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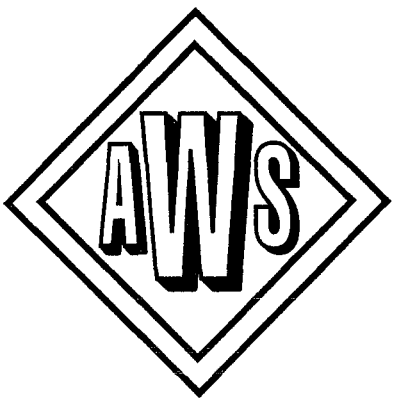
Welding Metallurgy

Carbon and Alloy Steels

Volume I
Fundamentals

George E. Linnert
GML Publications
Hilton Head Island, South Carolina, USA

Fourth Edition



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Preface

Readers of Welding Metallurgy in their comments about previous Volumes 1 and 2 of the Third Edition have offered helpful suggestions toward betterment of future editions. All offerings from students, engineers, experienced welding personnel, and educators have been carefully weighed by the author in planning this present revision. A principal aim in carrying out this work was to acquire updated information wherever available, but input from readers prompted several changes. One change will be found in the sequence of chapters, which now provides more logical progression from the structures and properties of metals, through the mechanics and effects of heating for welding, and finally to metallurgical description of typical welds in steel. Also, the remodeled text now includes additional material of a fundamental nature to assist in developing broader, analytical explanations for the chemical and physical events that arise in welding. The need for this assistance had been voiced by readers who are confronted with the complex technology of welding, but who have not had exposure to chemistry and physics of the depth needed to rationalize the phenomena encountered. Relationships between fundamental features of metals and their behavior in welding are pointed out to encourage development of more complete understanding of each particular happening in welding. This kind of awareness of the factors involved and the mechanics entailed aids greatly when a decision must be made regarding the most effective measure for dealing with a given troublesome situation.

Several features of the new text deserve comment. Metric practice has been employed as the principal system for dimensions and quantities because of expanding usage world-wide; however, U.S. customary units are in parentheses following SI units throughout the text and are included in most tables and figures. The text does not include references to particular articles in periodicals, reports, and books that served as resources because of the great number from which information was extracted. Instead, keywords from the International Welding Thesaurus are included in the text to guide readers to helpful literature for additional details whenever needed. Widely available computerized search services cognizant of these keywords can produce lists of relevant references, including those published henceforth. Each chapter concludes with a short list of selected publications under the heading "Suggested Reading." These are recent publications that provide broader range of coverage of the area being reviewed in the chapter.

Colleagues and organizations that assisted the author in collecting and preparing material for publication are so large in number that individual recognition here is not practical. The author is keenly aware of the great importance of this support. In the course of time, sincere appreciation will be expressed to contributors individually. Two organizations provided protracted help with their staffs and their facilities. The American Welding Society gave encouragement and assistance at every possible turn, and waited patiently for completion of the author's manuscript. Mr. Robert L. O'Brien, Director of Technical Services, for AWS at the time, arranged peer reviews to verify

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the manuscript's technical content. Mrs. Debbie Givens, Publishing Coordinator for AWS, deserves a note of appreciation for her diligence in arranging reproduction of the many line drawings of figures and graphs.

A bright spot in the lengthy publishing procedure was the engaging of Mr. Alexander M. Saitta by AWS as Production Editor to handle editing and formatting of this substantially larger edition of Volume I. Alex, a newcomer to the welding field, quickly demonstrated ability to fuse his language knowledge with the idiom of welding technology. In providing assistance on shortening the manuscript, Alex proposed the inclusion of "Technical Briefs" to avoid deletion of useful fundamental information — an effective format measure for which this author is very appreciative.

The Welding Institute, at Abington, England, with which the author was affiliated for many years as head of its North American Office, was extremely generous with staff assistance, and provided many photographs and photomicrographs for new illustrations. This new edition would have been very difficult to complete without the support received from TWI.

Hopefully, a revision of Volume II will receive similar support from the many colleagues and organizations during its preparation, and can be issued in a fourth edition without undue delay.

George E. Linnert
Hilton Head Island, South Carolina
December, 1994

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Chapter 1

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Background to Welding Metallurgy

Throughout industry, welding is the most widely used, cost-effective means for joining sections of metal to produce an assembly that will perform as if cut or formed from solid material. Proper application of welding technology by the user ensures the making of welds that are "fit for purpose" in virtually all kinds of service. Even in manufacturing operations which do not produce welded articles, production facilities would be difficult to construct without the use of welding. While most people would agree that nuclear power plants, spacecraft, and deep-diving submarines must make use of welding, they might not realize that many vital components, such as high-pressure piping systems, transducers, vacuum tubes, and a multitude of other articles must also use welding in practical production. Without welding, we would be hard-pressed to build computers, television systems, jet planes, and the many devices that support our present mode of living.

MILESTONES IN WELDING HISTORY

A brief historical review of welding will identify the driving forces that spurred its remarkable growth, and will help explain engineering constraints that have been placed on welding from time to time in past years. Although man began to pressure-weld noble metals such as gold more than 2000 years ago, and learned to forge-weld iron about 1000 years later, modern implementation of welding did not begin until a little more than 100 years ago. In the early 1880s, the acetylene torch and the electric arc were introduced as tools capable of fusion welding. Elementary forms of electric resistance welding processes were demonstrated about the same time. Therefore, in a single century just passed, welding has grown from virtual inception to its present indispensable role in industry.

Initially, proponents of riveting, bolting, screwed joints, folded seams, and other forms of mechanical fastening contrived to place obstacles in the path of welding. Admittedly, the early welding equipment and processes were crude. Welding techniques were essentially exploratory, and the results were not always satisfactory. Nevertheless, the potential of welding was recognized by many innovators, and they worked to improve the art and science of this new method for joining metals.

In 1917, a dramatic situation provided an ideal proving ground for welding. As the United States prepared to join the Allies in World War I, the crews of German ships in certain ports realized that their vessels would soon be seized. The crews acted to quickly put the vessels out of commission. Boilers and heat exchangers were purposely damaged by overheating, and propulsion systems were broken by jamming gears. Overall damage was so extensive that more than a year of repair work using

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customary methods would have been required to put these badly needed vessels in commission and to have them operate within the Allied merchant marine. However, at the urging of welding advocates, the Emergency Fleet Corporation organized a wartime welding committee which was given free rein to plan this massive repair project and to make maximum use of oxygen cutting and welding. The repairs were completed in less than half the estimated time, and the welding effort contributed greatly to the improved Allied shipping position in 1918.

After the Armistice, the Wartime Welding Committee members acted in 1919 to organize a not-for-profit technical body of interested persons and companies dedicated to further the advancement of welding and its allied processes. This organization grew to become the present American Welding Society (AWS).[1] At the 1919 milestone, however, welding processes were regarded by industry merely as means to repair metal articles and structures. Welding was not yet recognized as a production operation.

In a 20-year growing period (1920-1940), proponents of welding began to gain acceptance of its processes for production operations in addition to repair work. Industry was slow to recognize the advantages of welding, but the various processes steadily drew the attention of builders of steel-framed buildings, steel bridges, earth-moving machines, mining machinery, etc. Limited processes and consumables were available for production operations during this early period, but welding proved to be efficient and economical, and it gradually emerged as a major endeavor worldwide. Companies large and small became engaged in the manufacture of welding equipment, product research and development, and marketing. Research in welding was taken up by university laboratories, not-for-profit institutions, technical societies, and metal producers.

In 1935, the Engineering Foundation in New York City established the Welding Research Council (WRC), and since that time WRC and AWS have cooperated to encourage research in welding and the allied fields. By 1940, a budding welding industry had responded with an impressive array of new processes and improved filler metals and fluxes. A need was recognized during this early growth period to disseminate authoritative, up-to-date information on the rapidly developing processes. Comprehensive welding encyclopedias and handbooks emerged shortly after 1920, and periodic editions of the AWS *Welding Handbook* were prepared with open-end planning for master charts of the processes, standard definitions, and welding symbols. Efforts were also being directed to the establishment of guidelines for welding specific metals and alloys. Yet, this early bright picture was not without an occasional dark cloud. Although welding equipment was relatively inexpensive, processes and procedures were not always clearly defined and welders were not always adequately trained. It was not long before weld failures began to tarnish the industry's record. Because so many welding operations were being carried out without due regard for sound welding engineering and welder training, it became necessary for proponents of welding to launch a substantial educational effort to encourage and assist proper planning and performance of welding operations.

[1] Acronyms are used throughout this book for technical organizations. Full names and locations are provided in Appendix I - Acronyms.

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At the start of the next 20-year time frame (1940-1960), the welding industry was again confronted with a major challenge. Even before World War II, shipbuilders all over the world had been steadily moving toward welded construction to take advantage of cost savings over riveted construction. When hostilities became worldwide in 1941, a tremendous need arose for ships to transport materiel for the Allied Forces. Shipbuilders met this challenge by selecting a limited number of ship designs for production and specifying maximum use of welding for rapid hull construction. A large fleet was built and rushed into service. The ships sailed in ocean waters that ranged from warm to frigid.

The pressures of this international emergency forced an "art-before-science" approach to the shipbuilding task. Approximately 5000 ships were built for military transport service (mostly merchant ships and tankers of the *Liberty* and *Victory* design). Of these, about 20 percent developed cracking in the hulls and main decks in or near welds in steel plate. Some cracks occurred while the ships were at sea, and these cracks rapidly progressed to fractures sufficiently large to cause catastrophic breakup. Occasionally, cracking or major fractures occurred while these ships were in port, particularly during a sharp drop in ambient temperature, or during uneven loading or ballasting. After thorough investigation by a number of concerned companies and federal maritime safety agencies, ship fractures were found attributable to three principal causes — briefly,

(1) steel that had poor toughness, especially at low temperatures,

(2) hull and deck construction techniques that had not been refined to avoid points of severe stress concentration, and

(3) some questionable workmanship done under the intense production pressure of the wartime emergency.

Toward the end of the 1940-1960 period, two important endeavors would require the best welds that could be made. One was the fabrication of pressure vessels for the nuclear power plants in submarines, ships, and utility stations; the second was the building of solid- and liquid-propellant rocket motors for aerospace vehicles. Rocket motors required large thin-wall casings and pressure vessels. The components had to be light in weight despite the loads to be carried; therefore, high-strength alloys (some with barely adequate toughness) were used for construction. A few of the early welded rocket motor casings failed at welds during pressure testing because (1) welds contained small physical imperfections, (2) weld metal required unusual modifications in chemical composition to achieve mechanical properties comparable to those of the base metal, and (3) certain welding processes exerted influences on weld metal properties that were not anticipated or completely understood. These findings motivated research on the welding of high-strength steels and other alloys used in thin-wall cylinders and tanks that are expected to withstand proof testing and service loading which approaches yield strength. As a result of this work, welding is now used without reservation as the preferred joining method for these important constructions.

In the nuclear power field, the performance record of welding is virtually free of serious complaint. A few small problems have occurred which represent unavoidable consequences of modern welding processes, but these problems were not entirely unexpected (e.g., the effects of residual stresses at joints in the as welded condition).

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Three reasons can be cited for the highly successful use of welding in building nuclear power facilities. First, the metals and alloys used for fabricating welded components are thoroughly tested and governed by detailed standards covering property and weldability requirements. Second, the planning of welding procedures has benefited from extensive experience in building petrochemical plants and other facilities using these same materials. Finally, codes and detailed specifications have been established to cover qualification of welders, permissible processes, procedures, inspection, etc. In general, nuclear facility construction makes use of proven materials, processes, and procedures. Nothing is left to chance.

Many other examples can be selected from technical literature to illustrate ways in which welding has improved and expanded to meet demands of industry, including such widely diversified applications as (1) thick-wall pressure vessels for use in coal-gasification plants, (2) large offshore drilling platforms, and (3) miniature capsules and circuitry for microelectronic devices, which undoubtedly contain the smallest welds made by man. The welding industry has mounted an impressive record of successful applications, but weld difficulties are encountered from time to time, and many are of a metallurgical nature. A good example is described in Technical Brief 1, shown below.

THE FUTURE OF WELDING

American industry must achieve significant cost reductions and production efficiency over the next decade to maintain a healthy position in the world manufacturing market. The trend to use existing welding processes for appropriate applications has been recognized by perceptive industrialists as a means of appreciably reducing manufacturing costs. Production experience will verify that welding is the most efficient joining method, and the savings can be documented; but there is another trend in the USA which is having a counterproductive influence. Although a highly impressive record of welding process invention and equipment development can be credited to U.S. companies and laboratories over past years, budgeting in this area has been drastically cut. As a result, dedicated research and development in the USA on welding has decreased substantially. In time, this policy will allow other countries with greater ded-

TECHNICAL BRIEF 1:
Transition Joints Between Different Steels

When electric power utilities began to build steam plants that would operate at higher temperatures and pressures, stainless steel tubing had to be used in the high-temperature operating portions of certain components. However, cost considerations dictated that low alloy steel tubing be used in the lower temperature operating portions; consequently, transition joints had to be made in the pressure-containing tubular systems between these two markedly different kinds of steel. Welding engineers responded with appropriate filler metals and special procedures for welding these joints, and many thousands of such welds have been made and placed in service. While operating experience with these dissimilar-metal welds has been acceptable, cracking sometimes develops at the weld after long-term service, and remaking the joint becomes necessary. This complex, ongoing metallurgical problem will be treated in detail in Volume II.

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ication to welding research and development to originate and control the use of new processes. Results of this trend have already appeared in the welding equipment market, and supportive research in the metallurgical study of welding is also likely to decrease as the trend continues.

An encouraging trend in U.S. industry, however, is a strong movement toward greater mechanization of welding to reduce manufacturing costs. Welding is a labor-intensive operation, and manual welding requires skilled workers. The mechanization of welding has long been an aim of its promoters and users, and a wave of effort has swept through the welding industry in the direction of automation. This effort started with a surge of specially built units designed to perform a prescribed welding process and procedure on a specific assembly. Riding the crest of this wave is the robot, a programmable device intended to supplant the human welder. Purpose-built welding units and welding robots are being brought into manufacturing plants in increasing numbers; and, judging from future plans of welding equipment builders and the programs of technical societies regarding robotics and automated welding, efforts to automate welding will continue to grow. Profound changes will take place in manufacturing plants that incorporate welding in production operations. One aim of this book is to explain the importance of mastering the metallurgical behavior of metals during automated welding.

Welding automation should be more specifically defined because of encumbrances that it will place on the metallurgical behavior of the metals being welded. The term *complete automation* has been used to describe a completely controlled welding function. Complete automation infers that the operation is not only performed without the manipulative aid of a human welding operator, but that if conditions vary during welding, compensating adjustment is automatically made to assure an acceptable weld. This immediate adjustment to obtain the desired weld is called *adaptive control*. It is sometimes called *feedback control* or *closed-loop control* in the literature.

Some planners of complete automation require that the weld be nondestructively tested or examined during or immediately after its formation and before the welded article moves to the next stage of production. Completely automatic welding and inspection would reduce costs by decreasing the manpower required to make the weld and ensure that it is of acceptable quality.

All segments of industry, not only welding, will be pursuing complete automation because of the need for cost reduction. A trend in this direction is well underway in forging, machining, plating, and other industrial operations and processes; and mechanization of these processes in manufacturing has been amply demonstrated. However, the goal ahead is to fit many different operations into an articulated system to form an automated factory staffed by a minimal force of supervisors and trouble-shooting technicians. A number of forward-looking companies in the USA are planning the construction of completely automated factories. Welding processes must be readied to fit into these highly coordinated manufacturing facilities if welding is to maintain its position as the favored means of joining. Automated welding processes are described in Chapter 6 of this volume, along with facets of metallurgical behavior of steels during welding that requires consideration to maintain consistent, acceptable weld quality.

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Microelectronics is a technology that will assist in the complete automation of welding. Computers and microprocessors store data, analyze input, and issue output signals to controllers. A vital component of a complete system for automatic regulation is the sensory linkage between the analyzer/control unit and metallurgical reactions or changes occurring in the weld area during welding. Each process has different features related to weld quality that can be measured continuously to generate input signals for analysis. Signals can be very rapidly analyzed in a microprocessor, and any adjustment in operating parameters required to maintain weld quality can be made almost immediately through output commands from the microprocessor. This type of monitoring and response is termed *in-process* or *real time control.* Some welding processes generate easily detected electrical phenomena that can be continuously monitored for particular deviations which in turn can guide corrective measures. Other processes require more obtrusive features to be measured or appraised continuously as the weld is being made in order to feed corrective input to the microprocessor. A variety of sensory devices have been developed to serve as linkages between the microprocessor and the welding operation. These include:

(1) instrumentation for instantaneous measurement of electric current and dynamic electrical resistance,
(2) gauges for precisely measuring localized dimensional changes that occur during thermal expansion and contraction,
(3) coaxial optical systems for weld image viewing and machine vision analysis, and
(4) fiber-optic transmitters for thermographic monitoring of infrared radiation emitted from a point on a weld surface.

An important aspect of a sensory device is its ability to assess changes that stem from metallurgical peculiarities of the materials being welded. Painstaking development work is required for each sensory device to achieve a reliable, complete automation system that will meet the demands of industry.

WHAT IS WELDING METALLURGY?

What is welding metallurgy? And how does a knowledge of it contribute to the future of welding, especially to the effort of achieving complete automation of its processes? Discussion of these questions helps define the information included in this book, and how the information should be weighed and interpreted before being put to use.

Welding, in the broadest sense, is described as the art and science of joining metals by using the intrinsic adhesive and cohesive forces of attraction that exist within metals. This description encompasses metallic bonds as observed in various welded, brazed, and soldered joints; and it rules out joints accomplished with purely mechanical design, mechanical fasteners, or with nonmetallic adhesives. This description acknowledges that a certain amount of artistic skill is necessary in making a weld — skill that is acquired by practice rather than by scientific rationalization. The need for artistic skill in welding decreases, of course, as scientific and engineering knowledge increases. Therefore, to retain its position in the high-technology future as the principal method of joining metal components, welding processes must continue to improve and depend less on art by making maximum use of science and engineering.

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Metallurgy, simply defined, is the science and technology of metals, and consists of two main parts:

(1) *process metallurgy*, which involves the reduction of ores, refining of metals, alloying, casting, and the working and shaping of metal to semi-finished and finished products; and

(2) *physical metallurgy*, which includes heat treatment, mechanical testing, metallography, and numerous other subjects dealing with the application, design, testing and inspection of semi-finished and finished products.

At first thought, welding might seem to be merely a part of process metallurgy; that is, an operation for shaping metal into a finished product. However, welding is more than a constituent of process metallurgy or of physical metallurgy. Welding encompasses the entire scope of metallurgy, but requires a specialized viewpoint to comprehend the peculiarities of its processes. It is necessary, therefore, to concentrate on the study of *welding metallurgy*.

Both process metallurgy and physical metallurgy are involved in welding. For example, as nickel oxide is added to the thermit welding mixture of iron oxide and aluminum, the nickel oxide will be reduced to nickel during the thermite reaction, and it will be alloyed with the molten metal discharged from the crucible. Here, knowledge of process metallurgy is used, because the operation is similar to ore reduction in a furnace. Process metallurgy is involved in the formulation of flux coverings and core filling in arc welding electrodes. Many of the materials used for making slags in connection with the melting of metals in a furnace are also used in electrode fluxes for welding; limestone, fluorspar and rutile as used in making steel are three good examples. After minerals and other suitable materials are compounded to make a flux with the proper acidity (or basicity) and viscosity at welding temperature, process metallurgy techniques can be put to further use; the alloy composition of the weld metal can be altered by adding materials to the flux covering on the electrode, or the flux in its core.

The same alloying materials used in metal production are also used in powdered form in welding fluxes. For example, a steel electrode core wire devoid of alloying elements can be covered with a flux containing an addition of ferrochromium to form a chromium-containing alloy steel weld metal. The transfer of chromium from the flux to the weld metal during deposition of the electrode is highly efficient. Most flux-bearing arc welding electrodes, both flux covered and flux cored, contain additions of metals to function as deoxidizers, or to alloy with the weld metal. However, certain metallurgical precautions must be taken to ensure proper transfer of alloying elements, and to guard against pickup of unwanted minor elements that adversely affect weld properties.

Welding can be compared to a series of metallurgical operations involved in metal production, like steel making, but welding is performed on a very small scale with pertinent steps carried out in rapid succession. During most welding processes, a volume of molten metal (melt or bath) is formed (cast) within the confines of the solid base metal (mold). Weld metal initiates its solidification in a unique manner, unlike the molten metal cast in a mold (See Chapter 9). Yet, weld metal also has a susceptibility

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to blowholes and internal porosity caused by the evolution of gases, the same as experienced with ingots and castings (Figure 1.1).

The base metal of a weld can be preheated to retard cooling rate and solidification just as molds are often preheated to delay cooling of the contents. After solidification, the weld metal or nugget (ingot) can be placed in service in the as-welded (as-cast) condition, or it can be peened or worked (wrought) to obtain a specified shape or particular mechanical properties.

One striking difference between welding and other metal-producing operations is the contrast in the mass of metal being heated and worked, and the effect of mass on physical and metallurgical changes. Metal production operations usually deal with large masses that are subjected to relatively slow rates of heating and cooling. Welding, on the other hand, usually involves comparatively small masses that are heated very rapidly by intense heat sources and that cool rapidly because of intimate contact with a larger surrounding mass of colder base metal.

The structure and properties of metals are most readily observed and compared when they have been heated and cooled under equilibrium conditions, entailing extremely slow rates. Equilibrium conditions are seldom seen in conventional metalworking operations, and welding usually represents a further departure from equilibrium conditions. Consequently, it can be expected that weld zones are prone to display unusual structures and properties.

The hot and cold peening of weld metal is similar to hot forging or cold finishing mill operations, and the principles of process metallurgy apply. There are pro and con statements in the literature concerning the advisability of using peening on a weld. It is true that peening has resulted in unexpected difficulties in a number of instances. In many of these cases, however, peening was seized as an easily-applied remedy for a particular condition, perhaps to eliminate cracking, and little or no forethought was given to the eventual consequences of the operation (Figure 1.2).

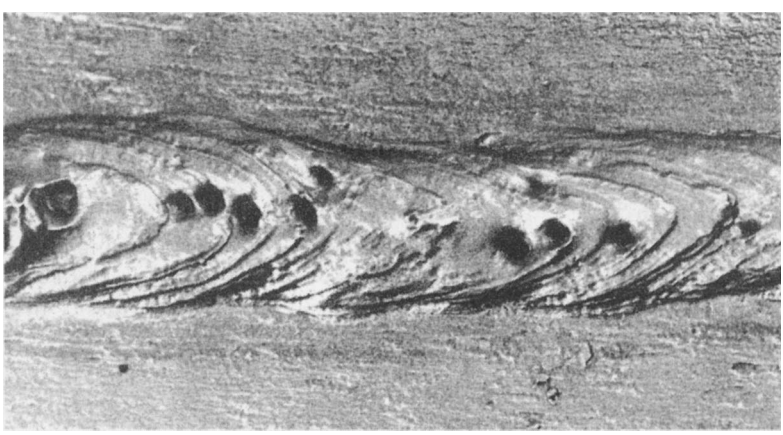


Figure 1.1 — Blowholes in a weld

Gases can erupt from the weld leaving blowholes not unlike the gas pockets on the surface of a casting or an ingot. Blowholes can be avoided most effectively through a knowledge of welding metallurgy.

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Figure 1.2 — Cracking in an arc welded corner joint as revealed by dye penetrant examination

A knowledge of welding metallurgy will assist in preventing the kinds of cracking that possibly can occur in or near welds. (Courtesy of The Welding Institute, England)

Peening is a useful operation if it is performed in accordance with sound metallurgical reasoning. Guided by a knowledge of process metallurgy, welds can be hot or cold peened to relieve shrinkage stresses. Cold peening the weld will increase the strength of the metal. In some instances, components made of cast or wrought steel can be welded into an assembly which then is hot formed or forged to produce a complicated shape. This shape might be difficult, if not impossible, to produce by casting or by forging alone. A knowledge of process metallurgy is essential to success in multiprocess production of this nature.

Many aspects of physical metallurgy are involved in welding. After a weld is made, postweld heat treatment may be required to alter the unusual microstructure and properties produced by rapid cooling. The treatment can be one designed to soften (anneal) the weld zone, or it can be a complete hardening and tempering treatment designed to obtain properties in the weld zone comparable to those of the base metal. Sometimes this postweld heat treatment is integral to the welding operation. For example, it is common practice to accomplish localized heat treatment of a resistance spot weld, when required, in the machine before the newly made weld is removed from between the electrode tips. Again, this postweld heat treatment can be a softening operation, or a more complex treatment. Immediately following formation of the spot weld nugget, a precise program of heating and cooling can be performed to carry the nugget and a calculated portion of the heat-affected zone through a bona fide heat-treating operation. The weld area can be allowed time to cool nearly to room temperature, whereupon a controlled surge of electrical current heats the metal locally to proper temperature for hardening. The withdrawal of heat by surrounding base metal

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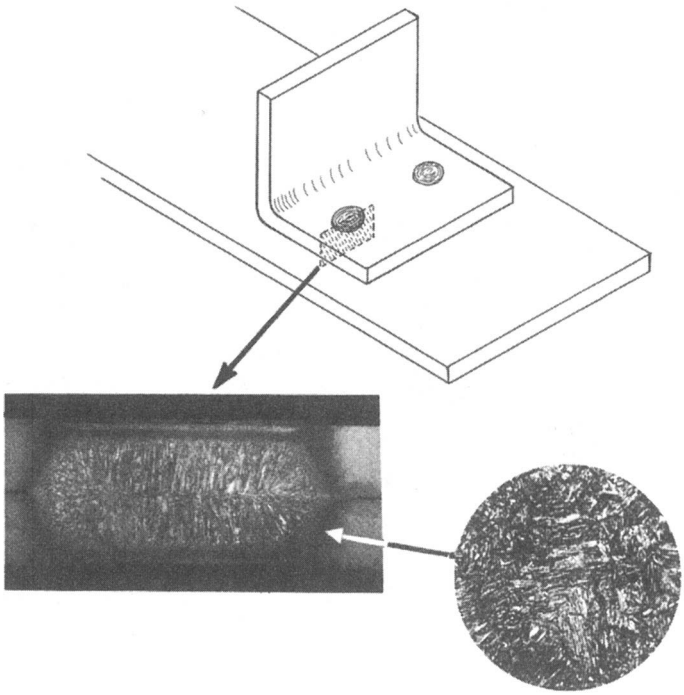


Figure 1.3 — Metallography is often used to examine microstructures of welds and their heat-affected zones in the base metal

This resistance spot weld between two alloy steel sheets has a hardened microstructure which will detract from the toughness of the weld.

and the cool copper electrodes is equivalent to a quenching operation. After another short cooling period, a final smaller surge of current is applied to temper the previously hardened metal. In some cases the entire operation, consisting of spot welding, hardening and tempering, may be carried out within a total time of two seconds (Figure 1.3).

Mechanical testing and metallography are important parts of welding metallurgy. Work is constantly underway to gather data on the strength and toughness of weld metal and welded joints so that new structures can be fabricated with confidence that the welded joints will be reliable during the service of the assembly. The metallographic microscope is the "workhorse" of welding metallurgy because it provides an inside view of the microstructural changes within the metal caused by the thermal effects of welding. By examining microscopic features, the metallographer can provide valuable data for diagnosing the fundamental causes of defects and can assist in the interpretation and classification of these defects. Progress in metallography has been truly spectacular as newer tools, such as the electron microscope and the electron probe microanalyzer, have been applied in welding studies (Figure 1.4).

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Metallurgists have drawn freely from the classic sciences, particularly from physics and inorganic chemistry, for basic knowledge. Recent technological demands involving the selection and the fabrication of steels have required broader studies. Other scientific fields, such as solid-state physics and nuclear physics, have required study because they hold explanations for some of the anomalous behavior encountered in new applications. The metallurgy of welding seems to have no limits as to the scope of science and engineering that must be probed to gather useful information. The many materials used in welding operations — and the wide variety of methods employed for heating, surface protection, application of force, etc. — extend the search for vital data to a diverse number of engineering fields, including ceramics, electronics, mineralogy, optics, thermodynamics, and ballistics.

Mechanical design is also an important concern. Welding, because of its versatility, makes it possible to assemble articles of almost any configuration with little difficulty. Yet, these assembled articles are expected to perform in service as if they were crafted from a solid piece of metal. Many structural failures have been blamed on a weld, but actually have been caused by inadequacies in design. This was proven in a number of instances by fashioning a similar article from a solid piece of metal and subjecting it to the same service conditions; the unwelded article failed in essentially the same manner as the weldment. These demonstrations have made design engineering an obligatory facet of welding metallurgy (Figure 1.5).



Figure 1.4 — Electron probe microanalyzer used on constituents in the microstructure of metals

(Courtesy of TI Research, England)

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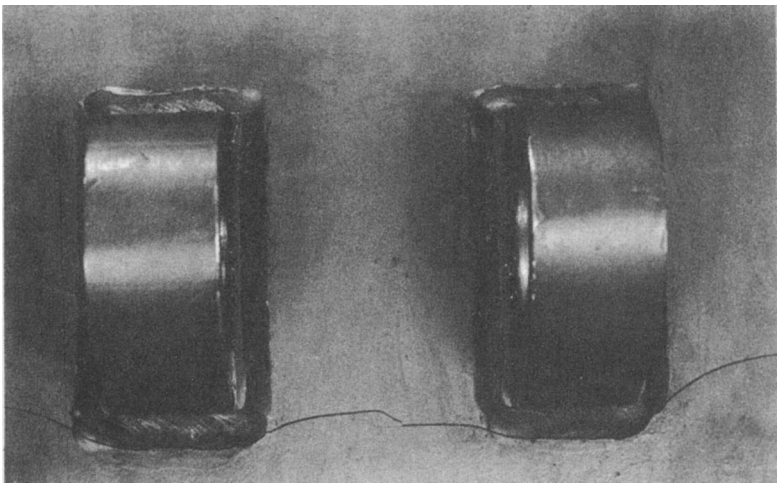


Figure 1.5 — Failure by fatigue in a weldment

Welding metallurgy relates joint design and endurance limit under dynamic loading to avoid fatigue cracking like that extending horizontally just below the fillet welds in this rugged-appearing weldment.

PUTTING WELDING METALLURGY TO USE

The aim of *Welding Metallurgy, Fourth Edition*, as of previous editions, is to present a tutorial text that will provide the reader with rationale for many of the important conditions, problems, and phenomena encountered in welding. This text is not intended as rote which is to be followed in a given welding application, or when dealing with a welding problem. Experience shows that each welding situation is unique when all influential factors and conditions are considered. Therefore, decisions regarding welding procedure must be based on circumstances in each application, and the required results "in toto." When a new application is studied in preparation for planning the welding procedure, there is usually good reason to review information from various sources. This preliminary exercise can help avoid problems like those that may have been experienced earlier, elsewhere, and can also capitalize on reported advances in welding technology. The intricacy of welding not only calls for individual study of each situation, but the technology that often must be put to use to ensure success is so vast that no single volume can hold all of the information that deserves review.

WELDING TECHNOLOGY RESOURCES

The multiple volume AWS *Welding Handbook* is a good example of a general reference, but specialized sources often must be consulted when seeking the details needed for complete planning of a welding procedure. This volume of *Welding Metallurgy* is tailored to serve as an additional specialized source; but attention can be directed to additional useful resources, some of which may not be appreciated until now because of the sheer bulk of welding literature that confronts the welding procedure planner.

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Each year approximately 5000 specialized articles, papers, documents, books, and cinematographic film and tape are added to the world's works on welding. A large part of the accumulated material continues to have value for aiding modern welding practices, but effective utilization of this vast resource requires good familiarity with its multimedia.

Books are good resources because most of them undergo peer review and intensive editing prior to publication, and this screening contributes to the reliability of the information therein.

Technical journals often contain articles and papers on welding because of widespread interest by the manufacturing sector, but only a limited number of the journals devoted mainly to welding give the subject meticulous coverage.

Technical papers on welding which focus on a particular aspect can be an excellent source of information. However, the profuseness of this portion of the literature can require a tiresome search unless a reference system is skillfully employed to pinpoint pertinent, applicable information.

Codes, standards and recommended practices covering welding and welded construction are issued by regulatory agencies, branches of the military, and by technical organizations. These documents embody much welding knowledge, but most of them do not include the technical rationale that would explain the need for a particular provision or requirement.

Patents are a unique resource for information on newest welding technology, but patents can be difficult to interpret because they may present only a concept that requires additional research and engineering before the invention can be utilized in practice.

Slides, motion picture films, and video tapes are available covering virtually the entire scope of welding technology from research endeavors to proper process application. Welding processes are shown in actual operation in films and video, and by magnification of the image, minute details are revealed that cannot be seen with the unaided eye. Playback can be in real time, or in slow motion to assist observation of details that occur in rapid sequence. High-speed cine photography has been employed to examine very short-lived phenomena, such as the modes of metal deposition from consumable electrodes during arc welding.

Fortunately, this tremendous mass of welding information has been digested electronically and organized into databases and programs to permit rapid searching and selective retrieval.[2] Computer software to a large extent consists of programs loaded with data on a specific subject or the requirements of a code or specification. The programming then assists in such steps as; calculations, conversions, interpretation of requirements, material choices, and selection of welding process and operating parameters.

An information service listed in Appendix XI, Weldasearch, deserves comment because of its focus on welding and many allied subjects, and the scope of its coverage. Weldasearch was started by The Welding Institute (TWI) in 1969 using key words

[2]Examples of electronic databases and software available at the present time are given in Appendix XI - Electronic Databases and Computer Programs.

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Figure 1.6 — Interactive dialogue between searcher at computer terminal and server at remote database can quickly assemble information on proper welding and inspection procedures

(Courtesy of The Welding Institute, England)

for indexing and cross-referencing. Professional staff reviewed each item before entry and prepared an abstract for cataloged storage. The key word system proved so effective that in 1974 the International Institute of Welding (IIW) published it as the *International Welding Thesaurus*, which presently in its third edition contains more than 1000 keywords for controlled language indexing. Today, Weldasearch contains more than 100 000 items. Both AWS and WRC advocate use of this database because of its completeness and the efficacy of its retrieval procedure. The files of Weldasearch can be searched for any defined topic by all means of communication, including on-line searching, which now is accessed via Orbit Search Service (Figure 1.6).

Databases, information services, and computer programs covering welding technology were introduced a relatively short time ago, but these proprietary resources are growing at an impressive rate. They allow rapid searching of extensive areas of technology, retrieval of pertinent information on a selected subject, and rapid transmission of findings to any point in the world via computer screen or hard-copy FAX. Every aspect of joining metals by welding, brazing, and soldering is covered to some extent among these multimedia; and they are usually quite current. However, it should be recognized that these resources do not generate new information; that is, they are not the "point of origin." Instead, they have recorded facts and data first presented elsewhere, and have staged this material in electronic format for convenient, rapid, selective retrieval.

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The Structure of Metals

Examination of metal structure in the vicinity of a weld is an important part of welding research and has helped gain a general understanding of welded and brazed joints. As metals and alloys are subjected to manufacturing steps, fabricating operations, and heat treatment, changes in structure which influence their properties and behavior are methodically documented. This information can be used to make predictions about strength, toughness, corrosion resistance, and other properties of welds, and often provides explanation for troublesome problems such as loss of strength, embrittlement, and cracking. Study of metal structure also assists in the development of improved construction alloys.

The thermal cycles involved in most welding procedures are quite unusual when compared with conventional hot working operations and heat treatments, so it is common practice to determine the structural changes produced by actual welding. The term *microstructure* is used to describe the structure of metals.

Various tools and techniques are used to study microstructure. A simple visual examination of etched metal surfaces and fractures will reveal some configurations in etched patterns that are related to structure, but magnification of minute details will yield considerably more information. Four widely used tools for examination of structures in metals are listed below:

(1) The low-power *magnifying glass*, when applied to etched metal surfaces, reveals gross details in microstructure. Also, telltale facets can be seen in the morphology of fractures.

(2) The *metallograph*, an optical microscope, is usually fitted with an inverted stage for convenience in scanning the flat face of prepared specimens. Metallographic examination usually requires magnification in the range of about 50 to 1500X. Because of the wave length of visible light, there is an upper limit of about 2000X for magnification with an optical microscope.

(3) The *x-ray diffraction camera* permits more positive identification of the basic crystallographic structures in metals by analyzing the diffraction of regulated x-rays as they are passed through a specimen and emerge to register as spots on a precisely positioned photographic film.

(4) The *electron microscope* is capable of magnifying at least 200 000X with remarkably good depth of focus and resolution. Images of metal microstructure are obtained either by electron beams transmitted through a specimen, or by beams that are reflected and emitted.

Other microscopes and analytical devices used in special metallographic studies are reviewed in this chapter. For example, the need frequently arises to know the

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chemical composition of minute phases and particles observed in a microstructure. The *electron microprobe analyzer* can analyze a precisely selected area as small as one micron (0.000 0394 in.) in diameter on the surface of a metallographic specimen.

Pursuit of theoretical physics enabled mankind to utilize nuclear energy, and while theoretical physics, thermodynamics, and chemical phase analysis can be applied to the study of metal structure, these methods are complex and difficult to verify by experimentation. No approach to the study of metals has been so broadly rewarding as the "atomistic" approach; that is to study metals and their structure from the perspective of the atoms of which the material is comprised. An atomistic framework is the basic perspective used in this text.

ATOMS

The nature of atoms and their role in the structure of matter, including metals, had been clearly hypothesized in early research, but only recently has a microscope become available that is capable of viewing an atom directly. This was first accomplished in 1960, using a *field ion microscope* which projected relatively crude registrations of atoms in the tip of a needle-like metal specimen. An atom is the smallest unit of matter that behaves like an element. Visualization of atoms can be started by picturing them as tiny solid spheres. Atoms exert attractive forces in all directions, and this achieves cohesion, or bonding, in a quantity of the element which often results in a solid mass of matter.

Atoms cannot be seen directly with commonly available magnifying instruments because the atom's diameter is only in the order of one angstrom (See Technical Brief 2). Atoms can be indirectly located by various examinations, using x-rays, electrons, and ions, which produce registrations on screens or photographic film that are related to the positions of the atoms in a specimen of the material. The x-ray diffraction camera produces films for interpretation called Laue photographs. The ionic technique used in the field emission microscope produces a registry of atoms on a screen at great

TECHNICAL BRIEF 2:
What Is An Angstrom?

An angstrom (Å) is one ten-billionth of a meter, often expressed as 1×10^{-8} cm. Because the angstrom is not a coherent SI unit, the nanometer (nm), one billionth of a meter, has been recommended in the metric system for indicating dimensions in this order of magnitude. However, the angstrom is widely used as a unit of measure in crystallography and related sciences because of its "close fit" to atom size. The angstrom unit, which is equivalent to 0.1 nm, will be used throughout this text.

One angstrom (Å), the approximate diameter of an atom, is equal to 0.000 000 003 94 in., or about four-billionths of an inch. The human eye cannot resolve an object smaller than about one hundred microns (0.00394 in., or about four-thousandths of an inch); it would be necessary to magnify an atom approximately one million times to see it as a mere speck. A magnification of about ten million times would allow the human eye to compare sizes of different kinds of atoms, and even greater magnification would be needed to perceive any details of atom construction.

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magnification and shows the positions of the atoms. Although these techniques have produced only "shadows" of the atoms in the specimen, or reflections from them, much can be surmised about atoms in the structure of metals. The atomistic view of structure, despite being somewhat superficial, has proven to be a functional concept, useful to all who are intent on efficient processing, fabrication, and utilization of metals.

In a simplistic view, atoms are pictured as tiny solid spheres in close proximity making up a mass of matter. Each individual atom is believed to consist of a central nucleus around which one or more electrons revolve at distances up to approximately one angstrom in diameter. The nucleus of the atom, consisting of a cluster of protons and neutrons, is very small, measuring only about 10^{-12} cm across (0.3937×10^{-12} in.). The electrons revolving around the nucleus are believed to be distributed on orbital layers, or *shells*, that have rather firmly fixed numbers of electrons on each shell. Figure 2.1 schematically illustrates the arrangement of nucleus and electrons in an atom of the metal zinc.

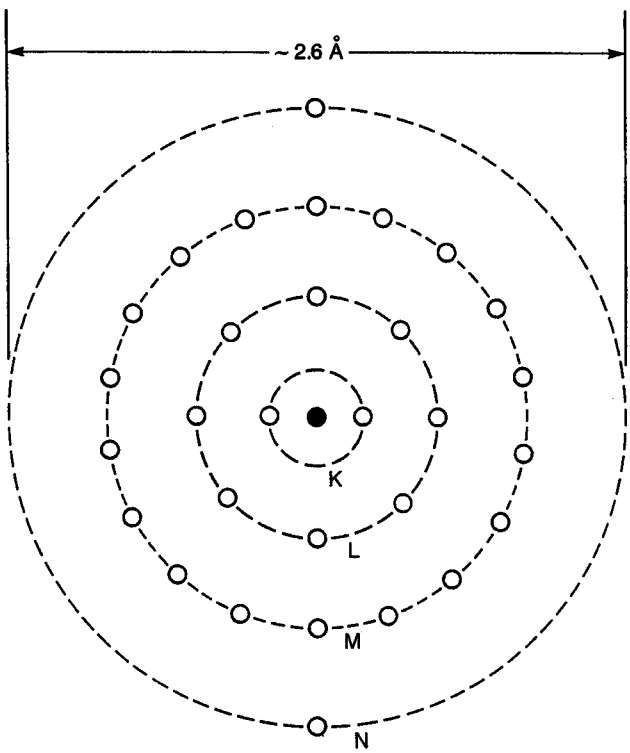


Figure 2.1 — Schematic arrangement of nucleus and electrons in an atom of the metal zinc ($_{30}Zn^{65}$)

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This concept of the atom is generally accepted, but there are factors that seem to refute certain aspects of this simple picture of the atom. As an example, previous mention that atom diameter is only about one angstrom is true of the smallest atom, that of hydrogen. The zinc atom in Figure 2.1 is indicated to be approximately 2½ times larger. This seems logical in view of the relative weight or mass of hydrogen as compared with that of zinc; however, as reasons arise to discuss various elements and their atom size some unexpected variations will be encountered.

Elementary Particles

The three electrically-structured constituents of atoms, the electron, proton, and neutron, are called *elementary particles* because they were the first to be identified, evaluated, and named. In early studies, these appeared to be the basic particles of which all atoms were constructed. These particles differ in ways that profoundly influence their role and behavior, both in the intact atom as well as a "free" particle. As shown in Table 2.1, the electron and the proton have equal, but opposite, electrical charges; the electron is negative, and the proton is positive. However, they are vastly different in mass. The electron has a mass only $\frac{1}{1837}$ that of a proton. The neutron is very slightly heavier than a proton, and displays no electrical charge. Despite their greater mass, the proton and the neutron are confined to a much smaller volume than electrons when they are grouped together to form the nucleus of an atom. In fact, the mass of an atom is contained essentially in the nucleus, where its protons and neutrons are held together by powerful forces.

No complete explanation has yet been developed for the forces that hold protons and neutrons together in the nucleus of an atom. The stability of nuclei suggests that attractive forces are the principal ones in operation. These attractive forces must be of short range because when techniques are applied to separate the elementary particles in the nucleus by a very small distance, perhaps in the order of one nucleus diameter, the binding force becomes negligible.

Atom construction should be examined beyond the three elementary particles which have been described because observations concerning radioactivity of certain elements can be helpful in understanding nondestructive methods of examination which apply various forms of radiation to weldments. When gamma radiation from elements such as radium and uranium was detected and the emission mechanism studied, researchers realized that atoms in these unstable elements were undergoing spontaneous, permanent intrinsic change. In addition to the radiation emitted, a stream of

Table 2.1 - Elementary Particles

Particle Name	Common Symbol	Electrical State		Mass
		Charge	esu*	gram
Electron	e	Negative	4.802×10^{-10}	9.107×10^{-28}
Proton	p	Positive	4.802×10^{-10}	1.672×10^{-24}
Neutron	n	None	0	1.675×10^{-24}

*Electrostatic Units

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particles, consisting of positively-charged alpha particles (actually helium atoms with two electrons removed), was being discharged. Also, atoms that disintegrated in this manner were undergoing transmutation to new chemical elements.

Continued research in atomic structure has isolated many more sub-atomic particles of an elementary nature. The *positron* was an early discovery made during analysis of cosmic rays. The positron was found to have the same small mass as an electron, but it carried a positive charge; therefore, the positron was essentially a "positive electron". A particle given the name *meson* has a mass several hundred times that of an electron, and can carry either a positive or a negative charge. Mesons exist in the nucleus of atoms, where they play a role in establishing the short-range forces that bind the elementary particles together.

The advent of high-energy particle generators in the 1930s allowed man to smash the nuclei of certain atoms and to analyze the fragments. The cyclotron and the linear accelerator produced an exciting number of new elementary particles; in fact, almost two hundred particles have been identified and named. Study of these particles is important to anyone seeking a complete understanding of the atom (e.g., the nuclear physicist), but details of the nature and possible function of the particles is not pertinent to welding metallurgy. The existence of these many elementary particles should be recognized, but it must be noted that most of them are the product of forcibly disintegrated nuclei, and whether these sub-atomic particles actually exist in the atom is unclear. These particles may be transitory forms of matter that facilitate the escape or transfer of energy from the disturbed nucleus.

It is not necessary to consider the *leptons* and *hadrons* that make up the majority of sub-atomic particles, but there is good reason to examine more closely the three elementary particles listed in Table 2.1. The proton and the neutron are indeed basic particles that form the nuclei of atoms, and electrons orbit each nucleus as illustrated in Figure 2.1; however, a number of important details must be added to this rudimentary picture of an atom.

A fundamental detail is the "spin" of particles. This spinning motion has not been observed directly, but physicists have postulated that all three elementary particles must have an axis of symmetry about which rotation takes place. Every manner of mathematical treatment applied to atomic structure (including the quantum theory) supports the concept of spinning elementary particles. This theoretical deduction provides a rational explanation for a number of properties of matter that are important to metallurgy, for example, magnetism. A preliminary study of magnetism will help illustrate the spin of particles and will emphasize the far-reaching significance of this feature.

To understand the significance of particle spin, a pertinent reminder can be offered that flowing electric current always generates a magnetic field. When the electron is examined, this corpuscle of negative electricity will be found to be spinning on an axis like a toy top. The spinning motion is analogous to current flow (i.e., electron movement or flow) and this imparts a negative magnetic moment. Next, the orbital path of the electron around the nucleus must be considered. This orbital motion is also analogous to current flow, and therefore a broader magnetic field is generated.

The spinning electron, on experiencing the magnetic moment from orbiting, will strive to align its magnetic axis parallel to the imposed field. This change in axial ori-

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entation is called *Larmor precession*. Interaction between the magnetic field from electron spin and the magnetic field from electron orbit can result in increased angular momentum. This feature is the product of moment of inertia about the axis of rotation and the spin angular velocity, just as linear momentum of a body moving along a straight line is equal to mass times velocity. Angular momentum, therefore, is the vector sum of the electron spin and orbital motion. As angular momentum increases, a stronger magnetic field is generated.

The axis of the spinning electron during Larmor precession undergoes slow gyration so that each of its poles describe a cone. Random orientation of particle axes from one atom to another finds them counterbalancing the magnetic moment of each other in substances. Consequently, no overall magnetic field is exhibited by the substance. When a magnetic field from an outside source is imposed, the axes are brought into more common orientation and the substance becomes more strongly magnetized.

The proton also spins on an axis, and its motion should be considered next. A proton carries a positive charge and its spin exerts a positive magnetic moment. For this reason the magnetic field of the proton is parallel to its spinning motion instead of being oppositely directed as in the case of the electron. Also, the proton has a larger mass and spins slower than the electron. Consequently, the magnetic moment of a proton (even of a whole nucleus) is only one-thousandth as strong as the magnetic moment generated by the electron.

Neutrons also spin, but they generate a weak negative magnetic moment. This magnetic effect is opposite to that anticipated from the direction of neutron spin, and is surprising in view of the absence of electrical charge. This finding led physicists to hypothesize that the neutron is made up of positively and negatively charged particles in equal strength to balance the static electrical charge. However, they believe the negative particles are further from the axis of rotation in the neutron and this causes some negative electrical influence to be exerted during spinning.

The fundamental concept of magnetism gained from studying the spin of elementary particles is that the magnetic properties exhibited by all substances are mainly effects of the motion of electrons within the atomic structure. The magnetic moments of nuclei and their constituent particles, on the other hand, are quite small and in general can be disregarded. The magnetic moment of atoms, therefore, appears to have three main sources;

(1) spin of electrons,
(2) orbital motion of electrons around the nuclei, and
(3) orientation change in the axes of the spinning electrons induced by an applied magnetic field.

Individual examination of the three principal elementary particles — the electron, proton, and neutron — will help gain an understanding of the atom as a whole. All of these particles play key roles in specific aspects of welding technology. Therefore, familiarization with each of the particles, per se, is pertinent.

Electrons

An electron has never been viewed directly as a tangible object. Knowledge of the electron is mostly hypothetical, but is supported by innumerable experiments in which

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the observed effects of electrons present good indirect evidence that their character is much like the reported consensus. Yet, scientists have debated at length whether an electron should be regarded as a point particle, or as a corpuscle of electromagnetic radiation. One view of electrons in terms of radiation recognizes that a stream of electrons exhibits wave length, and strong similarity exists between optical systems handling light and magnetic fields acting on electrons. Also, a cloud of electrons can exist in several states, and transition from one state to another usually results in the emission of photons, which are elementary quanta of radiant electromagnetic energy. Nevertheless, electrons have mass, momentum, and kinetic energy, and one way to understand the role of the electron in the atom is to picture an electron as a minuscule, indivisible particle with a strong negative electrical charge, as outlined in Table 2.1.

All atomic matter normally contains electrons, and the number and distribution of electrons in the atom determine to a large extent the chemical and physical properties of the element. The electrical charge carried by an electron is amazingly high, and this charge, along with energetic spin, enables the electron to exert strong effects despite its small mass. The principal properties of an electron are electrical charge, mass, spin, and wave length.

The wave length of electrons is a property that deserves further explanation. In Figure 2.1, electrons in the structure of an atom are depicted as spinning particles orbiting the nucleus on shell-like layers. This concept was proposed in 1913 by Bohr, who provided a model that appeared to fit the many working equations which were subsequently developed for calculating such features as orbit radii, orbital velocity, angular momentum, etc. Recent findings on atomic structure suggested to some scientists that the deployment of electrons in an atom is a more complex arrangement. They reasoned that electrons in the structure of the atom must have a wave length because electrons emitted as a stream, or beam, display wave length. Wave-apperceptive proponents visualize the atom as a nucleus surrounded by electron waves. Although there is some basis for this concept, description of the wave-like arrangement of electrons in the atomic structure is complex and lengthy. Fortunately, in final analysis, the model of an atom incorporating electron waves also has layers, or shells, of "charge density" surrounding the nucleus. This similarity between Bohr's concept and the wave theory permits continued use of the convenient, easily-visualized atom model with spinning electrons orbiting on shells around the nucleus as shown in Figure 2.1.

Electrons orbit the nucleus of the atom on shells that ordinarily remain stable because the inward centripetal force (from electrostatic attraction between the positively-charged nucleus and the negatively-charged electron) is counterbalanced by the outward centrifugal force, which is the angular momentum determined by orbital velocity. Bohr also provided a quantum hypothesis to explain why definite orbital shells are fixed for the electrons. The innermost shell is calculated to have a radius of 0.5 Å, and only two electrons can be accommodated on this first shell. The second shell is calculated to be four times larger; the third shell is nine times larger, and so on. Obviously, electrons must travel at different speeds on each shell in order to maintain discrete orbits. Electrons orbiting on shells closer to the nucleus must travel at higher velocities. Those electrons on the innermost shell have a velocity that is ½₁₃₇ the speed of light.

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Electrons on the next shell travel only one-half as fast as those on the first shell. The velocities of electrons orbiting on the remaining shells are reduced accordingly.

Both chemical and metallurgical studies give attention to specific electron orbital shells. As shown in Figure 2.1, the shells are commonly identified by alphabetical designations, starting with the letter "K" for the innermost shell immediately surrounding the nucleus, and continuing with the letters L, M, N, O, P and Q to identify a total of seven shells (as found in the heavier atoms). Some scientists prefer to use numerical designations for the seven principal shells, numbering the innermost shell with "1", and applying numbers 2 to 7 consecutively to shells of increasing diameter.

Each orbital shell of an atom is considered to bear no more than a specific number of electrons, with two electrons on the K-shell (No. 1), eight electrons on the L-shell (No. 2), 18 on the M-shell (No. 3), 32 on the N-shell (No. 4), 32 on the O-shell (No. 5), and more complex distributions on the P-shell (No. 6) and the Q-shell (No. 7).

The total number of electrons orbiting the nucleus increases as the mass of the atom representing a given element becomes larger. Each added electron is usually placed in orbit in the outermost shell unless this addition would exceed the limiting number for the particular shell, and when this is the case a new shell would be started. This statement regarding the addition and deployment of electrons is only partly true. It is not unusual for a new shell to be started before the completion of the predecessor shell. These variations in electron population on the shells affect the chemical and metallurgical behavior of the atom.

Application of quantum mechanics to the electron shell theory made it clear that the main shells have *subshells*. The orbits of these subshells are characterized by a principal quantum number (n), an angular momentum number (l), and a magnetic magnitude or quantum spin number (m). Full description of this area of electron theory can be found in any introductory book on atomic physics, however, a brief notation is included in this text to characterize four different states of motion by electrons in the subshells. Using quantum mechanics, a principal quantum number was obtained to distinguish the subshell orbits of each main shell. The orbital angular momentum (l) of 0, 1, 2 and 3 (in units $\hbar$) are identified by the letters s, p, d and f, respectively. A table is provided as Appendix X listing the electron configuration of each of the elements by giving the numbers of electrons normally present on each shell and subshell. This table will be useful as the role of electrons becomes evident in a number of important areas, including the chemical behavior of elements, bonding between the atoms in an aggregate, control of crystal structure, and phase prediction in alloying metals.

The concept of electrons as they are incorporated in an atom is important in welding metallurgy because electrons in orbit around the nucleus are not as tightly bound as are the protons and neutrons in the nucleus. Relatively little energy change is involved when an electron is moved from one orbit to another, or an electron is stripped free of an atom. The amount of energy possessed by an individual electron varies with the specific shell and subshell in which it is orbiting.

Electrons are bound in a given shell by energy measured in electron volts (eV). This unit is the energy change experienced by a particle having one electronic charge ($e = 1.602 \times 10^{-19}$ coulomb) in passing through a potential difference of one volt. One electron volt (eV) is equal to 1.6×10^{-19} joules. As applied to electron emittance (ion

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ization), the energy required to strip free an outermost electron ranges from about 5 to 25 eV.

There can be a shifting or "jumping" of electrons from one shell to an adjacent shell under various circumstances, but this change in orbital location must be complete and the electrons cannot stop in between shells. Consequently, these jumps must be accomplished by the introduction of a definite minimum amount of energy if the movement is outward to a larger diameter shell, or entails complete removal of the electron. If the orbital change is an inward movement to a location on a smaller diameter shell, there will be a release of energy as photons of electromagnetic radiation. Further details concerning the electron in the structure of an atom, particularly the movement of electrons in real materials, and especially in metals, are provided later in this chapter as aggregates of atoms are examined.

Free electrons can be generated rather easily in a variety of devices, and emitted in quantity in various ways, but since these particles carry a negative charge, their path, or trajectory, is easily controlled by applying magnetic fields along the beam pathway. If a cathode and an anode are arranged in space and sufficient electrical potential is applied, electrons will leave the cathode and flow to the anode. Of course, it helps to heat the cathode to aid electron emission, and to have a vacuum in the intervening cathode-anode space to avoid collision of the electrons with the atoms and molecules in air.

The *cathode ray tube* (CRT) is a classic illustration of a device which produces a controlled flow of electrons, however, the flow of electrons as free particles can be made to occur in a myriad of ways. When emitted as a free particle, the electron normally travels in a straight path. The velocity of the electron is increased as higher electrical potential (voltage) is applied between the emitting cathode and the anode. Electrons usually travel about ⅓ the velocity of light, but they can be accelerated to approach the speed of light. As higher velocities are attained, the mass of an electron increases by a small, but measurable amount.

A beam of electrons acts somewhat like x-rays because it also has wave form. In fact, in early research the wave form and wave length of electrons were established from the pattern of electron diffraction from the face of a solid crystal of nickel metal. The wave length of an electron is inversely proportional to its velocity, that is, as velocity increases the wave length decreases. Electrons with an applied voltage of 50 kV would be expected to attain a speed of about 100 000 kilometers per second (60 000 miles per second) and would exhibit a wave length of approximately 0.05 Å. Electron velocity near the speed of light (299 774 kmps, or 186 280 miles per second) would be achieved with applied potential of one million volts. Electrons with this velocity would exhibit a wave length in the order of 0.01 Å.

Some important and useful phenomena occur as electrons bombard the surface of a substance. The electron beam will not penetrate as deeply as the x-ray because the negative charge on the electrons causes a strong interaction with other particles in the atom structure, especially those particles carrying a positive charge. The electron beam is highly effective in eliminating dissolved gases, if the substance being bombarded is a metal. An electron beam impinging on a metal will produce fluorescence, phosphorescence, and radiation. Secondary electrons will be emitted from the surface area

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beneath the beam as well. If the electron beam has sufficient energy, the substance being bombarded will be melted and will possibly be vaporized (as occurs in electron beam welding and cutting processes). Electron beams also exhibit behavior for which scientists have yet to find explanation. This is especially true in the field of microelectronics, where electron flow through special conductors and the blockage of flow at insulating barriers are all-important in operating circuitry. For example, electrons have the ability to tunnel through the film-like layers of various metals that have been built up, sandwich style, and then treated in various ways by "doping". This *resonant tunneling effect* allows passage of electrons through the metal "sandwich" at several distinct energy levels. Utilization of this electron behavior could allow a single transistor to serve several functions in an integrated circuit.

Positrons

The positron, the electron with a positive charge and one of the many elementary particles, was first detected among the cosmic rays that come from outer space and concentrate in the earth's stratosphere. Cosmic rays, on entering the earth's atmosphere, cause unusual fragmentation of the nitrogen, oxygen, and carbon atoms encountered by the rays. The atomic debris produced by this cosmic radiation consists mostly of positively charged particles (protons), and a smaller amount of heavier nuclei. Positrons were not easily detected among the debris because of their very short life. Electrons (negatively charged) are in abundance almost everywhere and the strong attraction between dissimilar charges brings the electrons and positrons forcibly together, whereupon annihilation occurs with an outburst of gamma radiation. These positively charged particles, positrons, can be produced in high-energy accelerators, and they are also emitted in small amounts by certain elements in radioactive form (e.g., Na, Co, Cu, Ge). These sources can be used to carry out a recently developed high-resolution NDE method that holds great promise for examination of metals. The *positron annihilation* (PA) technique determines certain lifetime measurements of the photons that comprise the gamma rays emitted during the annihilation process. Analyses of the lifetime data enables determinations to be made of minute material changes, and the detection of defects that are considerably smaller than can be resolved by most other NDE methods.

Atomic Nuclei

A review of an intact nucleus of an atom will help illustrate the individual properties of protons and neutrons. The term *nucleon* is often used to describe protons and neutrons when they are combined in the nucleus of an atom. Nucleons are pictured as being ball-like, with a diameter of approximately 2.5×10^{-13} cm. Nucleons are held to the confines of a spherical field by extremely high short-range attractive forces between the elementary particles. Despite their close packing, nucleons are believed to be moving around inside the nucleus and spinning, because all elementary particles maintain this motion whether they are contained in the atomic structure or are in free flight.

The size of the spherical configuration which results when the nucleons form a bona fide nucleus provides a surprise, because the diameter or volume is not a simple arithmetical function of the number of nucleons present. Nuclei are much smaller in

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size than would be expected if related to the total number of component nucleons. For example, a nucleus containing a couple of hundred nucleons (as would be present in a rather heavy atom) might have a diameter only six times that of a single proton. Yet, there is a relationship between the number of nucleons present and the diameter of the nucleus, and all atomic nuclei appear to have approximately the same density. This has been estimated at the tremendously high value of 100 000 tons per cubic millimeter (about 1.75 million tons per cubic inch). This value, in turn, suggests that the nucleus of an atom occupies only about two parts in 10^{12} of the volume of an atom.

In view of the constancy of density in the nuclei of the elements, it would seem reasonable that the spherical nuclei would increase in volume proportionately with the number of particles contained, but this is not the case either for the atomic nuclei or for the overall size of atoms. There are many unanswered questions about the "size" of atomic particles. Unexpected variations are found in the physical dimensions of atoms as well as in certain phenomena that would be expected to correlate closely with atom size. These aberrations are discussed under such topics as atom size and *neutron-capture cross-section.*

Protons

The proton is the positively-charged elementary particle that serves as the basic building block for the nucleus of an atom. When compared with the electron, the proton has an equal, but opposite electrical charge. From the standpoint of mass, the proton is 1837 times greater than the electron, yet the proton is much smaller in size. Consequently, the proton has a tremendous density commensurate with that of the nucleus of an atom.

The characteristics of protons can be studied rather easily because the particle can be generated in quantity and the motion of the protons can be controlled by virtue of their positive charge. The hydrogen atom, when stripped of its lone electron, is simply a proton. No other element has a single proton as its nucleus. There are, however, two variations of the hydrogen atom (isotopes) that include neutrons in the nucleus along with the single proton, and these will be detailed because of their great importance. When the hydrogen atom (having only a proton in its nucleus) is stripped of its orbital electron, the remaining particle carries a single positive charge. Other elements can be stripped of their electrons to form positively-charged atoms or nuclei, and then these particles can be manipulated in experiments with the aid of applied electrical or magnetic fields.

Atoms will carry one positive charge for each electron stripped away. The helium atom is a favorite for this kind of experimentation. When helium is stripped of its two orbital electrons, the nucleus that remains consists of two protons and two neutrons and it carries a double positive charge. A stream of helium nuclei is called an *alpha ray.* Alpha particles are emitted during certain phenomena in nature, such as the radioactive disintegration of radium.

Protons, as fast-moving particles, are utilized in many ways. Of course, they play a major role in electric arc operations, but this comes about quite naturally as the counter-flow to the passage of electrons. Although many applications utilizing protons actually employ atomic nuclei (deuterons, alpha particles, and ions), nevertheless,

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simple protons (hydrogen nuclei) produced in the cyclotron are frequently used as high-energy sub-microscopic bullets in atomic research. When a substance is bombarded by fast-moving protons, these particles travel only a very short distance into the target substance (perhaps about 0.005 cm, or about 0.002 in.) because of the abundance of oppositely charged particles (electrons) present. The strong attraction of dissimilar charges causes direct collisions of protons and atoms of the target substance, and results in a condition termed ionization.

Neutrons

A neutron, as shown in Table 2.1, is very slightly heavier than a proton, and is the only elementary particle that exhibits no electrical charge. Even though the neutron was recognized as a nuclear particle in early research, scientists have yet to arrive at a consensus understanding of its nature. Despite uncertainties about the neutron, a working hypothesis has developed which enables man to accomplish much with this particle. The foremost accomplishment, of course, is the advent of commercial nuclear power generation. Nuclear weapons must also be mentioned, but attention should be directed to unique uses of neutrons in analytical and metal examination procedures pertinent to welding metallurgy; such as:

(1) composition profiling,
(2) crystal structure identification,
(3) radiography,
(4) magnetic property determination, and
(5) residual stress measurement.

Study of the neutron has presented a special challenge, because although it can be emitted as a free particle, its electrical neutrality does not allow acceleration and manipulation with applied electrical or magnetic fields as allowed by the electron, proton and other particles that carry a charge. The neutron does have a very weak magnetic moment, and this is one reason why scientists have speculated that the neutron possibly is a proton combined with an electron which is an arrangement that would account for electrical neutrality. This view is supported by experiments with neutrons that found the particles to be quite unstable when removed from nuclei. Free neutrons tend to transform into a proton by releasing an electron plus a *neutrino*, and to exhibit radioactivity. Half-life of free neutrons appears to be approximately 13 minutes.

The magnetic moment of the neutron is -1.93 μ_N which is only sufficient to have these particles interact with unpaired electrons in magnetic atoms. The cause of this weak magnetic moment is suspected to arise from slightly off-center distribution of the electron with respect to the rotational axis of the spinning neutron.

Absence of an electrical charge on the neutron is very important because it enables the neutron to approach an atomic nucleus without being repelled by the positive charge of the nucleus. Consequently, a neutron, when colliding with an atom, can enter the nucleus; whereupon any number of remarkable actions may take place. The frequency of collision between a neutron in free flight and the atoms of a target material is relatively low because atomic nuclei are extremely small and this provides ample open space within the atoms for the free-moving neutrons to pass within the interatomic spaces without colliding with any particles. Neutrons are not particularly prone

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to react with the electrons present, but instead are destined for nuclear interaction. This is quite different from the attenuation of x-rays which expend their energy principally on the electron shells. The electrical neutrality of the neutron enables a beam of these particles to penetrate to a remarkable depth when it strikes a target material. The penetration can amount to as much as five centimeters (about two inches) in steel, and to almost 30 cm (12 in.) in aluminum. This penetration capability is utilized in neutron radiography where the beam is attenuated to a lesser extent than are x-rays by heavier atoms, and where unique selectivity is exhibited as the beam expends its energy on lighter atoms.

Neutrons are not ordinarily found in the free state outside the nuclei of atoms, but they can be emitted or liberated from nuclei in the following ways:

(1) bombardment of a suitable target material by charged particles in an accelerator,

(2) irradiation of a substance with gamma rays, and

(3) release of a suitable kind of atom during nuclear fission.

The velocity of neutrons emitted from nuclei depends on the production technique employed, but once in flight nothing can be done to increase the speed of neutrons because they are unaffected by an applied electrical or a magnetic field. Considerable energy is needed to free a neutron from the very high short-range attractive forces that bind nucleons together. The minimum energy required for neutron emittance is probably in the vicinity of five MeV, but this minimum depends on a number of conditions, for example, the ratio that exists between the numbers of protons and neutrons present in the nucleus. When energy above this level is applied, perhaps by particles from an accelerator striking target nuclei, the neutrons emitted can have a velocity close to the speed of light. These particles are referred to as *fast neutrons*. Although the neutrons emitted in free flight travel in a straight line, they spin and exhibit wave form.

Neutrons cannot be accelerated once in free flight, but their velocity can be reduced in a controlled manner. Control is accomplished by directing a beam of fast neutrons through a "moderator", which is a permeable barrier made of relatively light elements such as a thin sheet of aluminum, or a block of paraffin or wax. Slower-moving neutrons produced by this technique are called *thermal neutrons* because their speed is approximately equal to the movement of a hydrogen molecule in a quantity of this gas at room temperature and atmospheric pressure. Thermal neutrons have a velocity of only 2200 m/sec (7218 ft/sec), and at this velocity they offer a kinetic energy of 0.0253 eV. Also, thermal neutrons exhibit a wave length of 1.8 Å, which has a significance related to the crystallographic structure of metals. Because this value is comparable to the center-to-center spacing of atoms in a solid, it offers possibilities for measurement of lattice parameters by diffraction.

The two general kinds of neutrons, as differentiated by velocity, are important to keep in mind, because while fast neutrons are easier to generate or eject from nuclei, thermal neutrons display much greater effectiveness when a stream of them is directed at a solid substance. Comparison of the behavior and effects of fast neutrons versus thermal neutrons requires examination of the mechanics of passage of particles through the atomic structure of the target substance.

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High-flux reactors are often used as a source of neutrons, and modern reactors can produce a beam of controlled velocity, wave length, and alignment. Precise beam control allows a number of important metallurgical determinations to be made; usually without damage to the specimen, and including measurement of crystallographic parameters, and levels of residual stress that exist in a section of metal at localized points or areas.

When a freely-moving neutron does collide with the nucleus of an atom, a number of different reactions can take place and the outcome depends largely on the kind of atom struck and the velocity of the neutron. The most important of these are the following:

(1) diffraction of the neutron to a new trajectory (i.e., scattering),

(2) displacement of the struck atom to an adjacent site,

(3) ejection of one or more neutrons from the nucleus,

(4) capture of the neutron by the nucleus to form a heavier atom, and

(5) fission of the nucleus to form lighter atoms.

Nuclear scientists have found these reactions, particularly neutron capture and fission, more readily accomplished by thermal neutrons than by fast neutrons. Since the neutron does not experience a repulsive force, as protons do, it appears that the slower moving thermal neutron has a greater opportunity to enter the nucleus, remain captured (at least momentarily), and then expend its kinetic energy.

Controlling the velocity of neutrons is a critical part of utilizing their chargeless kinetic energy to obtain a desired reaction. When neutron-capture results in the formation of a heavier atom, the new entity is usually radioactive. When fission occurs it usually produces two nuclei of slightly unequal mass and is accompanied by the ejection of from one to five free neutrons. A certain amount of gamma radiation is also emitted as fission occurs. Those neutrons emitted almost immediately after fission are called *prompt neutrons*, or *secondary neutrons*. More neutrons can emerge seconds later as unstable fragments decay and become stable nuclei. These are called *delayed neutrons*.

Neutron capture intrigued not only nuclear scientists, but also practical metallurgists and welding engineers because of the vital role it played in nuclear power technology. In addition to the selectivity exercised by the nuclei of atoms for thermal neutrons, the atoms of various elements displayed great differences in the number of interactions, or captures, that occurred between their nuclei and incident neutrons. Naturally, the degree of change that took place among the atoms of a given element and the amount of radioactivity generated were dependent on the number of interactions and captures that occurred between neutrons in flight and the atomic nuclei of the element.

To measure the probability of an interaction of a given kind taking place between a nucleus and an incident neutron, a special concept of geometrical cross-section for atoms and their nuclei was devised. An arbitrary unit of area measurement was adopted and termed the *barn* (b). The barn was set at 1×10^{-24} cm^2, and is defined as the area in which the number of interactions occurring in a specimen exposed to a beam of neutrons is equal to the product of the cross-section, the number of nuclei per unit volume in the specimen, and the number of neutrons in the beam that would enter the specimen if their trajectories were perpendicular to it. In Chapter 3, when the influence of irradiation on mechanical properties is reviewed, neutron-capture cross section is

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described from the standpoint of the number of barns ascribed to various elemental metals which are present in steels as residual or as alloying elements. The quantity of neutrons passing through a given area is quantified as *neutron fluence rate*.

The elementary particle, the neutron, plays a vital role in controlling energy within the atom. The short-range forces that bind the nucleons together are tremendous, and removal of a proton from the nucleus requires energy a million times greater than the energy of any chemical reaction involving similar masses. However, any incident that puts a sufficient burst of energy into a nucleus, such as the impact and entry of a high-speed particle, may upset the balance of internal nuclear forces and exceed the minimum energy needed to initiate disintegration. When a neutron strikes the nucleus, a very important aspect is whether energy is required to carry the reaction to completion or, on the contrary, whether energy is released in sufficient quantity during the reaction to cause continued reaction in nearby nuclei. The stability of a nucleus, that is, its resistance to disintegration, depends on the relative numbers of protons and neutrons present. Atoms of lesser mass have nuclei with approximately equal numbers of protons and neutrons.

Heavier elements, for example, uranium, have a greater number of neutrons relative to the protons in their nuclei. Protons in large number in a nucleus are difficult to hold, so the binding force of excess neutrons serves to insure stability. However, if the nucleus contains a large number of protons with barely enough neutrons to bind the nucleus together, the nucleus will be more likely to split (fission) when bombarded by a high speed particle. When a neutron strikes an atom that is susceptible to fission, the impacting neutron is captured and causes the nucleus to split and release one or more additional neutrons. These neutrons are quickly absorbed by other nearby atoms, which in turn split and simultaneously liberate more neutrons. Obviously, this can be the onset of an uncontrolled reaction. When fission does occur under these conditions, all offspring nuclei possess a positive charge. The electrostatic force of like-charges drives the smaller nuclei apart until they are separated at least beyond the short-range forces. This separation may occur, of course, with explosive violence.

The most effective way of accomplishing nuclear fission, to release some of the energy within the atom, is by thermal neutron bombardment. Application of this technique to selected elements (e.g., uranium-235, and plutonium-239) has allowed man to accomplish fission with closely controlled release of energy (as in nuclear power generation), or with runaway chain reaction (as in an atomic bomb). A more direct means of utilizing nuclear forces as energy is to cause fusion of free nuclear elementary particles. The amount of energy available when protons and neutrons are forced to combine into a nucleon can be estimated from the following:

(1) Neutron mass, ${}_0n^1$ ..... = **1.00898 amu***

(2) Proton mass, ${}_1H^1$ ..... = **1.00814 amu**

Sum ..... = **2.01712 amu**

(3) Mass found when the proton and the neutron are combined to form a nucleon (deuteron), ${}_1H^2$ ..... = **2.01474 amu**

Difference ..... = **0.00238 amu**

**Atomic mass unit*

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TECHNICAL BRIEF 3:
Thermonuclear Fusion

Thermonuclear fusion has been the object of intensive research for nuclear power generation because it holds great promise for utilizing nuclear forces as energy. Lighter elements enter into the fusion process more readily than the heavy elements. Hydrogen is the prime example of a low-mass element that can be made to undergo fusion to produce heavier elements and to release a tremendous amount of energy through the process. Iron appears to have the limiting array of nuclear particles for exothermic nuclear fusion behavior. Elements heavier than iron resist undergoing fusion for reasons not entirely understood. When the atoms of heavy elements are somehow compelled to fuse together, the combined mass of all new atoms produced will be slightly greater than the combined mass of the original atoms. Obviously, energy must be added to carry out the fusion process with heavy elements. Scientists believe that the heavier elements that make up part of planet Earth were formed by nuclear fusion that took place inside stars (e.g., the Sun) where ample energy was available for endothermic fusion.

The difference in mass after the proton and the neutron have combined to form a nucleon is the *annihilation energy* expended during the binding action of *thermonuclear fusion* (see Technical Brief 3). An atomic mass unit of 0.00238 is equal to 2.2 MeV.

Atoms of many elements favor particular values of *neutron velocity* (i.e., kinetic energy) at which they capture more-readily impinging neutrons and then react in some characteristic manner. An ultrasensitive analytical method called *neutron activation analysis* (NAA) makes use of this mechanism and can determine quantitatively the presence of certain elements in extremely small amounts. The NAA method is based on a resonance phenomenon and requires a high-intensity source of neutrons. NAA can be a very useful tool in welding research because of its capability to determine the location and the dynamics of elements present in trace amounts; for example, as little as 15 μg of hydrogen per gram of metal.

Atom Construction

One hundred and nine kinds of atoms (elements) have been identified and differentiated by the manner in which elementary particles are apportioned and deployed in their construction, and several additional elements are under study. The scheme of electron and nucleus portrayal in Figure 2.1 will continue to be used as other kinds of atoms are reviewed.

In all atoms, the total number of protons and neutrons in the nucleus is approximately equal to the atomic weight, that is, the mass of the atom as determined principally by its dense nucleons. The additional mass contributed by its electrons is virtually insignificant. The atomic weight reported in most textbooks for an element is often the average weight of one atom of the element as compared with an arbitrarily selected reference element or standard.

Many years ago, hydrogen, the only element that does not contain a neutron in the nucleus of its atom, was used as the standard because of its unique simplicity. Because the hydrogen atom consists of only one proton and one electron, its atomic weight was arbitrarily set at one (1.000). However, hydrogen proved to be a poor choice as a stan-

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