METALS AND HOW TO WELD THEM

THE JAMES F. LINCOLN ARC WELDING FOUNDATION
CLEVELAND OHIO

Progress Through Study

Metals

and

How to Weld Them

SECOND EDITION

By

T. B. Jefferson

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The James F. Lincoln Arc Welding Foundation

Purposes, Activities, Organization

The James F. Lincoln Arc Welding Foundation is a non-profit educational organization established in 1936 by The Lincoln Electric Company through a deed of trust, "to encourage and stimulate scientific interest in, and scientific study, research, and education in respect of, the development of the arc welding industry through the advance in the knowledge of design and practical application of the arc welding process."

The Foundation's activities consist of both fostering the development of knowledge of arc welding and making this knowledge generally available at minimum cost. Its fields of activity are in schools, colleges, industry, business and agriculture.

In its award programs, the Foundation has made awards and provided scholarship funds for papers describing improvements and developments in arc welding and its application. Programs have been conducted covering all phases of manufacturing, design and research. Programs have been conducted to encourage design of welding highway bridges. A program for textbook manuscripts has produced three college texts. Other books have been published to present the information gathered in the various award programs.

Two award programs have been conducted to encourage farmers, agricultural leaders and educators to investigate how welding may contribute to improved farming methods. Two books were the direct results of this program, and two supplemental teaching manuals for farm welding were also developed. Strip film, manuals and project sheets have also been prepared for vocational agricultural training.

An annual design competition is conducted for college engineering undergraduates. An annual program for high school students is also sponsored. Engineering libraries have been established in over 250 accredited engineering schools in the United States.

TRUSTEES AND OFFICERS OF THE FOUNDATION

Inquiries about the Foundation and its work are welcomed and communications may be directed to:

THE JAMES F. LINCOLN
ARC WELDING FOUNDATION
CLEVELAND 17, OHIO

PREFACE TO FIRST EDITION

The authors prepared this volume to fill a need for those who are curious as to what happens when working with metals. Metals have become a most important part of our everyday life, yet few people know much about them. It is the feeling of the authors that a basic knowledge of metals will enable those working with metals to do a better job while using the materials to a better advantage.

No matter what type of work is being done on metals eventually there arises the problem of joining them. Since the only logical way to join metals for permanence is to weld them, the subjects of "Metals and How to Weld Them" seem to make a perfect combination for the better use of modern materials and methods.

"Metals and How to Weld Them" has been written for all who are interested in welding who want a better understanding of what takes place when welds are made. This volume has been designed as a text for classroom or home study use. It is equally well suited to serve as a reference book for the student, the craftsman or the engineer who must deal with welding, metals and their related problems.

All of the welding processes and their uses are discussed but the greatest emphasis has been placed on the basic fundamentals of metallurgy and the various metals that might be welded. Though metallurgy is generally considered a highly technical subject, the authors simplified the discussion of this subject to make it readily understandable, even though the reader may not have had prior knowledge of metallurgy. It has been the authors' desire to present this material in such a manner as to be understood by high school students should this book be used to supplement their study. By the same token, however, even a graduate engineer may obtain a better understanding of metals and metallurgy from this presentation.

The welding of various metals is discussed in separate chapters. The problems that may be encountered in welding any commercial metal, from aluminum to tool and die steels, are covered completely. There is a special chapter devoted to hardsurfacing and an extremely important chapter on how to make good welds. The Appendix, in addition to a weldor's dictionary, include a number of tables of useful information pertaining to welding.

No special credit has been given for the illustrations appearing in "Metals and How to Weld Them" because many of the photos used came from the unidentified photo files of THE WELDING ENGINEER. It is known however, that many of these were contributed by companies serving the welding industry. To these companies and other organizations serving the welding field the authors are deeply indebted for pictures and other data presented in this book.

CHICAGO, ILLINOIS — T. B. JEFFERSON

CLEVELAND, OHIO — GORHAM WOODS

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PREFACE TO SECOND EDITION

The rapid advance of welding since the first edition of METALS AND HOW TO WELD THEM has produced new knowledge and understanding of welding techniques and procedures as they relate to specific metals. These developments dictated a complete review of the entire text to determine the need for and requirements of a second edition.

The first edition of METALS AND HOW TO WELD THEM sold 30,000 copies. Its unqualified acceptance readily justified the decision to print a completely revised second edition and make the changes and improvements necessary to maintain the text's reputation of being one of the foremost in its field.

Many sections have been completely rewritten. Editorial clarifications in language and sentence structure have been made on every page. Where appropriate, the text has been modified to reflect industry's trend toward welding mechanization. Almost all illustrations and data have been replaced or improved. An entirely new chapter on the exotic metals has been added. The book has been completely reset in a new, easier-to-read type face, and the headings have been restyled and rearranged to aid the reader by supplying an outline of subject matter coverage to quickly acquaint him with the chapter and serve as a guide for future reference. All of these changes have been made in the interest of easier reading and better understanding.

This major revision has not altered the book's basic purpose. Its objective remains unchanged: namely, to equip the average reader with a practical knowledge of the structure and properties of metals and how these metals adapt to welding. It is intended as a reference book for students, weldors, plant managers and engineers. To accomplish this, technical explanations and descriptions have been simplified for easier understanding.

The officers and trustees of The James F. Lincoln Arc Welding Foundation are grateful to Mr. T. B. Jefferson for his suggestions, editorial review and willingness to make available, for illustrations, the photo file of THE WELDING ENGINEER. Special acknowledgement is also made to the skill with which Mr. Watson Nordquist executed the major portion of the reorganization, restyling and writing of this second edition.

Charles G. Herbruck, Secretary

CLEVELAND, OHIO — THE JAMES F. LINCOLN

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WHAT'S THIS ALL ABOUT?

The progress of man really started at the time he began to use metals. Until man became the master of metals life was hard, cruel and difficult. Many people seem to think these conditions of life have not changed very much. But do you realize how much easier life is because of metals? Without metals many products we know as common necessities would be impossible, while other items would be very unsatisfactory substitutes by presentday standards.

Without metals our activities would depend on our ability to use wood and stone. Stone axes and hammers may have served the caveman, but they would not meet the needs of skilled craftsmen of today. With only stone and wood available as materials, practically all our modern conveniences would be non-existent. We would not have modern means of transportation—the automobile, ocean liner, train or airplane. Likewise, we would not have modern means of communication—the radio, telephone or television. In fact, we now depend so much on metals it is difficult to think of how we could live without them.

Early man probably discovered metals as a result of building his campfires on the sands of a desert or lake shore. These sands contained copper, and possibly tin or aluminum. The heat of the fire caused them to melt, and the hot molten metal flowed out over the sand. As the metal cooled, it hardened into a solid piece. It was then that early man realized he had a new material with which to work—a material we now know as metal. This metal was not in a very usable shape, just an icicle in the sand, but man soon learned that he could cast this metal in usable shapes by making small molds in the sand. Metal then became valuable.

We call the period of history when man was limited to the use of stone and wood, the Stone Age. His first experiences with metals led him into the Bronze Age. Bronze is a metallic material made up of copper and one or more other metals, like tin or zinc or aluminum, that melt at a relatively low temperature. And then, about 1400 years before Christ, people in Egypt and the countries of Asia Minor along the Mediterranean Sea began to use iron in making tools, weapons and other products. This was the beginning of the Iron Age of civilization.

In those early days, our ancestors could not always make castings in the exact shape desired. The small-village craftsman was unable to create enough heat to melt some metals for casting. Iron, for instance, requires much higher temperature to melt it than bronze does. So the ancient craftsman frequently hammered the rough casting into a more useful shape. The use of heat made his job easier. This was man's first attempt at forging, and even today we have blacksmiths who still shape metal by hammering. It wasn't until about 200 years ago that man first developed machines with which he could make castings and forgings repeatedly, to the same exact shape desired.

When man first attempted to join pieces of metal together, he faced more problems. In the beginning he limited himself to joining metal in the same manner by which he had joined pieces of wood.

Fig. 1-1. Forging is one of our oldest crafts. From this shaping of metal by heat and hammering came the idea of forcing metal together by forge welding, a process which has become obsolete for most purposes.

Later, man learned that he could heat two pieces of metal and then force them together by hammering. For centuries, craftsmen used this practice of *forge welding** to join metals. (Fig. 1-1). Unfortunately, the heat and pressures applied in this process were not great enough for complete fusion of the two pieces being joined. In *fusion* the metal would be melted sufficiently for a thorough blending of the material in

*Definitions of italicized words are listed at end of chapter, and in the "Dictionary of Metallurgical and Welding Terms" at back of this book.

both pieces . . . hardening, as they cool, into a single, continuous solid mass. In forge welding, however, the effect was more a mechanical locking-in of the two surfaces in contact, and any fusion was limited to the thin outer "skin" of the two surfaces. With these conditions, a relatively low force when applied in certain ways could break the joint and separate the pieces.

The discovery and invention of modern welding processes, starting about 70 years ago, provided man with the ideal means of joining metal plates or shapes, castings to castings, forgings to forgings, or forgings to castings. This is how metals should be joined—by fusion, resulting in a complete, permanent union of the two pieces with the weld area being stronger than either of the pieces joined. With the proper welding materials and techniques, man now can join together almost any two pieces of metal so as to become a single unit. Overlapping of pieces to be joined is not necessary, and thickness at the weld area can be held to the thickness of the member to either side.

Arc welding today is widely accepted as the best, the most economical, the most natural and the most practical way to join metals.

All metals are weldable provided the proper process and techniques are used. Occasionally an attempt to weld metal ends in failure because one of these two factors—the proper process or the proper technique—has been overlooked. If, however, the engineer and the weldor understand the composition, structure and properties of a metal, they will be able to design and make better welds. This creates a close relationship between the metallurgy of a metal and its weldability.

What Is Metallurgy?

Metallurgy is the science and technology of extracting metals from their ores, refining them, and preparing them for use. It includes the study of metals—their composition, structure and properties—and how they behave when exposed to different conditions of use. Let's look at this definition more closely. It contains words that may be new to you.

Ore is the rock or other natural form in which we find a metal. Most of the metals used commercially are not found in a pure state. By this we mean you probably wouldn't find iron, for example, all by itself buried in a mountainside. It and other metals are usually combined by Nature with other elements, which often are undesirable in the finished product.

You probably know what an *element* is. It is Nature's building block. We have 26 letters in the alphabet, and each is different from all the others. If a child has a block for each letter, he can build an almost endless number of words. Similarly, each element is a substance different from all others, and these can be mixed or joined together by Nature or by man to build an almost endless number of materials. There are only 103 elements, and everything on Earth and possibly in all the Universe is an arrangement of some of these elements.

An element can never be broken down into two other substances; however, the smallest unit of an element is the atom—a particle that has all the characteristics of the element but is so tiny we can't see it even under the microscope. We need millions of an element's atoms all locked together before we have enough to do anything useful.

Many of these elements are metals. Most of us know what a metal is. Technically, a *metal* is an element that has all or most of the following characteristics: it is solid at room temperature; it is opaque (you can't see through it); it conducts heat and electricity; it reflects light when polished; when viewed under a microscope, it is seen to be made up of tiny crystals; it expands when heated and contracts (shrinks) when cooled.

There are still other characteristics of all metal elements, but these do not directly concern us and don't mean much except to the laboratory man. The word metal also is used for a material which has strong metallic characteristics, even though it has more than one element. Bronze is a good example, since it contains some combination of tin, zinc, aluminum, lead, silver, phosphorus, silica or other elements, in addition to copper, its main ingredient. Metallurgists call this type of material an *alloy* to indicate it is not a pure metal element.

Metallurgy is a big subject. Most metallurgists (scientists or engineers working in this field) are specialists, just like some people in the building industry are carpenters, while others are masons, plumbers, electricians or painters. There are two main divisions of metallurgy—process and physical.

Process metallurgy deals with the first operations—getting metal from a mine into the form of basic mill products, such as structural plate or bar stock.

The processing of metals requires many steps, which may be grouped as follows: (1) extracting metals from the ore, that is, separating the metals from the unwanted materials of the earth and rock in which they are found in Nature; (2) refining them, that is, separating the various metals extracted from the ore, in order to have a relatively pure metal for further processing; and finally (3) the conversion of relatively pure metals into usable combinations (alloys) and basic forms such as castings, sheets, structural shapes and plates for use by other industries.

Physical metallurgy relates to the composition of metals and what happens to their structure and properties during shaping, fabricating, heat treating, and so on.

Briefly, *composition* refers to what elements are present in the alloy and in what amount. For example, a common low-carbon steel (SAE 1020) is made up mostly of iron but also has from 0.18 to 0.23% carbon, 0.60 to 0.90% manganese, not more than 0.04% phosphorus, and not more than 0.05% silica. Note that in this material none of these elements, other than iron, amounts to even 1% of the total weight. Yet, these elements greatly influence the strength of the alloy and its weldability.

The *structure* refers to how these elements arrange themselves within the alloy. Further on in the book, we'll learn about the formation of crystals and how these affect the way metals behave under various conditions. *Properties* of a metal are those characteristics by which we can tell how good it will be for a particular use. Hardness is one important property.

A study of physical metallurgy may require testing the metals before, after, and often even during the process of converting them into useful products. People with special training perform most of these tests, especially those requiring laboratory equipment. However, an understanding of what these people do is extremely helpful in making good welded joints.

Tests may be made in a variety of ways: by pulling a metal apart to determine its strength, by denting the metal to determine its hardness, by bending the metal repeatedly to determine when it will fail from fatigue, or by some other test to find out how satisfactory the metal will be for a particular purpose. The quality of a welded joint is often determined by these same tests.

There are many ways to examine a piece of metal. One is to merely "look it over" to see if it is standing up under service; or, an x-ray examination might be made to see if there are any hidden defects. Regardless of how the testing or examining is done, it is a part of physical metallurgy.

Why Metallurgy Is Important

Although the term itself is mysterious to some people, metallurgy is of wide interest and importance. Many thousands of people are employed in the casting, rolling, drawing, and extrusion of metals. Hundreds of thousands of people are engaged in the manufacture of finished consumer products from these basic mill shapes.

Everyone is dependent to some degree on metals. Most of us have daily contact with metals. After thinking about it for a few moments, most of us know we could not get along without metals. But few people realize that man used metals for many centuries without ever knowing very much about them or the reasons for their varied and often strange behavior.

Why is it that some metals are brittle at room temperature, while others are brittle only when extremely cold or when extremely hot? Why will some metals stretch while others won't? What makes some metals stronger than others?

For a long time man did not know enough about metals and their properties to answer questions like these. However, metallurgical research during the past 100 years has given us such knowledge. As a result, we now do much better in using the right metal in the right place for a specific purpose.

Metallurgists have developed new ways to obtain metals from their ores. As a result, industry has metals of higher quality with which to work. Metallurgists have learned to combine various metals to produce new alloys possessing better properties for a particular type of application.

Improved methods of producing metal now provide us with a wide range of useful mill products of necessary shape, size, accuracy, composition, and so on . . . to meet the needs of specific applications. We use machinable metals, formable metals, and weldable metals. Nearly all metals can be welded, but some more readily than others.

As a result of research, we know what happens when metals are suddenly heated and cooled as in welding. Metallurgical research is also of great help in the constant improvement of welding equipment, materials and practices.

Where Does Metallurgy Fit Into Welding?

Study of the arc welding process involves both process metallurgy and physical metallurgy. What happens first in the welding operation, the heating and melting of the metal, is a subject for process metallurgy. Further study of the operation as it continues through the cooling of the metal into a solid state, and the subsequent shaping or machining, is an application of physical metallurgy.

Let's review what takes place when you make a weld.

Intense heat is needed to melt the metal, causing it to be fluid in the immediate weld area. This heat comes from the arc which forms as electric current jumps across a gap in an electrical circuit (Fig. 1-2). The gap exists between the welding electrode (a metal wire or rod to

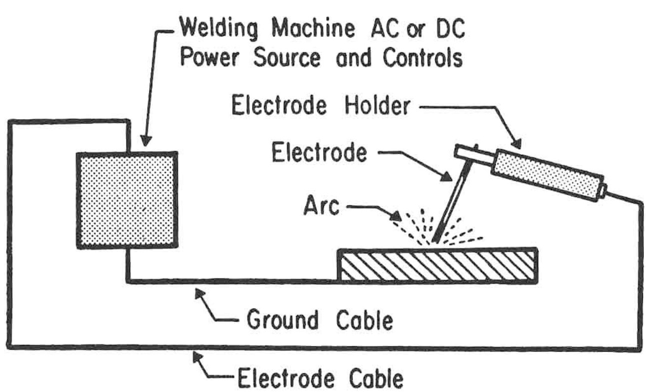


Fig. 1-2. In arc welding, current flows through the welding electrode, jumps the gap to the workpiece, and then returns to the source. The arc that occurs in the gap creates the heat for melting the metal.

which electrical current is fed from a power source) and the *base metal* or workpiece.

A common practice, when joining two plates of metal, is to first cut a groove along the line where the plates meet. This provides room for penetration by the heat to the full thickness of the metal. The space between the workpieces must be filled up with metal as strong or stronger than the base metal. This filler metal comes from the electrode, which it gradually consumes (uses up) as it welds.

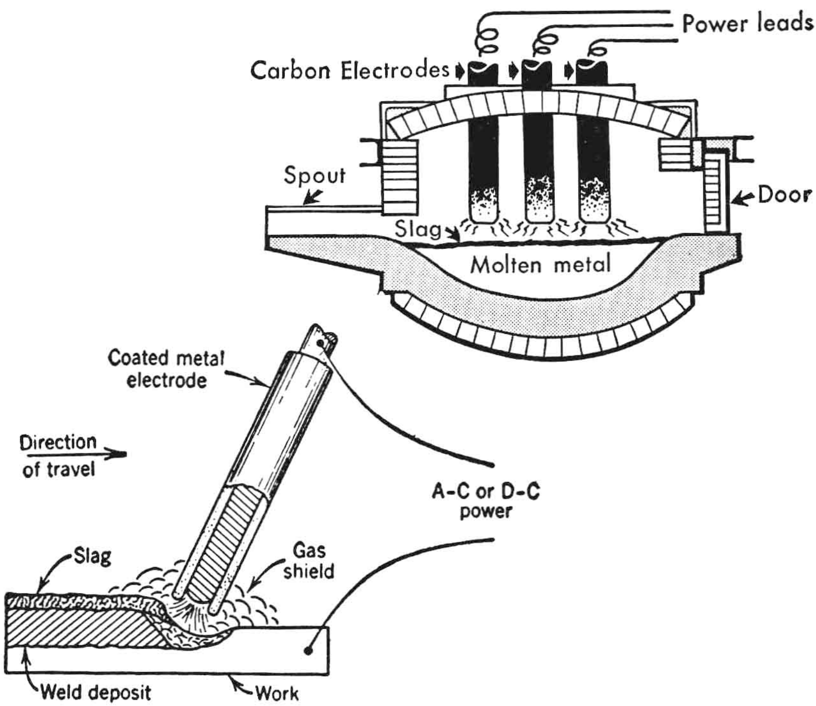
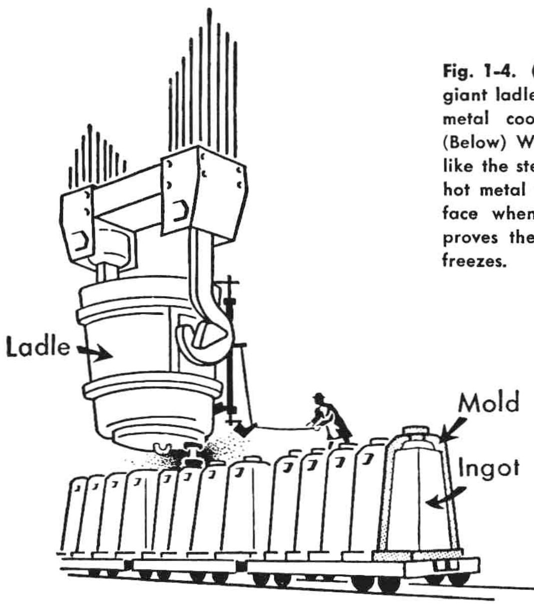


Fig. 1-3. (Above) In electric furnace production of steel, the arc from huge carbon electrodes keeps the metal bath in a molten condition. (Below) Similarly, the metal in the joint directly under the welding electrode is kept molten by the arc. The intense heat and boiling effect provides a high quality weld metal comparable to the fine "electric steels".

The heat from the arc not only melts the base metal, it also melts the electrode; and the molten metal drops from the electrode into the joint.

Welding is very much like steelmaking (Fig. 1-3). As the intense heat from the electric arc melts base metal and electrode filler, a small amount of molten metal collects within the joint. This weld puddle is like the molten contents of an electric arc furnace used in



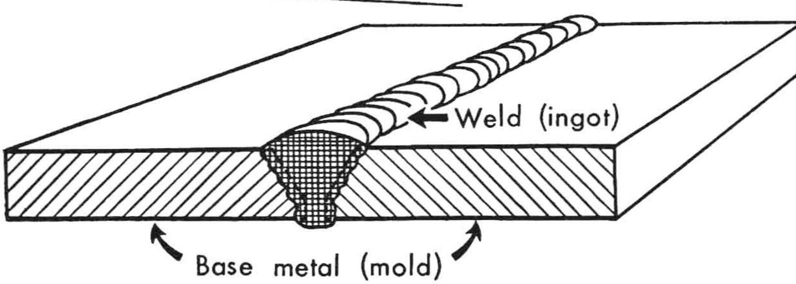


Fig. 1-4. (Left) Hot furnace steel drained into a giant ladle is then emptied into molds. The liquid metal cools and hardens into a solid ingot. (Below) Weld metal deposited in a "V" joint is like the steel-mill ingot. Impurities in the pool of hot metal float or are caused to float to the surface when they become slag. This action improves the quality of ingot or weld metal as it freezes.

steelmaking. In both welding and furnace operation, the formation of a non-metallic blanket called slag, over the molten metal, helps to control the temperature and cooling rate, and assists in preventing and removing impurities from the metal.

Since the molten puddle in the weld joint is confined within a limited area, it might further be compared with molten steel when poured into the ingot mold, after first having been tapped or drained from the furnace into a big ladle (Fig. 1-4). In the welding operation the base or parent metal is often preheated, just as the ingot mold is preheated, to prevent the molten metal from cooling too rapidly.

As the weld metal cools, it solidifies or "freezes." The same thing happens to the steel in an ingot mold. Very often a completed weld is placed in service "as welded." At other times, it is further processed by heat treatment, which will be discussed in a later chapter. Or, it may be shaped, machined, or the weld flattened by rolling. As in the case of steel mill products, this hot or cold working is for the purpose of meeting the particular requirements of the application.

By these comparisons it may be seen that both process (metal producing) metallurgy and physical (metal working) metallurgy have an important place in all welding operations.

Welding Metallurgy

Fortunately, a weldor needs know only "how to make a weld" and not all the engineering behind welding . . . for, in addition to metallurgy, welding involves electrical, mechanical and ceramic engineering.

Many welds are made without any knowledge of metallurgy. However, the average weldor who develops an understanding of some basic principles of the subject can greatly improve the quality of his work. He can successfully weld metals that would be very troublesome to other weldors, and he can in general simplify his own job.

Correct application of welding metallurgy principles helps to avoid mistakes that could weaken a weld. It assists in developing techniques which reduce stresses and strains associated with the expansion and contraction of metals during heating and cooling. A knowledge of welding metallurgy explains what happens as a result of welding heat and helps the weldor to avoid the undesirable effects of improper welding practices.

Welding metallurgy may seem like a difficult subject, but it need not be if taken in easy stages and in sequence. In this way, the basic fundamentals become known and these will provide easy solution of many annoying welding problems. With a knowledge of the tie-in between welding and metallurgy, the weldor can turn out a welded product that will meet the engineering objectives: lighter in weight, stronger, more pleasing in appearance, and less costly.

Definitions of New Words

Alloy. A material having metallic characteristics and made up of two or more elements, one of which is a metal.

Base metal. Often called *parent metal,* the metal used in workpieces being joined together.

Composition. The contents of an alloy, in terms of what elements are present and in what amount (by percentage of weight).

Element. A substance which can't be broken down into two other substances. Everything on Earth is a combination of such elements, of which there are only 103.

Forge welding. A process of joining metals by pressure, usually with the assistance of heat but at temperatures below that at which there would be true fusion.

Fusion. Melting of metal to the liquid state, permitting two contacting or neighboring surfaces to partially exchange their contents with the result that there is a thorough blending of the compositions after cooling.

Metal. An element that has all or most of these characteristics: solid at room temperature; opaque; conductor of heat and electricity; reflective when polished; expands when heated and contracts when cooled. For all practical purposes, we also use the word *metal* in speaking of many *alloys*—materials having metallic characteristics, even though they may contain more than one element including non-metals.

Metallurgy. The science and technology of extracting metals from their ores, refining them, and preparing them for use.

Ore. The rock or earth in which we find metals in their natural form.

Physical metallurgy. That division of metallurgy applying to the changes in structure and properties of metals as a result of shaping, fabricating and treating.

Process metallurgy. That division of metallurgy applying to the extracting, refining, and primary shaping of metals into a usable form.

Properties. Those features or characteristics of a metal that make it useful and distinctive from all others.

Structure. The way in which the elements of an alloy, or the atoms of one element, are arranged.

Review Questions

1. How did man first discover metals?
2. Why is welding so ideally suited for joining of metals?
3. What are the three major activities covered by process metallurgy?
4. Why are metals tested?
5. How can welding be compared to the making of steel in an electric furnace?
6. What happens in the welding process?
7. What is slag?
8. How does slag help in the welding process?
9. Is a knowledge of metallurgy necessary for welding?
10. How can metallurgical knowledge be applied to improved welds?