron, or malleable iron.

The bottom of the cupola is formed by two semicircular hinged doors. A prop supports both doors and a sand bottom. This sand bottom is made so that it slopes toward an opening in front of the cupola. The opening is called the *breast-hole*. After igniting the bed charge (coke), the breast is made up by mixing one part fire clay with two parts fire sand. An opening of approximately 2.5 in. is left as a taphole. This is plugged with a cone-shaped mixture of fire clay and molding sand called a *bott*. The bott is inserted to permit molten iron to collect. Once the iron is collected, the bott is knocked out and the molten metal flows out of the taphole, down the spout, and into the ladle.

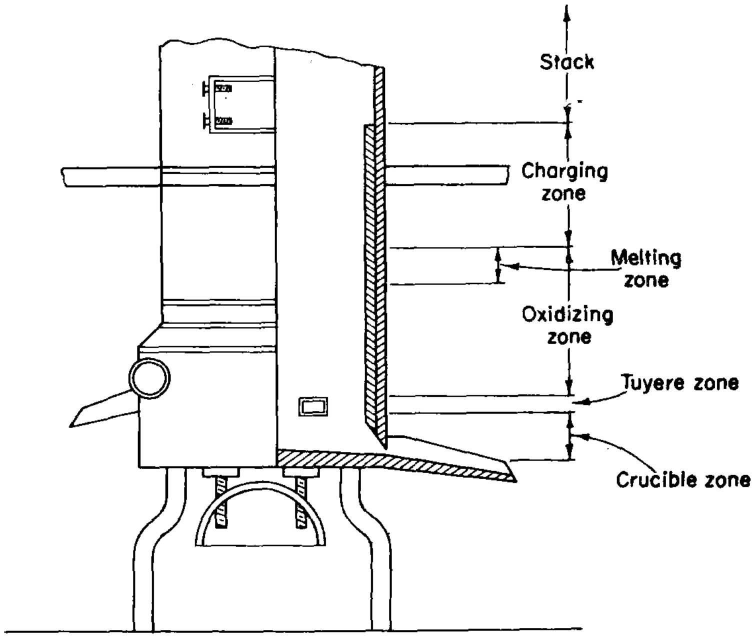

FIGURE 1.3 Cupola.

Encircling the lower part of the cupola are the *tuyeres*. These are openings in the side of the furnace through which air passes into the combustion zone. Each tuyere has a sight window in it so that the condition of the molten iron may be watched. At the back of the cupola and below the tuyeres is the *slag hole*. The slag hole is also plugged with a bott.

A bed charge of coke is placed in the bottom of the cupola. The larger pieces of coke are placed at the bottom of the bed charge, after which the bed charge is completed to a depth of approximately 60 in. above the tuyeres. This bed charge is ignited with a torch through the breast-hole.

Charges of iron and coke are placed on top of the bed charge. Cupolas have different melting ratios. A 10:1-ratio cupola dictates a charge of 700 lb of iron to 70 lb of coke. The cupola should be filled to the charging door with successive charges of iron and coke.

After an hour and a half has passed, the blast is turned on and the air from the tuyeres causes the temperature within the cupola to melt the iron so that after about 10 minutes iron appears at the taphole. The bott is inserted, and the molten iron is allowed to collect for about 5 minutes. The bott is knocked out, and the molten metal is permitted to run into a ladle. A new bott is inserted, and the process is repeated.

1.5 CHARGE CALCULATIONS

If a cupola is examined carefully after a heat, it will be noted that a groove exists in the lining. This groove locates the high-temperature zone. The bed charge should reach this zone.

EXAMPLE 1

It is assumed that a groove exists 54 in. above the sand bottom in a 42-in.-diameter cupola. Calculate the weight of the bed charge if coke weighs 30 lb/ft^3.

Solution: The weight of the bed charge

$$w_b = \frac{\pi d^2}{4}(h_b)(W) = \frac{\pi(3.5^2)}{4}(4.5)(30) = 1300 \text{ lb}$$

$W = 30$ lb/ft^3
d = diameter of cupola = 42 in. = 3.5 ft
h_b = height of bed charge = 54 in. = 4.5 ft.
$w_b = ?$

EXAMPLE 2

Assume that not more than 9 in. of coke is burned at a time in Example 1 and that this layer of coke is covered by a layer of iron that weighs 10 times as much as the coke. Calculate (a) the weight of the regular charge of coke, and (b) the weight of the iron in this charge.

Solution: (a) The regular charge of coke

$$w_c = \frac{\pi d^2}{4}(h_c)(W) = \frac{\pi(3.5^2)}{4}(0.75)(30) = 216.5 \text{ lb}$$

$W = 30$ lb/ft^3
$d = 3.5$ ft
$h_c = 9/12 = 0.75$ ft
$w_c = ?$

(b) The weight of the iron charge

$$w_t = w_c(10) = 216.5(10) = 2165 \text{ lb}$$

ratio = 10:1

1.6 MELTING RATIO

The melting rate of a cupola is generally 10 lb of iron per hour per square inch of cross-sectional area. Cupolas may have melting ratios of 10:1, 8:1, and so on.

EXAMPLE 3

Assume a melting ratio of 8:1 and a melting rate of 6 lb per hour per square inch. (a) How much iron is melted in an hour in the cupola in Example 2? (b) How many charges are needed to produce iron for one 8-hour day?

***Solution*:** (a) The iron melted per hour, assuming no losses:

$$I_h = \frac{\pi d^2}{4}(M_r) \qquad d = 3.5 \text{ ft} = 42 \text{ in.}$$

$$M_r = 6 \text{ lb/hr/in.}^2$$

$$r = 10{:}1$$

$$= \frac{\pi(42^2)}{4}(6) \qquad I_h = ?$$

$$= 8313 \text{ lb/hr}$$

(b) The charge needed for an 8-hour run:

$$N = \frac{8(I_h)}{w_i} \qquad w_i = 2165 \text{ lb}$$

$$N = \text{number of charges}$$

$$= \frac{8(8313)}{2165}$$

$$= 31$$

1.7 VOLUME OF AIR

To determine the quantity of air needed to melt the charge, it is necessary to calculate the volume of air needed to burn a pound of carbon.

To burn 1 lb of carbon requires 2.67 lb of oxygen. Since air contains 23% oxygen by weight, the weight of air required to produce the 2.67 lb of oxygen is

$$\frac{2.67}{0.23} = 11.6 \text{ lb of air}$$

If air weighs 0.08 lb/ft^3, the volume of air required for every pound of carbon is

$$\frac{11.6}{0.08} = 145 \text{ ft}^3 \text{ of air}$$

EXAMPLE 4

Using the ratio 10:1, calculate (a) the air needed for complete combustion, (b) the air needed to melt 800 lb of iron at this ratio, (c) the coke needed to melt 800 lb of iron at ratios of 10:1 and 6:1, and (d) the air needed to melt 800 lb of iron at ratios of 8:1 and 6:1.

***Solution*:** (a) at 10:1, 70 lb of coke melts (from the text):

$$70 \times 10 = 700 \text{ lb of iron}$$

The volume of air needed for complete combustion:

$$70 \times 145 = 10{,}150 \text{ ft}^3 \qquad 145 \text{ ft}^3 \text{ of air/lb}$$

Coke is 88% carbon. Therefore, the volume of air needed to burn 70 lb of coke and melt 700 lb of iron is (only the carbon burns)

$$10{,}150 \times 0.88 = 8932 \text{ ft}^3 \qquad (\text{use } 9000 \text{ ft}^3)$$

(b) The air needed is

$$\frac{800}{700} \times 9000 = 10{,}286 \text{ ft}^3$$

(c) The coke needed to melt 800 lb of iron:
At 10:1:

$$\frac{800}{10} = 80 \text{ lb of coke}$$

At 8:1:

$$\frac{800}{8} = 100 \text{ lb of coke}$$

At 6:1:

$$\frac{800}{6} = 133 \text{ lb of coke}$$

(d) The air needed to melt 800 lb of iron
At 8:1:

$$\frac{10{,}286 \times 100}{80} = 12{,}857 \text{ ft}^3$$

At 6:1:

$$\frac{10{,}286 \times 133}{80} = 17{,}100 \text{ ft}^3$$

1.8 MANUFACTURE OF STEEL

The purification processes shown in Fig. 1.1 produce as an end product one of the classes of steel by controlling the lining of the furnace and either removing or adding ingredients. Acid-lined furnaces have linings of silica, sand, and brick. Chemically, silica is acid. Basic linings are made from magnesite.

The union of iron and carbon produces plain steel. In order to achieve special characteristics in steel, other elements are added. The special characteristics desired may be deep hardening, strength, corrosion resistance, high heat resistance, resistance to abrasion, impact, or others. The elements that may be added to produce these characteristics (not in the order listed above) are molybdenum, manganese, chromium, nickel, tungsten,