

MIL-HDBK-723A

30 NOVEMBER 1970

MILITARY HANDBOOK

STEEL AND IRON WROUGHT PRODUCTS



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**DEPARTMENT OF DEFENSE
WASHINGTON, D.C.**

MIL-HDBK-723A

Steel and Iron Wrought Products

1. This standardization handbook was developed for the Department of Defense in accordance with established procedure.
2. This publication was approved on 30 November 1970 for printing and inclusion in the military standardization handbook series.
3. This handbook provides basic and fundamental information on steel and iron wrought products for the guidance of engineers and designers of military materiel. The handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.
4. Every effort has been made to reflect the latest information on steel and iron wrought products. It is the intent to review this document periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and recommendations for changes or inclusions to The Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, ATTN: AMXMR-MS .

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Preface

This is one of a group of handbooks covering metallic and nonmetallic materials used in the design and construction of military equipment.

The purpose of the handbook is to provide technical information and data about steel and iron wrought products for use in achieving the objectives of the Defense Standardization Program. The handbook is intended for use, as applicable, in engineering design, development, inspection, procurement, maintenance, supply, and disposal of equipment and materials. Whenever practicable, the various types, classes, and grades of materials are identified with applicable government specifications. Corresponding technical society specifications and commercial designations are listed for reference.

The numerical values for properties listed in this handbook are in agreement with values listed in the issues of specification in effect on the issue date of the handbook. The handbook values may, in some instances, differ from those listed in current specifications because of revisions or amendments made to specifications after publication of the handbook. In connection with procurement, it should be understood that the issue of specifications listed in the contract govern requirements.

Whenever specifications are referred to in this handbook, only the basic designation is given, all revision and amendment symbols are omitted. This is done for simplification and also to avoid the necessity of correcting the handbook whenever specifications are revised or amended. Current issues of specifications should be determined by consulting the latest issue of the "Department of Defense Index of Specifications and Standards".

The basic handbook was prepared by the Materials Engineering Section of the Denver Division of Martin-Marietta Corporation and the Army Materials and Mechanics Research Center, Watertown, Mass. Comments on the handbook are invited and should be addressed to:

The Director
Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
ATTN: AMXMR-MS

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Chapter 1

Introduction

PURPOSE

MIL-HDBK-723A was developed for the Department of Defense (DOD) in accordance with standard procedure and in compliance with policies and requirements of the Defense Standardization Program (DSP).

DOD Directive 4120.3-M establishes and, together with Defense Standardization Manual 4120.3-M, "Standardization Policies, Procedures and Instructions", implements the DSP. Because of the comprehensive description of the DSP provided in these documents a detailed discussion is not presented here. However, the following definition of standardization, taken from DOD Directive 4120.3-M, in effect summarizes the DSP.

"Standardization is the adoption and use (by consensus or decision) of engineering criteria to achieve the objectives of the DSP. These criteria are applied, as appropriate, in design, development, procurement, production, inspection, supply, maintenance, and disposal of equipment and supplies".

As implied in the preceding definition, the mission of the DOD with respect to standardization is to develop, establish, and maintain a comprehensive and integrated system of technical documentation in support of design, development, engineering, procurement, inspection, maintenance, and supply management.

MIL-HDBK-723A is one of a group of standardization handbooks covering the metallic and non-metallic materials used in the construction of military equipment. These handbooks are

part of the previously referenced integrated system of technical documentation developed, established, and maintained by the DOD in support of the DSP.

The basis for the development of MIL-HDBK-723A then is the DSP. The specific purpose of MIL-HDBK-723A is to provide technical information and data on steel and iron wrought products for use in achieving the objectives of the DSP. The provisions of DOD Directive 4120.3 apply to all departments and agencies of the DOD, consequently, the data provided by the handbook are intended for application, as appropriate, in design, development, procurement, production, inspection, maintenance, supply, and disposal of military equipment and supplies.

SCOPE

1. **General.** MIL-HDBK-723A contains technical information and data pertaining to the wrought products of three ferrous materials; wrought iron, carbon steels, and low alloy steels

2. Definitions.

a. **General.** The terms carbon steel and low-alloy steel apply to a large number of ferrous alloys. Various designations, such as, trade names, specification numbers, and descriptive phrases, are commonly used to identify the various alloys; a practice that quite often leads to misunderstanding and confusion. To avoid that problem, the following definitions of the handbook subjects are provided.

b. **Wrought iron.** (American Society for Testing and Materials - ASTM definition.) A ferrous

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material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron, with which, without subsequent fusion, is incorporated a minutely and uniformly distributed amount of slag.

c. Carbon steel. (The American Iron and Steel Institute - AISI Definition.) Carbon steel is classed as such when no minimum content is specified or guaranteed for aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium; when the minimum for copper does not exceed 0.40 percent; or when the maximum content specified or guaranteed for any of the following elements does not exceed the percentages noted; manganese, 1.65; silicon, 0.60; copper, 0.60.

d. Alloy steel (low alloy steel). (The AISI Definition.) By common custom, steel is considered to be alloy steel when the maximum range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65 percent; silicon, 0.60 percent; copper, 0.60 percent; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels; aluminum, boron, chromium up to 3.99 percent, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect. Small quantities of certain elements are present in alloy steels which are not specified or required. These elements are considered as incidental and may be present to the following maximum amounts: copper, 0.35 percent; nickel, 0.25 percent, chromium, 0.20 percent, molybdenum, 0.06 percent.

3. Contents.

a. General. It is anticipated that this handbook will be used by personnel engaged in any of a variety of occupations including engineering design, development, procurement, inspection, manufacturing, supply, maintenance, and disposal of military equipment and materials. To satisfy the wide range of interest of this audience the subject of steel and iron wrought products is covered from the smelting of iron

ores through to the production and ultimate use of the wrought products.

Unlike other handbooks of the series, MIL-HDBK-723A does not contain a complete listing or tabulation of minimum physical and mechanical properties values for the various alloys included in the subject categories. Properties of this type, commonly referred to as design allowables, are available in other publications, for example, MIL-HDBK-5, industrial handbooks, and material specifications. Repetition of these data is unwarranted and beyond the scope of the handbook. As indicated in the following chapter summaries, the handbook is intended to provide practical information about the production, availability, working, and use of steel and iron wrought products.

b. Chapter 1. Chapter 1 is a short introductory chapter in which the purpose and scope of the handbook are defined. In addition, applications for the data presented in the handbook are identified, and a brief review of iron and steel wrought product development and use is presented.

c. Chapter 2. Chapter 2 deals with fundamental concepts and principles of iron and steel production and technology. First, the production of pig iron by the reduction smelting of iron ores in a blast furnace is described. Then, by explaining the use of this basic material, the methods currently used to produce wrought iron and steels are introduced. In the discourse on steel production, the difference between carbon and alloy steels is explained by describing how the properties and characteristics of steel are affected by carbon and other common alloying elements. The chapter concludes with a brief treatise of the basic principles of ferrous metallurgy which discusses: the structure of metals; the iron-carbon system; the theory of heat treatment; isothermal transformation diagrams; and hardenability.

d. Chapter 3. In Chapter 3, the wrought product forms in which wrought iron, carbon steels, and alloy steels may be obtained are identified. Pertinent information is given about each of the various forms, including, how each is

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made, and size limits. The remainder of the chapter deals with how the wrought product forms of the subject materials are worked. The main topics covered are: heat treatment, machining, forming, and joining.

e. Chapter 4. Chapter 4 is concerned with the identification and definition of selection criteria, that is, those factors upon which, in keeping with good practice, the selection of materials of construction should be based. The most common uses found for iron and steel wrought products are structural applications where the primary purpose of the material is to sustain some applied load. Therefore, the mechanical properties of these materials are usually of singular importance. For this reason, the subjects of mechanical properties, mechanical testing, elastic analysis, and brittle fracture have been treated in considerable detail in Chapter 4. Not only have the various mechanical properties been identified, but associated test methods are described, and the significance and use of the properties in selecting materials is explained.

In the final section of the chapter the general problem of material selection is considered. The importance of identifying and considering all requirements in searching for a solution to a material selection problem is developed by examining the relationship to intelligent material selection of topics such as: essential design requirements; material properties and characteristics, manufacturing and producibility factors; material availability; and total project costs.

Selecting a material for a particular application can be a simple or very difficult task depending upon the limiting factors involved. In some cases, previous experience is directly applicable to the problem and the proper material is selected almost automatically. At other times, the material may be selected on the basis of availability and cost alone. However, selecting the proper material is usually not such a simple task. Design requirements, functional requirements, environmental requirements, the size of the structure and its elements, the limitations of manufacturing facilities and equipment, producibility features of the material, total cost of

the program, and many other factors which directly influence material selection must be accorded due consideration.

To determine the most suitable material for an application it is necessary to first identify all of the pertinent requirements and factors with which the material must be compatible. Next, candidate materials are selected and evaluated with respect to these requirements, and, on the basis of comparison, the proper material can be selected. This seems to be a simple and straightforward procedure; however, in practice, due primarily to the nature of structural metals, more often than not one or more compromises must be made in choosing the material. In other words, it is usually impossible to find a material that totally meets all of the essential requirements.

f. Chapter 5. Quality assurance, which is the title and subject of the fifth and final chapter of the handbook, is obviously an ambiguous phrase which, to be meaningful, must be identified with a particular subject. Since iron and steel wrought products are raw materials, the meaning of "quality assurance" derived in Chapter 5 is based on application of the term to the purchase of raw materials. It is defined as: a general descriptive phrase that serves to identify any, and all, of the means available and used by a purchaser of raw materials to assure himself that the materials he orders and receives are of acceptable quality.

To assure that the quality of purchased material meets the required or desired level, the purchaser must assume a number of responsibilities. He must define the exact requirements to which the material must conform; communicate these requirements, completely and explicitly, to the material producer; obtain confirmation from the producer that the requirements are realistic and that the producer is willing to supply material to them; contract for purchase of the material; and inspect the material to confirm that it meets the requirements.

The use of material specifications and associated standards simplifies this system. Specifications and standards have been developed and issued by government agencies, industrial societies and organizations, private

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companies, and others. The use of these specifications serves to simplify and standardize communications between the buyer and producer of raw materials. Since this is a MIL-HDBK, the use of government specifications and standards is emphasized in Chapter 5, although industrial specifications, such as ASTM, AISI, SAE (Society of Automotive Engineers), ASM (American Society for Metals), are examined and compared to government specifications on the basis of purpose and scope.

In addition to the explanation of the purpose and use of material specifications and standards, Chapter 5 deals with the inspection of iron and steel wrought products. To confirm that a material meets specification requirements, it is necessary to perform examinations and tests. Depending upon the material and specification involved the inspection may be cursory or extensive. The tests and methods normally used to inspect ferrous wrought products are identified and their purposes explained together with the significance of the results obtained.

Chapter 5 also contains a cross index tabulation of government and industrial specifications and standards applicable to the handbook subjects.

APPLICATIONS

4. Objectives. This handbook is intended to be used in achieving the objectives of the Defense Standardization Program, established in DOD Directive 4120.3. Essentially, it serves as a means of disseminating technical data and information about ferrous wrought products to cognizant and interested personnel of the Department of Defense and associated government and industrial organizations. The use of the handbook in fields of interest such as; design and development engineering, procurement, inspection, manufacturing, maintenance, and supply of military equipment and materials certainly does not require explanation or elaboration. Rather, it is the limitations of the handbook which should be identified.

5. Limitations. First, this handbook does not contain design allowables, that is, a listing

of mechanical and physical properties values for the various alloys covered by the handbook. Design allowables for these alloys are published in various documents, such as; MIL-HDBK-5; appropriate Military, Federal, American Society for Metals (ASM), ASTM, Society of Automotive Engineers (SAE), and AISI material specifications; Metals Handbook (published by ASM); the Aerospace Structural Metals Handbook; to name but a few. These and other appropriate references should be consulted for design allowable properties values. Also, consultation with Materials Engineering organizations to confirm design values, regardless of the source, is recommended.

Second, this handbook, although it contains considerable data relative to material specifications and standards, is neither, and should not be referenced in a purchase order or contract. Materials specifications have been developed specifically to communicate material requirements from the buyer to the material producer. Standards contain supplementary data and are used to augment the scope of specifications. These documents are designed for use in the purchase of materials and should be specified in the contract or purchase order. The handbook only explains the use of specifications and standards and has no function in the procurement of materials.

BACKGROUND

Even before the time of recorded history man knew how to reduce iron-rich ores to make a usable form of iron. From this modest beginning, the current technology of iron and steel production evolved. Numerous ferrous alloys and products are marketed today; allowing the consumer to choose the alloy with the combination of properties and characteristics that best suit his needs. However, even the wide variety of steels currently available does not satisfy all of the demands of industry. The demand for new alloys to satisfy more stringent environmental and functional requirements stimulates research and development efforts, with the result that the technology continues to expand.

The use of ferrous materials in military equipment undoubtedly dates back to the initial

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discovery of crude wrought iron. In more recent eras, carbon and alloy steels have been, and are being, used extensively in military equipment and structures. Aside from the fact that these materials are ideally suited to the application, they are also inexpensive, relatively easy to fabricate, and readily available in large or small quantities. To illustrate the versatility of these materials and their importance to defense and military efforts it is necessary only to recount a few familiar applications. For example, various carbon and alloy steels are used in tanks, jeeps,

trucks, ships, and earth moving equipment. Some of the higher strength alloy steels have been used in airborne structures of both aircraft and missiles. These examples are cited to demonstrate the versatility of the ferrous wrought products, which derives from the wide range of properties and characteristics developed, collectively, by the various alloys. Therefore, even in the space age, carbon and alloy steels continue to play a vital role in military and defense efforts.

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Chapter 2

Iron and Steel

PIG IRON PRODUCTION

Iron and steel production begins with the mining of iron-rich mineral deposits known as iron ores. Iron is present in the ores in the form of chemical compounds, not as free iron, because the element iron is so active chemically that it does not exist in nature in the free state. The important iron compounds, as related to iron and steel production, are the oxides of iron. In the United States the important ores are, hematite, magnetite, and limonite, which contain ferric oxide (Fe_2O_3), ferrosferric oxide (Fe_3O_4), and hydrated ferric oxide ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$), respectively,

Iron is extracted from iron ore in a blast furnace. A blast furnace, shown in vertical cross-section in Figure 1, is essentially a tall steel shell erected on a concrete base. The inner surfaces of the furnace, lined with refractory materials, form three distinct sections: the cylindrical hearth at the bottom; the upward and outward sloping bosh located directly above the hearth; and the stack.

The blast furnace process of extracting iron from ore is a reduction smelting process. Free iron is obtained by developing conditions in the furnace whereby the iron oxides in the ore are converted, through a series of oxidation-reduction reactions, to free iron and carbon compounds. In operation, ore and other solids are fed into the furnace through the top and the iron and waste materials are drawn off at the bottom of the furnace. Ordinarily, once a blast furnace is started up it is operated continuously until it must be shut down for repair or for some other reason.

The solids are fed into a blast furnace through a two-hopper, two-bell system, incorporated in the conical cover on the stack. The solids, consisting chiefly of iron ore, coke, and limestone, are conveyed to the top of the furnace in open-end cars called skips. The solids are discharged into the small hopper and collect on the small bell forming the bottom of the hopper. The small bell is lowered and the solids drop onto the bell shaped bottom of the large hopper. When the proper charge has collected on the large bell it is lowered and the charge is deposited on top of the material in the stack. The two bells operate independently, and at least one is closed at all times to prevent the escape of gases and flames through the top of the furnace.

Pre-heated air is blown into the furnace through nozzles, called tuyeres, located at the top of the hearth. The tuyeres, usually about 20 in number, are equally spaced around the circumference of the hearth. In the vicinity of the tuyeres, the oxygen in the air reacts with the carbon in the coke to form carbon dioxide (CO_2), which, at the prevailing elevated temperature, reacts with the excess carbon present to form carbon monoxide (CO). As the carbon monoxide travels upward through the charge of solid materials it contacts and reacts with the iron oxides in the ore. The oxides are converted, through a series of oxidation-reduction reactions, to free iron, carbon dioxide and carbon monoxide. Reaction of the oxides with carbon monoxide accounts for a majority of the iron reduced in a blast furnace, although approximately 20 percent is produced by direct reduction of the oxides reacting with carbon.

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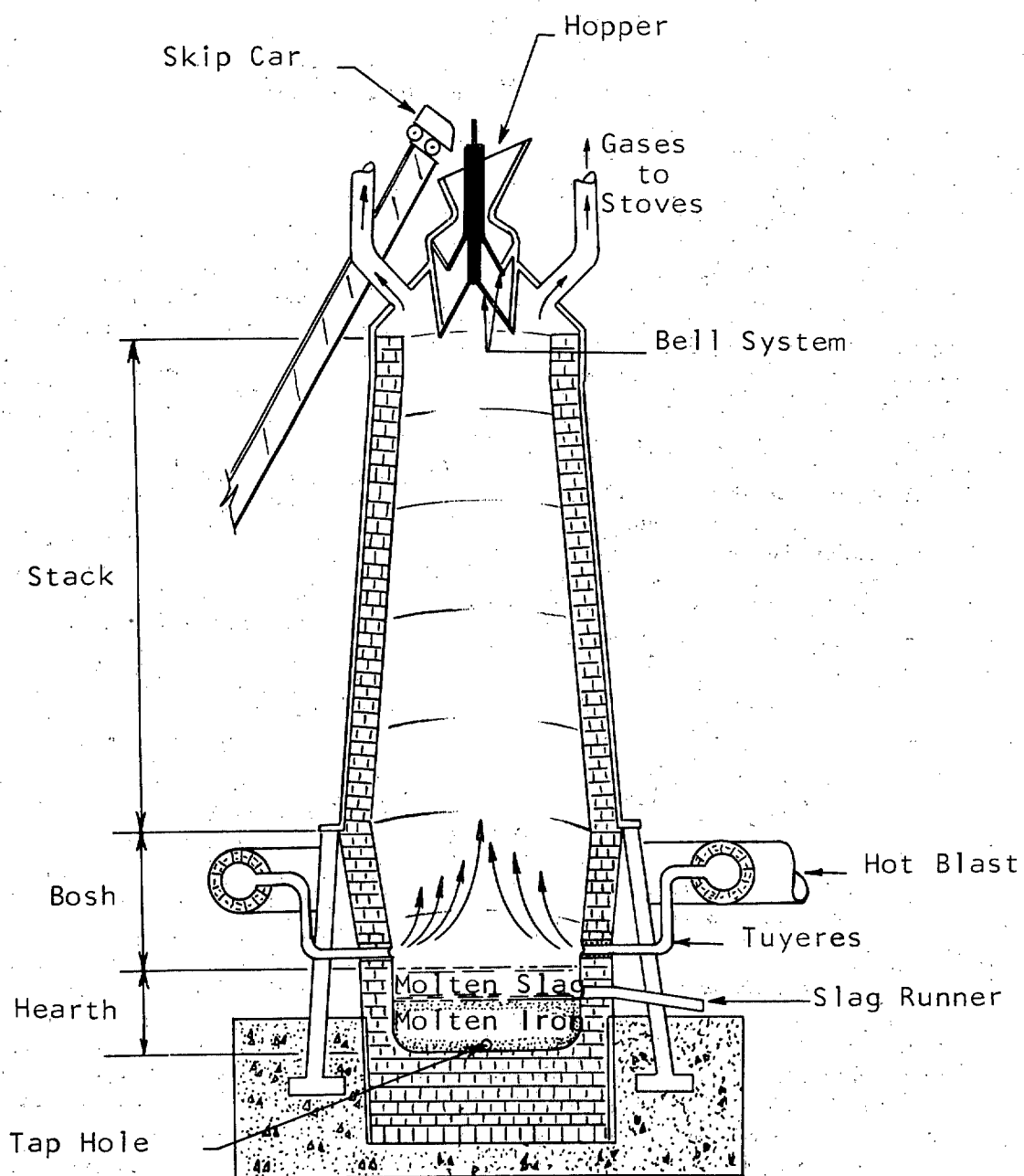


FIGURE 1. Vertical Section Through a Blast Furnace

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The reducing reactions begin in the charge near the top of the furnace where the prevailing temperature is 300 to 400°F. As the charge descends in the stack, the concentration of CO increases, and the temperature becomes progressively higher; in the vicinity of the tuyeres the temperature exceeds 3000°F. The higher temperatures and increased quantity of CO combine to accelerate the reactions as the charge descends into the furnace.

The limestone in the charge also reacts to the increasing temperature as the charge descends. Limestone is essentially calcium carbonate (CaCO_3), which decomposes at temperatures above 1500°F to form lime (CaO), and carbon dioxide (CO_2). The lime reacts with the gangue (waste materials in the ore), and with the ash that is produced by combustion of the coke near the tuyeres. The product of these reactions is a nonmetallic material known as slag.

In the stack the charge is a mixture of the various solid materials and hot gases. As the solid charge descends and passes through the bosh, it is converted first into a pasty mass and finally, in the lower portion of the bosh, into molten iron and molten slag. The molten materials collect in the hearth and, since they are immiscible, the less dense slag floats on the iron. The molten slag and molten iron are drawn off periodically through ports provided in the hearth. Because the two materials collect at different levels they are drawn off through separate ports. The slag, when it is drawn off, is either discarded or processed for sale as ballast, aggregate, or insulation material.

The third product of the blast furnace process, hot gases, are exhausted through offtakes in the conical cover on the stack. After a number of cleaning operations they are passed into a stove and burned. The heat produced by their combustion is used to pre-heat the air that is forced into the furnace through the tuyeres.

When the molten iron is drawn off, it is passed through troughs and collected in refractory-lined ladles. As it passes through the troughs any slag flowing with it is skimmed off and disposed of.

The molten iron in the ladles is used either as a molten charge in steel making furnaces or it is taken to a pig casting machine and cast into small blocks, called pigs, weighing approximately 100 pounds each. It is from the latter form that the material derives the name pig iron.

The pig iron produced in a blast furnace is not pure iron. During the smelting process the iron dissolves impurities such as sulphur, phosphorus, manganese, silicon, and other elements that are contained in the coke, ore and other materials in the furnace charge. Pig iron is produced in different grades, for example: open hearth basic, foundry, malleable, bessemer, which vary in chemical composition to meet use requirements.

WROUGHT IRON PRODUCTION

The methods now used to produce wrought iron differ considerably from the primitive methods employed thousands of years ago. The ancients undoubtedly discovered iron by accidentally reducing it from a surface deposit of iron rich ore. From that time on wrought iron has been produced directly from iron ore. The practice probably persists in less advanced areas of the world even today, although the production of wrought iron directly from ore disappeared from commercial practice in the United States around 1900. Wrought iron is now produced by indirect processes, that is, by remelting and refining pig iron.

In 1875, Henry Cort introduced a process for making wrought iron in which pig iron and scrap iron could be used as well as ore. An improved version of this process known as the "Puddling Process", was used successfully for many years in the United States, retaining commercial significance until the Aston process was introduced, about 1930.

The "Puddling Process" was carried out in a reverberatory furnace. Pig iron was melted in the hearth of the furnace, the bottom of which was formed of iron oxide, while the sides were lined with hematite ore. Iron oxide was added to the molten metal and the mixture was stirred manually to accelerate the oxidation reactions by which carbon and other impurities in the iron were eliminated. During this refining process an

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iron-silicate slag was formed. Since pure metals have higher melting points than alloyed or impure metals, as the contaminants were eliminated from the pig iron, the melting point of the iron gradually, but continuously, increased. Refining continued until the temperature of the furnace (about 2600°F) was not sufficient to keep the metal in the molten condition. The slag, with a lower melting temperature than the refined iron, remained molten. As manual stirring was continued a pasty mass of plastic refined iron, impregnated with molten slag, was produced. The material was then divided into ball shaped portions, weighing 200 to 500 lbs. each, which were taken from the furnace while still at welding temperature and subjected to a squeezing or pressing operation to eliminate excess slag. The resultant blooms were immediately rolled flat to form bars which were then cut into short lengths. These were then assembled into a pile, reheated to welding temperature, and rolled to eliminate more slag and simultaneously weld the individual bars together to form a single bar.

The skill of the operator directly affected the quality of individual heats of wrought iron produced by the hand-puddling process. Consequently, there was considerable variance in the composition and quality of the material produced by this process. Also the manual nature of the operation limited the amount of material that could be produced in one heat. These process limitations prompted the development of various machines which were intended to improve the quality and quantity of the wrought iron produced. Although these efforts met with varying degrees of success, none of the devices or processes developed were completely satisfactory. Generally, the various machines were designed to eliminate the manual stirring operations. The melting and refining of the pig iron and subsequent operations were still carried out in one furnace. While some of the machines did produce larger heats than were possible by hand puddling, the production of material of consistent quality continued to be a problem.

The Aston process, which was first used on a commercial production basis in 1930, proved to be a practical solution to the problem. Wrought

iron can be produced in large quantity by this process and the quality of the material can be consistently maintained at a high level. This process differs considerably from either the hand puddling or mechanical puddling processes that preceded it. The various operations, such as, melting of the pig iron, refinement of the pig iron, preparation of the slag, and mixing of the constituents, are each carried out separately in equipment provided for that specific purpose.

In brief, the pig iron is melted in a cupola, tapped into a ladle where it is desulfurized, and then poured into a Bessemer converter where it is further refined. The refined iron is then tapped into a ladle for transportation to the processing area where it is poured at a controlled rate into the ladle of a processing machine which contains a specially prepared iron-silicate slag. As the iron is poured, the ladle containing the slag is moved back and forth to assure proper mixing of the iron and slag. When the iron is poured into the ladle the temperature of the slag is several hundred degrees below the freezing point of the molten refined iron. Consequently, the iron solidifies rapidly and the dissolved gases in the iron are entrapped. The resulting small explosions, by which the entrapped gases are liberated, shatter the metal into small fragments which collect at the bottom of the ladle. At the prevailing temperature the small pieces of iron weld together to form a ball of refined iron impregnated with molten slag. When the reactions stop, the excess slag is poured off and the spongy ball, which weighs 6000 to 8000 pounds, is dumped on the platform of a large press. The excess slag is squeezed out of the ball which is reduced to a solid bloom. The bloom is then reduced to any of a number of wrought forms through a series of rolling operations.

In finished form, wrought iron produced by the Aston Process contains about 2 percent slag, by weight. The slag is distributed throughout the iron matrix in the form of minute fibers which may number more than 250,000 per square inch of cross sectional area. The multitude of slag inclusions are responsible for the excellent resistance of wrought iron to progressive corrosion, since they serve as natural barriers that confine the corrosion to the surface of the material.

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STEEL PRODUCTION

6. General. Before delving into the intricacies of steel production the two classes or types of steels covered by this handbook, carbon steels and low alloy steels, will be briefly examined. Definitions of these steels were given in Chapter I, however, for convenience they are repeated here.

a. Carbon steel. (The AISI Definition). Steel is classed as carbon steel when no minimum content is specified or guaranteed for aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium; when the minimum for copper does not exceed 0.40 percent; or when the maximum content specified or guaranteed for any of the following elements does not exceed the percentages noted: manganese, 1.65; silicon, 0.60; copper, 0.60.

b. Alloy steel. (The AISI Definition). By common custom, steel is considered to be alloy steel when the maximum range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65 percent; silicon, 0.60 percent; copper, 0.60 percent; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels; aluminum, boron, chromium up to 3.99 percent, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect. Small quantities of certain elements are present in alloy steels which are not specified or required. These elements are considered as incidental and may be present to the following maximum amounts; copper, 0.35 percent, nickel, 0.25 percent; chromium, 0.20 percent; molybdenum, 0.06 percent.

c. Low-alloy steel. Since this handbook covers only carbon and low-alloy steels it is necessary to qualify the preceding definition. Low alloy steels, for this handbook, are defined as steels with a total alloy content of five percent or less. This figure includes the constructional high strength low-alloy steels, and the AISI-SAE steels defined in Chapter 5.

7. Effects of Alloying Elements

a. General. Steel, in the generic sense, defines a family of iron-carbon alloys which, collectively, develop a vast range of physical, mechanical and chemical properties. There are many different types and alloys of steel, each capable of developing a particular combination of properties and characteristics that make it uniquely suitable for one or more applications. The versatility of steel is derived from two factors:

(1) Properties can be changed by thermal treatment; and

(2) The addition of one or more alloying elements, in proper amounts and proportions, can effect further changes in properties and characteristics.

The combined effect of these factors is demonstrated by the widespread application of the various steels produced today. Carbon steels, corrosion resisting steels, tool steels, high-hardenability alloy steels, low-alloy high-strength structural steels, spring steels, maraging steels, and others are produced in many alloys and forms each with a distinctive combination of properties and characteristics. A user may choose the alloy and form that best meets his requirements. The tremendous versatility of steel accounts for the fact that it is the most important metal produced today.

The heat treatment of steels will be covered later in this chapter. In this section the effects of various common alloying elements on the properties of steel will be discussed.

Even the carbon steels are not pure iron-carbon alloys. The previously listed definition of carbon steel indicates that elements other than carbon are present in these steels. Some of these are intentionally included in the composition of the steel, while others are present as impurities. Actually, all of the commercial plain carbon steels contain limited amounts of manganese, sulfur, phosphorus and usually some silicon. In addition they may contain, normally in trace amounts only, one or more of the other common alloying elements.

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The carbon steels are produced in two grades, the plain carbon steels, and the free cutting or free machining grade. These steels conform with the composition limits of the AISI-SAE designations. Further composition restrictions are provided by applicable specifications, which usually limit the amounts of carbon, manganese, sulfur and phosphorus permitted in the steel. In the plain carbon steels, sulfur and phosphorus are considered as impurities and maximum limits are specified. Carbon and manganese are purposely included in the composition of these steels and permissible ranges are specified for both elements.

In the free machining alloys, sulfur, and in some alloys, phosphorus and lead, are also controlled within specified limits as well as carbon and manganese.

Despite the fact that other elements are purposely included in the composition of plain carbon steels, carbon is the principal alloying element, and the properties of a steel are primarily dependent upon the amount of carbon alloyed with the iron. For practical purposes, therefore, a plain carbon steel may be considered as one in which only carbon is added to the iron for the singular purpose of controlling the properties of the steel. Manganese and silicon, which are intentional additions to the compositions of plain carbon steels, do affect the properties of the steel, but they are not added specifically for that purpose. The effect on properties is a secondary function of these elements; silicon is added as a deoxidizing agent, while manganese, also a strong deoxidizer, in addition combines with the sulfur to form manganese sulfide, thereby restricting the formation of a less desirable compound, iron sulfide. The free machining alloys retain the carbon steel classification because the extraneous elements are added to the iron-carbon alloy in small amounts well within the composition limits of the AISI designation for carbon steels. The principal effect of the additions is to achieve improved machining characteristics, as compared with a comparable plain carbon alloy.

By contrast with the carbon steels, an alloy steel is one to which one or more elements, in

addition to carbon, are added to the iron specifically to effect a change or changes in properties. These elements impart special properties to steel that cannot be obtained in a plain carbon steel. Some of the common alloying elements of steel are discussed briefly in the succeeding paragraphs.

b. Carbon. The principal alloying element in carbon steels is carbon. Theoretically, the carbon content range for steels extends from approximately 1.7 percent carbon (by weight) to 0.001 or less. In actual practice, commercial carbon steels are produced with carbon content ranging, in nominal figures, from about 1.0 percent to approximately 0.05 percent.

The properties of a carbon steel are dependent upon the amount of carbon in the steel. Hardness, toughness, strength, ductility, and weldability are all directly affected by carbon. The hardness and strength of carbon steels in the as-rolled condition increase with increasing carbon content up to approximately 0.85 percent carbon. The maximum hardness that can be achieved by proper heat treatment of carbon steels also increases with increasing carbon content up to 0.60 percent carbon. Ductility, toughness, and weldability generally decrease as carbon content increases.

c. Manganese. Manganese is an active deoxidizer and, in addition, combines with the sulfur to form manganese sulfide. This constituent enhances the machining characteristics of the free machining carbon steels. When sulfur is present as an impurity, the formation of manganese sulfide restricts the formation of iron sulfide. Iron sulfide is detrimental to the hot rolling and forging characteristics of steel, producing a condition known as "red shortness" or "hot shortness", that is, the material is susceptible to tearing or cracking at rolling or forging temperatures. Manganese enhances the hardenability of the steel because it decreases the critical, or minimum, cooling rate necessary for hardening a steel.

d. Silicon. Silicon in the form of ferrosilicon is used as a deoxidizer and hardener in both alloy and carbon steels.

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e. **Nickel.** Nickel increases impact resistance and toughness, particularly at low temperatures. It lowers the critical temperatures of steel for heat treatment and enhances hardenability. In the high strength low-alloy structural steels which receive no more than an air-quench, nickel is used to obtain given strength levels at lower carbon content than would otherwise be required. As a result the ductility, toughness, and fatigue resistance of the steels are improved.

f. **Chromium.** Chromium enhances hardenability, improves wear and abrasion resistance, and promotes carburization.

g. **Molybdenum.** Molybdenum enhances hardenability, and widens the temperature range for effective heat treatment.

h. **Vanadium.** Vanadium is a strong deoxidizer and also inhibits grain growth.

i. **Aluminum.** Aluminum is a strong deoxidizer and, like vanadium, inhibits grain growth. Aluminum improves the nitriding characteristics of steel when present in amounts of approximately 1 percent.

j. **Boron.** Boron serves one purpose in steel; it increases hardenability.

k. **Multiple alloying elements.** A combination of two or more of the above alloying elements usually imparts some of the characteristic properties of each. Constructional chromium-nickel-alloy steels, for example, develop good hardening properties, with excellent ductility, while chromium-molybdenum combinations develop excellent hardenability with satisfactory ductility and a certain amount of heat resistance. The combined effect of two or more alloying elements on the hardenability of a steel is considerably greater than the sum of the effects of the same alloying elements used separately. The general effectiveness of the nickel-chromium-molybdenum steels, both with and without boron, is accounted for in this way.

Various combinations of alloying elements are employed by the different producers of high strength low alloy steels to achieve the mechanical properties, resistance to atmospheric corrosion, and other properties that characterize those steels. Carbon is generally maintained at

a level that will insure freedom from excessive hardening after welding and will retain ductility. Manganese is used principally as a strengthening element. Phosphorus is sometimes employed as a strengthening element and to enhance resistance to atmospheric corrosion. Copper is used to enhance resistance to atmospheric corrosion and as a strengthening element. Silicon, nickel, chromium, molybdenum, vanadium, aluminum, titanium, zirconium, and other elements sometimes are used, singly or in combination, for their beneficial effects on strength, toughness, corrosion resistance, and other desirable properties.

8. Steelmaking Processes

a. **General.** Various processes have been developed to produce carbon and low-alloy steels from pig iron and scrap steel. In the United States the processes of the greatest commercial significance are: the basic open-hearth process; the acid Bessemer process; the basic-oxygen process; and the electric arc process. Each process is distinctive, with inherent advantages and disadvantages, but, there are marked similarities in the fundamental elements of these processes.

In each process, refining of the raw materials is an essential operation. The raw materials used to make the steel contain various metallic and non-metallic elements as impurities. To make steel, many of these impurities must be removed or reduced in amount to a level that can be tolerated in steel. In all of the previously listed steel-making processes, refining is accomplished by promoting chemical reactions, principally, but not exclusively, oxidation reactions. Carbon, manganese, iron, silicon and other elements are oxidized during the refining period. Many of the oxides evolve as gases or enter the slag thus reducing the amounts of the extraneous elements in the iron.

During the refining process elements that are needed in the steel, such as, carbon and manganese, are removed from the iron along with the impurities. Consequently, each process is designed to permit the addition of selected materials to the molten metal so that the amounts

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of carbon, manganese and other desirable alloying elements in the steel can be adjusted, within limits, to produce a steel of the desired composition.

As steel is refined during the course of these processes, its oxygen content is increased. Various means are employed to deoxidize steels. Deoxidizing and ingot practices are discussed after each of the processes are described.

As a final prelude to the process description, it should be noted that steel making processes are classed as either basic or acid processes. Classification depends upon the type of furnace lining used, which can be either an acid or a basic refractory material. The slag that forms during the process must be compatible with the lining, that is, a basic slag for a basic lining, and an acid slag for an acid lining. Silica (SiO_2) is a common acid furnace lining, while magnesite (MgCO_3) and dolomite (Magnesite + CaCO_3) are basic linings. The open-hearth, Bessemer, and electric arc processes may be operated as basic or as acid processes. In the United States the basic open-hearth process is the predominant process, accounting for more than 80 percent of the steel produced.

b. The basic open-hearth process. The open-hearth process is a regenerative process that employs a furnace with the following features: the hearth is shallow, usually elliptically shaped, and lined with basic refractory materials; the hearth combines with the front and back walls and the roof to form the combustion chamber; and the combustion chamber is closed at each end by similar structures that include the burners and also the air-gas passageways that are part of the regenerative system.

During operation of the furnace, the burners are fired alternately. One burner fires for approximately 20 minutes, it is then shut-off and the other burner is fired for a like period of time. Pre-heated air and gases enter the furnace through the regenerative system passageways at the end of the combustion chamber where the burner is firing. The gases and combustion products travel the length of the furnace, being exhausted through the regenerative passageways at the opposite end of the chamber from which

the air and gases entered. When the burners are alternated, the flow of air and gases is reversed.

The hot exhaust gases enter the regenerative system through the passageways at the end of the combustion chamber. They are passed through a regenerative chamber at the exhaust end of the furnace and from there to the exhaust stack.

Regenerative chambers are located at each end of the furnace. They are large brick chambers in which firebricks are arranged in a criss-cross pattern to form vertical and horizontal passages for the air and gases to pass through. The firebricks are arranged so that as much of their surface area as possible is exposed to the gases flowing through the passages. As the hot exhaust gases from the furnace pass through a regenerative chamber heat is transferred to the firebricks. When the burners are alternated the air and gas flow through the furnace is reversed. Air and gases now pass through the heated chamber, absorbing heat as they do so, and then enter the combustion chamber. In this manner, the regenerative chamber at one end of the furnace is being heated by exhaust gases while the chamber at the other end of the furnace is preheating the air and gases entering the combustion chamber. The function of the chambers are interchanged whenever the burners are alternated.

An open-hearth furnace is charged through water-cooled, hydraulically operated doors in the front wall of the furnace. Solids are charged first. Usually the solid charge includes solid pig iron, scrap steel, iron ore and limestone. The charge is melted by heat from the long sweeping flame of the operating burner. When the solids have nearly melted, molten pig iron is added to the charge and the refining period begins. The first phase of the refining period is known as the ore boil. A slag forms on the molten metal and the silicon, manganese and phosphorus in the pig iron are oxidized and enter the slag. Carbon is also oxidized, forming carbon monoxide gas which, as it boils off, agitates the bath causing the slag to foam and increase in volume. When the volume of the slag is sufficient, it is drawn off or flushed out through a door at the rear of the furnace. The slag contains silicon, phosphorus, and manganese, so the flush serves as a means of reducing the quantity of these elements

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in the heat. The flush is continued for as long as necessary to assure a thorough flushing of the heat, which may be for two hours or more.

The ore boil continues until the carbon content in the melt diminishes and the temperature of the bath rises. With increasing temperatures the limestone begins to decompose forming carbon dioxide and calcium oxide (lime). This phase of the operation is known as the lime boil because of the vigorous reaction caused by the release of the carbon dioxide. The lime rises to the surface and a strong basic and reducing slag is formed which is capable of retaining phosphorus and sulfur.

The lime boil subsides due to depletion of the limestone and when most of the lime has risen to the surface the working period begins. Almost all of the impurities have been eliminated by this time, except for carbon, of which there is usually a slight excess. Any alloy additions are made during this period, and oxidation is continued to reduce the amount of carbon and any other elements in the steel to the proper and desired levels. When a suitable composition is achieved, as determined by analysis of samples from the heat, the heat is tapped.

The molten steel and slag are drawn-off through the tap hole, which in stationary furnaces is located at the center and near the back of the hearth. The tap hole which is sealed with dolomite and clay, is opened when the heat is ready to tap. The steel flows out of the furnace and into a refractory lined spout or runner that directs the steel into a large ladle. The slag follows the steel out of the furnace and into the ladle where some is retained as an insulating cover for the steel. The excess slag overflows into a slag pot.

c. The Acid-Bessemer process. Although the Bessemer process may be operated as either an acid or basic process, only the acid process is of commercial significance in the United States, consequently, this discussion is restricted to the acid process only.

The furnace in which the Bessemer process is carried out is known as a converter. The converter is a large, open topped, pear shaped, steel shell vessel, the inside surfaces of which are

lined with acid refractory materials, predominately silica. The bottom surface of the refractory lined chamber is pierced with numerous small holes, or tuyeres, which lead from the chamber into the windbox below the chamber. The converter is trunion mounted so that it can be tipped to the horizontal position for charging and pouring. One of the trunions is hollow and compressed air is piped through it to the windbox. From the windbox the air passes through the tuyeres into the refractory lined chamber.

The converter is tipped to a horizontal position for charging. Molten pig iron is a common charge, although solids, such as roll scale, scrap and solid pig iron can be added to the molten charge. After the converter is charged the compressed air is turned on and the vessel is slowly rotated to a vertical position. The air, under 15 to 30 psi pressure, passes through the tuyeres and is blown through the charge. The silicon, manganese and carbon in the pig iron are oxidized rapidly, in the order mentioned, by the oxygen in the air passing through the charge. The progress of the blow can be determined by changes in the flame coming from the open end of the converter. When the blow is completed the air is shut off and the converter is tilted to pour the steel into a large ladle. Ferromanganese is added as the steel is poured into the ladle. The purpose of this addition is to convert the iron oxide and iron sulfide in the steel to MnO and MnS. The carbon in the ferromanganese also reacts with oxygen in the steel to form carbon monoxide, which as it boils off agitates the bath and helps to distribute the manganese more uniformly.

d. The basic-oxygen process. This process was developed in Linz, Austria and is sometimes referred to as the LD process (Linz-Dorowitz). Other names by which it is known are the direct oxygen process and the oxygen converter process.

The process is carried out in a converter somewhat similar in shape and construction to the Bessemer converter. However, in this process the inside surfaces of the vessel are lined with basic refractory materials and the bottom surface is solid and does not contain tuyeres.

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The basic oxygen converter is tilted to a horizontal position for charging. Solid scrap is usually charged first and makes up about 25 to 30 percent of the charge. Molten pig iron is added after the scrap, along with some roll scale and lime. After charging the converter is rotated to a vertical position and a water-cooled oxygen lance is lowered into position above the charge. High purity oxygen (98%) under 100 to 150 psi pressure is blown onto the surface of the charge. The charge is refined by the resulting oxidation reactions. The difference in density of refined and unrefined metal, and the evolution and boiling off of carbon monoxide gas, produce a violent agitation and circulation of the bath which brings fresh metal into contact with the oxygen, thereby accelerating the refining process.

Completion of the process is indicated by a change in the flame at the mouth of the converter. When the process is completed the oxygen lance is withdrawn and the converter is rotated to a horizontal position where the slag is skimmed off. The converter is then rotated in the opposite direction and the steel is poured into a large ladle.

e. Electric arc processes. Steel can be made in electric arc furnaces by either acid or basic processes. However, the basic process is generally used to produce electric arc steels that are converted into wrought products. Therefore, this discussion is restricted to the basic electric arc processes.

Two types of electric arc furnaces have been developed, the direct-arc type and the indirect arc type. Of the two, the direct-arc furnace is the more common.

The carbon or graphite electrodes of the indirect-arc furnace are located above the charge and are positioned in-line with a gap between them. The arc is struck between the electrodes and the charge is heated by radiation.

The modern direct-arc furnace employs a different principle. Three electrodes are used, each connected to a single phase of a three phase current. The electrodes are held in the vertical position by external supporting structure and

pass through openings in the furnace roof. Heat is generated by arcs that are struck between the electrodes and the charge.

Direct arc furnaces are versatile units with definite advantages as compared to the other types of furnaces discussed previously. The advantages include:

(1) Fuel burning furnaces require an oxidizing atmosphere to support combustion of the fuel, but in an electric arc furnace a neutral or reducing atmosphere can be developed and maintained.

(2) The heat generated by the electric arc is pure heat. Neither liquid nor gaseous fuels are burned in the furnace, consequently, the hazard of contaminating the bath with impurities normally contained in a liquid or gaseous fuel is eliminated.

(3) Very high temperatures can be attained in electric arc furnaces and temperatures can be accurately controlled.

(4) Refining and alloying can be controlled to meet exacting requirements. By comparison with other processes the operating costs of electric arc furnaces are relatively high. In the strict sense, the electric arc processes do not compete with other processes, being used primarily to produce clean, high quality steels, generally, tool steels, stainless steels, and the like.

A direct arc furnace is usually charged with carefully selected steel scrap of known composition. To assure an excess of carbon in the charge, coke, anthracite coal, broken electrodes or other forms of carbon are usually added to the scrap. Ore, limestone, and alloying elements may be included in the initial charge or they can be added later after the metal charge has melted.

After the charge is laid in the hearth the electrodes are lowered into position and arcs are struck between the electrodes and the charge. As melting progresses silicon, manganese, and phosphorus begin to oxidize and, with the lime, form a slag. As the oxidation reactions continue the temperature of the bath is increased to about 2900°F to promote oxidation of the carbon and also to increase the fluidity of the bath. With

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increased fluidity, solid inclusions rise to the slag and are retained there.

The initial oxidizing slag is made up of lime, silica and iron oxides. When the bath is sufficiently refined by the oxidation reactions, the oxidizing slag is removed and a reducing slag is built by adding fluorspar, lime and carbon to form calcium carbide. The carbide slag reacts with the oxides of iron, manganese, vanadium, chromium, and tungsten, that are in the slag, reducing them, thus returning the metals to the steel. The basic slag also reduces oxides in the steel, and converts sulfur to calcium sulfide (CaS) which is retained in the slag. During this period, any necessary alloy additions are made and when analyses indicate that the desired composition has been achieved a final deoxidizer is added, the temperature is raised to about 3000°F, and the steel is tapped into a ladle.

Vacuum arc melting is a process for refining and improving steel. In this process, the steel is first melted in an electric arc furnace to produce a special ingot suitable for remelting. This ingot, when properly processed, then serves as an electrode in a vacuum arc furnace. The furnace is placed under a vacuum, an electric current is applied, and the electrode melts under heat of the electric arc into a copper crucible. Metal turbulence caused by the electric arc, and the high rate of heat transfer through the water cooled walls of the copper crucible, make possible a sound ingot structure.

Vacuum arc melting effectively lowers oxygen, nitrogen, and hydrogen, and nonmetallic inclusions carried over from the first melting can be significantly reduced in the vacuum remelt. Steels produced by this method are generally more uniform and finer grained in structure and have better mechanical, chemical, and physical properties than those obtained by conventional air melt processes. Equipment, processing, and process controls are, however, generally more complex, stringent, and costly than conventional steel making processes. Vacuum arc process steels are premium quality grades used for specialized applications such as for aircraft applications.

9. Ingot and Deoxidizing Practices. The preceding process descriptions stopped at the point where the steel was tapped into a ladle. At this point the steel is ready to be poured into ingot molds. Ingot and deoxidizing practices are the next subjects discussed.

a. Ingots. Ingots are produced in a variety of types, sizes, and shapes depending upon the wrought product to be manufactured. The cross sectional shape of an ingot may be square, rectangular, slab, round or polygonal, any functional shape that fits the ingot to the final wrought product and provides for economical processing. Ingot mold cavities are usually tapered from one end to the other so that the ingot is either smaller or larger at the top than at the bottom. The taper, or draft, allows the mold to be stripped from the casting. Depending upon the direction of the taper, molds are classed as either big-end-up or big-end-down type molds.

Like most metals, steel contracts during solidification, thus, the volume of the solid is less than that of the liquid from which it forms. When molten steel is poured into an ingot mold the metal in contact with the mold surface freezes almost immediately, establishing the outside surface of the ingot. With the extremities of the casting established by the solidified skin, it is apparent, since solidification progresses from the outside surfaces inward, that the difference in volume between the liquid and solid steel must produce some effect. If the difference in volume is not compensated for in some other way, a cavity forms in the section of the casting that freezes last. The last portion to solidify is usually the upper central portion of the ingot and the cavity that forms there is called a pipe. This effect is shown schematically in Figure 2. The only way to eliminate the pipe is to crop (cut off) the end of the ingot.

The pipe can be confined or concentrated at the top of the ingot by regulating the solidification of the casting. Big-end-up molds promote progressive solidification of the casting from the bottom upward. When a refractory lined collar, or hot top, is added to the mold a portion of the molten steel is insulated and a reservoir of mol-

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ten metal is provided to feed the ingot as it solidifies, thus compensating for the contraction that occurs. In this manner the pipe can be confined to the hot top portion of the ingot.

Hot tops can, and are, used effectively both with big-end-up and with big-end-down type molds to minimize the portion of each ingot that must be cropped.

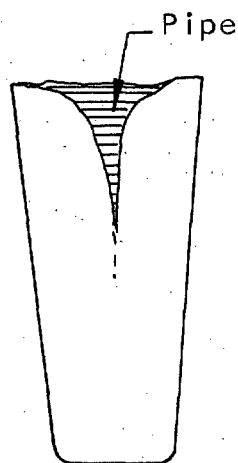


FIGURE 2. Pipe in an Ingot

b. Deoxidation practices

(1) General. Molten steel usually contains oxygen in the form of iron oxide, and as a dissolved gas. If the steel is not deoxidized before it is cast, the oxygen reacts with carbon to form a gas (CO) which evolves during solidification of the steel. The amount of gas evolved during solidification can be controlled effectively by various deoxidation practices. Deoxidizers can be added to the steel in the furnace, in the ladle, in the mold, or by a combination of these methods, to effect complete or partial deoxidation of the steel, as desired. Common deoxidizers are ferromanganese, ferrosilicon and aluminum.

Three types of steel, classified according to deoxidation, are: killed steel, semikilled steel, and rimmed steel.

(2) Killed Steel. Killed steels are those that have been so thoroughly deoxidized that they lie quietly in the mold because little or no gas is evolved. Killed steels are usually cast in big-

end-up hot top molds. Generally killed steels are used when a sound, homogeneous structure is required. Alloy steels, carburizing steels, steels for forgings, are typical applications for killed steel.

(3) Semikilled Steel. Semikilled steel is not as thoroughly deoxidized as killed steel. Some oxygen is present to react with the carbon to form CO when the steel is poured into the ingot molds. Steel of this type generally contains more blow-holes and inclusions than killed steel. Semikilled steel is used extensively for heavy structural shapes and plate.

(4) Rimmed Steel. A relatively small amount of deoxidant is added to rimmed steel and a considerable amount of gas evolves and rises to the surface as the steel solidifies. An ingot of rimmed steel has an outside skin of low carbon content steel, an intermediate zone which contains blow-holes of various sizes, and a core of metal rich in carbon, sulfur and phosphorus. Rimmed steel has a good surface finish and a high degree of ductility which makes it useful for thin sheet, wire, tinplate and similar products.

(5) Capped Steel. Capped steel practice is a variation of rimmed practice. The steel is poured into big-end-down molds with a constricted top (bottle top) to facilitate capping. The rimming action is allowed to begin but is terminated after a short time by sealing the mold with a steel or cast iron cap. An addition of aluminum or ferrosilicon to the top of the top surface of the molten steel has the same effect as capping and is sometimes used in place of a cap. The product is an ingot with a thin skin or rim which is relatively free of blow-holes and with less segregation than rimmed steels. Steel of this type is used to make sheet, strip, tin plate and bars.

FERROUS METALLURGY

10. The Structure of Metals. Metallic materials, together with the other substances in our world, can be divided into three basic classifications: elements, compounds, and mixtures.

a. Elements. Elements are substances that cannot be broken down into simpler substances by ordinary chemical methods. For example, iron, carbon, manganese, sulfur and phosphorus are

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included among the more than 100 elements discovered to date.

b. Compound. A compound is a substance produced by a chemical reaction between two or more elements. The constituents of a compound unite in definite fixed proportion by weight. The properties of a compound differ from those of its component elements. Compounds, unlike elements, can be decomposed by chemical reactions into simpler substances, that is, into elements, and/or other compounds. Iron carbide (Fe_3C), also known as cementite, is a compound.

c. Mixtures. Mixtures are produced by the intermingling of elements, compounds, or both. The composition of a mixture is not governed by the law of definite proportions, as are compounds, and the components of a mixture may be intermingled in various proportions. The constituents of a mixture can be separated by purely physical means and each component in a mixture retains its own properties. An often cited example, air, is a gaseous mixture of nitrogen, oxygen, argon, carbon dioxide, water vapor and other gases.

d. Solutions. Solutions are a specific kind of mixture in which the components are so completely miscible as to be indistinguishable under the optical microscope.

Elements, the fundamental substances from which other substances are made, are, in turn, composed of atoms. It is convenient to visualize an atom as a miniature solar system composed of a nucleus surrounded by electrons which revolve in what may be considered as concentric orbital shells located at discrete distances from the nucleus. The electrons are small particles of unit negative charge. The nucleus is composed of protons and neutrons. Protons are small particles with an equal but opposite charge to that of an electron, that is, they bear a unit positive charge. Neutrons are small electrically neutral particles. The mass of a proton is 1836 times that of an electron, while the mass of a neutron is 1839 times that of an electron.

Atoms are essentially electrically neutral, possessing equal numbers of protons and electrons. The number of protons in the nucleus of an atom is unique for each element and is called the atomic number of the element. Of course the

number of electrons possessed by an atom is also equal to the atomic number.

The electrons surrounding the nucleus of an atom are grouped in specific and distinct energy levels commonly described as orbital shells. Progressing away from the nucleus, each additional shell may contain successively more electrons. The first shell may contain two electrons; the second, eight electrons; the third, eighteen electrons; and so forth. The outermost shell of electrons is known as the valency group. The properties of the elements are strongly related to electrons in this group, which are known as valence electrons. When the outer shell is completely filled the atom is very stable and does not combine with other atoms. Some of the inert gases are examples; helium, atomic number 2, has one electron shell filled with two electrons, and neon, atomic number 10, has two complete shells of two and eight electrons respectively. Provisional stability is achieved when the third and higher shells contain eight electrons. For example, argon, atomic number 18, has three electron shells, the first two are complete with two and eight electrons respectively, while the third shell, although incomplete, contains the stable number of eight electrons. Argon is also included among the inert gases.

The ability of atoms to combine with like atoms to form crystals or with other atoms to conform compounds is governed by the valence electrons. Metals typically have positive valence, that is, their atoms tend to give up electrons in chemical reactions leaving them with more protons than electrons. In this state, the atoms possess a positive charge and are called positive ions. Non-metals tend to accept electrons and form negative ions.

Ionic compounds are formed between strongly metallic and strongly non-metallic elements. Electrons are transferred from the metal atoms to the non-metal atoms, forming positively and negatively charged ions. The electrostatic forces acting between the oppositely charged ions bond the ions together as a molecule of the new compound.

Solid metals, under ordinary circumstances, are crystalline materials. By definition, a crystal consists of atoms arranged in a pattern that

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Body-Centered Cubic Face-Centered Cubic Unit Cells

FIGURE 3. Unit Cells of the Body-Centered Cubic and the Face-Centered Cubic Crystal Structures

repeats periodically in three dimensions. The space-lattice is a useful and convenient concept for describing the geometric arrangement of atoms within a crystal. A space-lattice is a geometric construction depicting the three dimensional arrangement of atoms in space for a specific crystal structure. Therefore, a space-lattice consists of points in space, not lines or planes, and the lattice is understood to extend indefinitely in space in a regular arrangement within which each point has identical surroundings. In practice it is often inconvenient to use a point lattice, consequently it is common practice to connect the points by straight lines to form an equivalent line lattice. Also, it is often more convenient to describe a space-lattice in terms of a unit cell, which is the smallest group of points which, when repeated in all directions, will develop the space-lattice.

Most metals solidify in one of three crystal structures; the body-centered cubic; the face-centered cubic, or the close-packed hexagonal. The crystal structure of iron is body-centered cubic at temperature below 1697°F. Between 1697°F and 2535°F it is face-centered cubic and from 2535°F to the melting point, 2795°F, it is body-centered cubic again. The ability of a substance to exist in more than one crystal structure is known as polymorphism and the change from one structure to another is referred to as a polymorphic transformation. The unit cells of the body-centered cubic and the face-centered cubic structures are illustrated in Figure 3.

When a solid metal is heated sufficiently it melts and becomes liquid. If heating is continued the liquid metal eventually boils and is transformed to a vapor. To effect these changes in physical state a considerable amount of thermal energy must be supplied to the metal, which

in turn, manifests itself as increased potential and kinetic energy of the metallic atoms. The vapor state is the highest energy state of the three states in which a metal can exist. In the vapor state, the kinetic energy of individual atoms is so great that their gravitational and chemical attraction for each other is overcome. Their movement is a rapid, random, independent vibration, restricted only by the container and collisions with other atoms. Obviously, the arrangement of atoms in a gas is unordered and continuously changing.

As a gas is cooled it loses thermal energy and the average kinetic energy of the metal atoms diminishes. As cooling continues the vapor condenses into a liquid. In the liquid phase the atoms are still capable of a relatively free and independent motion, although such motion is much more restricted than in the vapor phase. Continued cooling of the liquid, of course, further reduces the kinetic energy of the atoms. At the freezing point, the mutual attraction of some neighboring atoms prevails over their kinetic energies and small groups of atoms form at random within the mass of liquid. The atoms in these groups align in the definite ordered geometrical arrangement characteristic of the metal's crystal structure. Some of these groups become relatively stable and serve as crystal nuclei to which other atoms are attracted and become attached. The atoms continue to align in the definite geometric arrangement of the metal's crystal structure as the nuclei grow in three crystallographic directions. Because of the random orientation and distribution of the nuclei the crystals develop rather freely in the liquid during the initial phase of solidification. Inevitably, however, individual adjacent crystals approach each other and further growth is impaired by mutual interference. As a result of the mutual

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interference on every side, the crystals form geometrically irregular external surfaces. The irregularly shaped crystals thus formed are commonly referred to as grains. Because the crystals nucleate and grow in different orientation, the surface atoms of adjacent grains are mismatched and grain boundaries are formed by the distorted layers of atoms between normal grains. Each grain boundary atom, as a result of the distortion, exists in a higher-energy state than that which is typical for the atoms within the grains. Grain boundaries then, are regions of abnormally high free energy, a condition that significantly affects the mechanical, physical, and chemical characteristics of a metal. First, the less densely packed arrangement along the grain boundaries furnishes a path for more rapid transfer of atoms than do the aligned atoms within the grains. Second, because they exist at higher energy levels, grain boundary atoms tend to react more readily with corrosive media than the normal atom within the grains. Third, foreign or impurity atoms tend to concentrate at grain boundaries where they can be fitted in more readily. Fourth, nucleation, for precipitation and eutectoid reactions involving the formation of one or more new phases, occurs at grain boundaries. Fifth, below the recrystallization temperature grain boundaries are stronger than the matrix crystals, while above the recrystallization temperature the relative strengths of the grain boundaries and the matrix crystals are reversed.

The metals are elements that possess, to some degree, particular properties that are referred to as metallic properties. One particular characteristic of metals, already discussed, is the type of atomic bond which they form. The bond of course is the metallic bond in which the atoms in the metal share electrons. The electrons are relatively free to move from atom to atom and form what is commonly referred to as an electron cloud or gas. Metals also possess metallic luster. They are opaque, generally are good conductors of heat and electricity, and are, to some extent, malleable and ductile.

While metals are elements possessed of metallic properties, there are other substances that also possess metallic properties. These substances, which are combinations of two or more

elements, are called metallic alloys, or more commonly, alloys. At least one of the components of any alloy is a metal. The importance of alloys is indicated by the fact that the majority of the metallic materials used in structural applications today are alloys rather than metals.

Elements can combine either as compounds, or as mixtures. Compounds, as previously discussed, are formed when atoms of the reacting elements unite in a definite ratio by weight. Compounds are identified by chemical formulas, for example: water, H_2O ; iron-carbide, Fe_3C . Mixtures, however, are combinations of elements that are not governed by the law of fixed proportions. In mixtures the component elements may be intermingled in any desired proportion. It was previously noted that solutions are mixtures. Liquid solutions are commonplace and everyone is quite familiar with them. Brine, a solution of salt in water is a common example. In true solutions, single atoms or molecules of one substance are uniformly dispersed throughout another in such a manner that the identity of the dispersed substance is lost. Sugar, for example, will dissolve in water, but the solution will remain clear. The combination of sugar and water becomes a single-phase liquid which is homogeneous within the limits of observation. A true solution is a uniform mixture of a solute (the dissolved substance) and a solvent (the substance in which the solute dissolves).

Solutions are not restricted to liquids; solid solutions form in a manner similar to liquid solutions. Brass, for example is a solid solution of zinc atoms dissolved in copper. When zinc is added to copper to form brass, zinc atoms substitute for some of the copper atoms in the crystal structure. This type of solid solution is called a substitutional solid solution.

Another form of solid solution is the interstitial solid solution. In this type of solution the solute atoms do not replace the solvent atoms but rather occupy positions between the normal positions of the solvent atoms, that is, at the interstices. The solution of carbon in iron is an example of this type of solution.

In any alloy, when the components are completely soluble in the liquid state, the solubility

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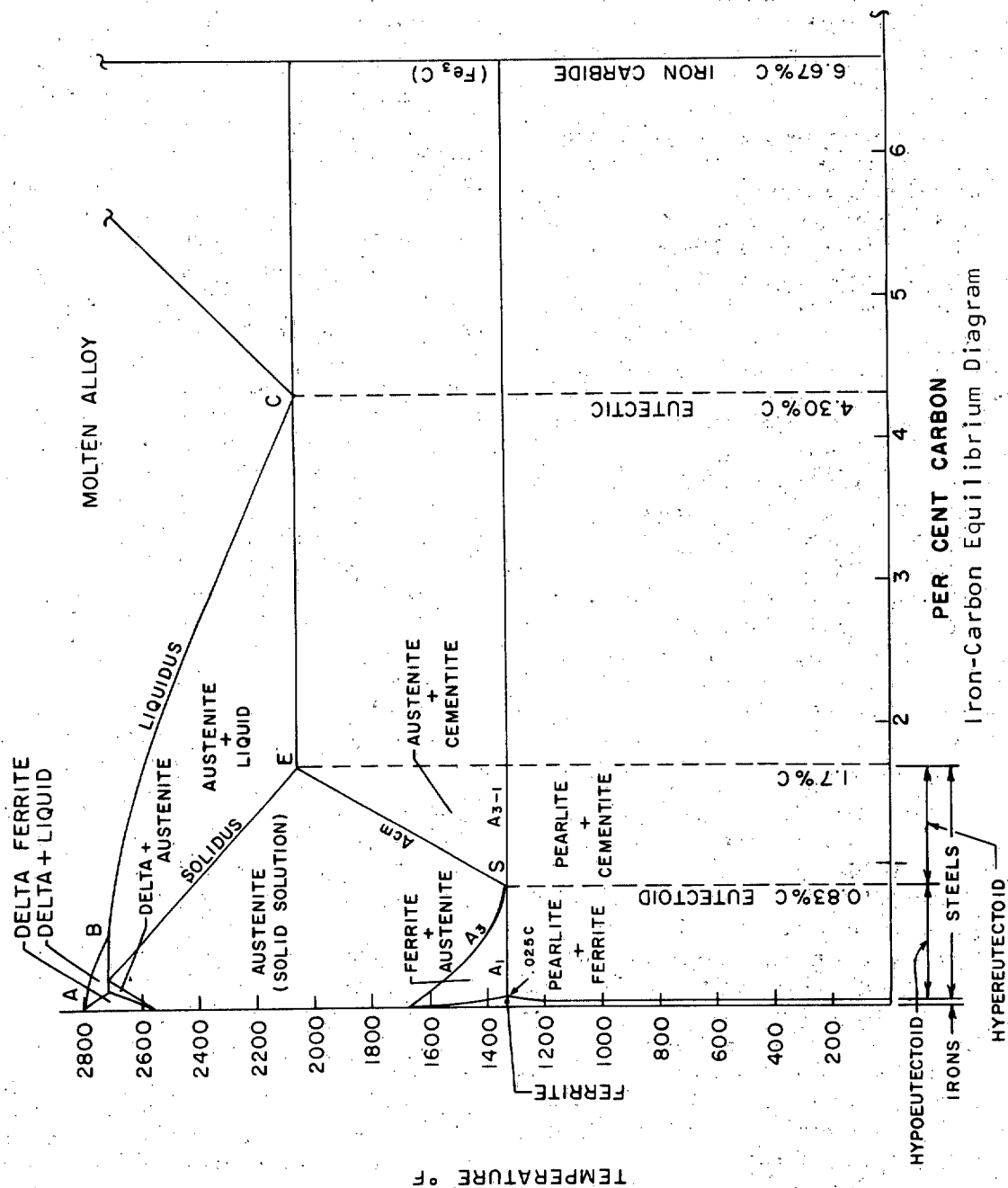


FIGURE 4. Equilibrium Diagram-Iron-Carbon System

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may or may not change upon solidification. When complete solubility persists in the solid state, the alloy will consist of one phase, a solid solution. If, however, the solubility of the components in the solid state is negligible, they may form more than one phase upon solidification. A phase is generally defined as a microscopically homogeneous body of matter; as related to alloys, a phase may be considered as a structurally homogeneous and physically distinct portion of the alloy system. For example, when an alloy solidifies, or freezes, the phases formed may be a chemical compound and a solid solution, or two solid solutions. Before the alloy solidifies completely, a solid solution may exist in equilibrium with a liquid. In each of these examples, two phases of the alloy are involved.

II. The Iron-Carbon System. Equilibrium diagrams are graphs or maps of the temperature and composition boundaries of the phase fields that exist in an alloy system under conditions of complete equilibrium.

The equilibrium diagram of the iron-carbon system, from 0 percent to 7 percent carbon by weight, is shown in Figure 4. This is the only portion of the system pertinent to steels. Extensive reference will be made to the diagram in the following discussion.

Pure iron is polymorphic, that is, it exists in more than one crystal structure. In the case of pure iron the crystal structure changes with temperature. The crystal structure of pure iron is body-centered cubic up to 1670°F. This polymorphic form of iron is called alpha-iron. From 1670°F to 2535°F, the stable crystal structure of pure iron is face-centered cubic, designated as gamma-iron. Above 2535°F iron again has a body-centered cubic crystal structure and is known as delta-iron. This form is stable up to the melting temperature 2795°F. These points are identified on the equilibrium diagram along the zero percent carbon ordinate.

The polymorphic transformations of iron account for the very great importance of steel as a structural material. Gamma-iron is capable of dissolving, in solid solution, approximately forty times more carbon than alpha-iron. This fact, as

will be developed later, is of considerable industrial importance.

Carbon is soluble, to some extent, in all three of the polymorphic forms of iron. The extent of these solid solution phase fields are indicated in Figure 4. The solid solution of carbon in alpha-iron is known as ferrite or alpha-ferrite. The maximum solubility of carbon in alpha-iron is 0.025 percent by weight at 1333°F.

Austenite is the name applied to the solid solution of carbon in gamma-iron. Gamma-iron can dissolve a maximum of 2.0 percent carbon, and this at a temperature of 2065°F. The solid solution of carbon in delta-iron is called delta-ferrite or delta solid solution (Δ SS). The maximum solubility of carbon in delta-iron is 0.10 percent at 2715°F.

In addition to the solid solutions just described, carbon and iron form a hard, brittle intermetallic compound, iron carbide (Fe_3C), which is commonly referred to as cementite. In steels, under equilibrium conditions, carbon occurs as iron carbide rather than as free carbon. For that reason the equilibrium diagram of the iron-rich portions of the iron-carbon system is often called the iron-iron carbide equilibrium diagram.

Two points of particular interest and importance in equilibrium diagrams are points C and S, Figure 4. C is the eutectic point and S is the eutectoid point. The eutectic reaction is an isothermal reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the solution. A eutectic is defined as an intimate mechanical mixture of two or more phases having a definite melting point and a definite composition.

A eutectoid reaction is an isothermal reversible reaction in which a solid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the solution. Therefore, a eutectoid is a mechanical mixture of two or more phases having a definite composition and a definite temperature of transformation within the solid state.

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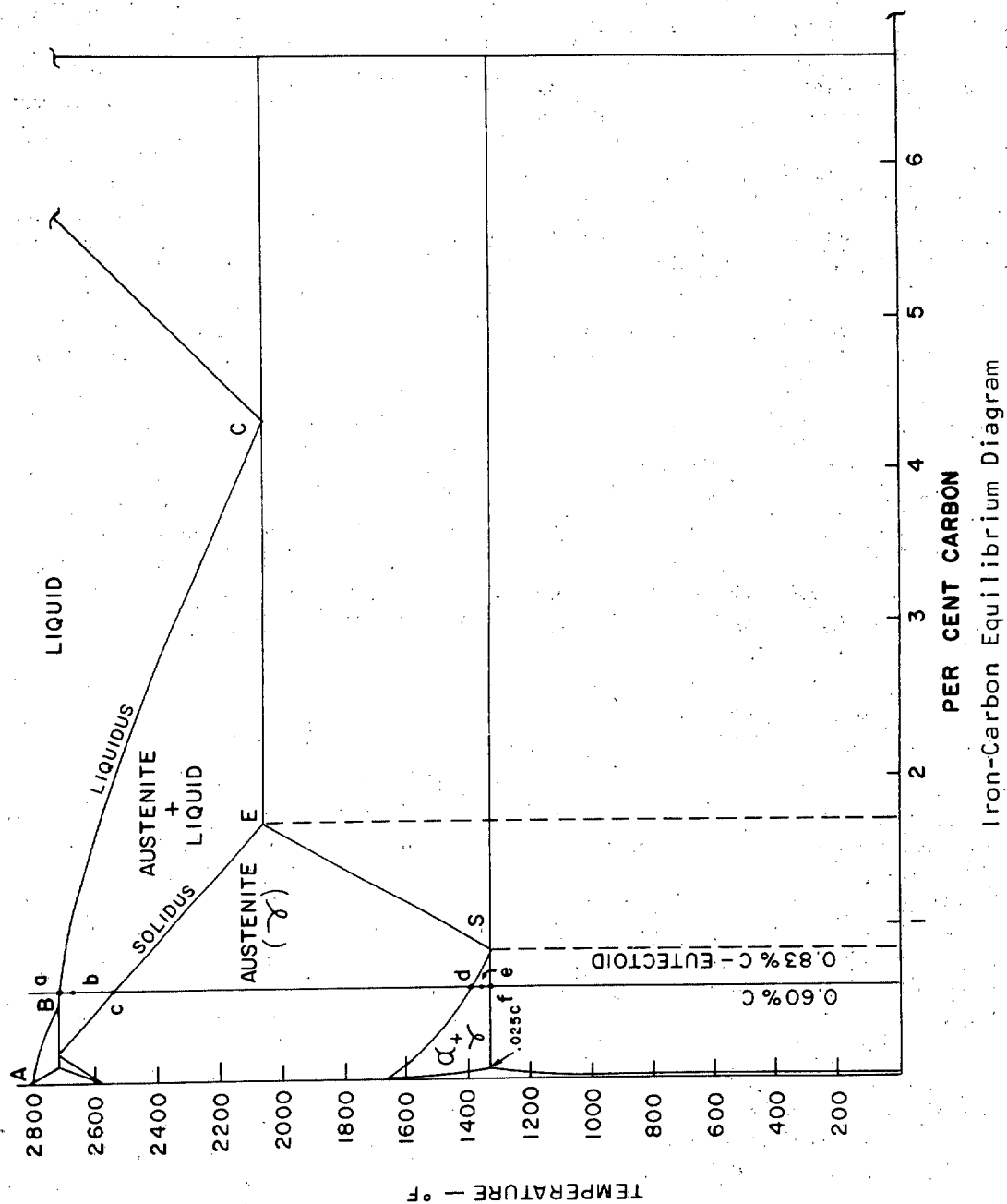


FIGURE 5. Equilibrium Diagram-Iron-Carbon System

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In the iron-carbon system the eutectic is a mixture of austenite and iron carbide. The iron-carbon eutectic contains 4.3 percent carbon by weight and forms at 2065°F when the liquid solution is cooled under equilibrium conditions. It should be noted that the eutectic composition has the lowest melting temperature of any alloy in the iron-iron carbide system. As carbon content is decreased in the system, the melting point increases along line C-B-A, Figure 4.

The eutectoid of the iron-carbon system contains 0.83 percent carbon by weight. The eutectoid, which forms at 1333°F is a mixture of ferrite and cementite, called pearlite. As indicated in Figure 4, steels containing more than 0.83 percent carbon are hypereutectoid steels, and steels with less than 0.83 percent carbon are hypoeutectoid steels.

The temperatures at which the solid state transformations take place are called critical temperatures or critical points. The loci of these critical points, which establish the boundaries of the phase fields, are identified at A_1 , A_3 , A_{cm} , and A_{3-1} , in Figure 4. Note that the 1333°F isotherm located at the left of the eutectoid point is designated as A_1 , while to the right of the eutectoid point it is identified as A_{3-1} .

Another interesting reaction is indicated on the equilibrium diagram at 2700°F to 2800°F and from 0 to 0.5 percent carbon. The reaction is a peritectic reaction, which is essentially an inversion of a eutectic reaction. In the latter, there is a transformation of one phase to two on cooling. In a peritectic reaction two phases convert to one on cooling.

The iron-carbon equilibrium diagram and other two-component system diagrams are called binary diagrams. Interpretation of these diagrams is not difficult, as shown by the following example.

The first step in using a binary diagram is to identify the alloy of interest. For this example consider an alloy containing 0.60 percent carbon and 99.40 percent iron. After the alloy has been selected a vertical line is drawn through the diagram at the selected composition. In this example the line starts at the 0.60 percent carbon point on the abscissa, as shown in Figure 4.

Now, assume that the alloy is heated to 2800°F and held at that temperature until the system is in equilibrium. From this temperature the alloy will be slowly cooled, under equilibrium conditions, to room temperature.

At 2800°F the alloy is a liquid solution of 0.60 percent carbon and 99.40 percent iron. Crystals of austenite begin to form in the liquid when the temperature of the alloy reaches the point where the constant composition line intersects the liquidus curve, A-B-C, at point "a", Figure 5. By drawing an isotherm through point "a" and noting where it intersects the solidus curve, the composition of the first austenite crystals to form can be determined. In this instance the first austenite crystals will contain about 0.20 percent carbon. Now, assume that the alloy has cooled to the temperature at point "b", 2650°F. Another isotherm drawn through point "b" intersects the solidus at the 0.30 percent carbon ordinate, which indicates that the austenite formed at 2650°F will contain 0.30 percent carbon. The isotherm through "b" intersects the liquidus at the 1.20 percent carbon ordinate, so that liquid at 2650°F contains 1.20 percent carbon. Next consider the isotherm between the 0.30 carbon ordinate and the 1.20 carbon ordinate to be a lever with its fulcrum at the 0.60 carbon ordinate. For simplification the fulcrum and terminal points of the lever will be identified as x, y and z, as shown in Figure 6.

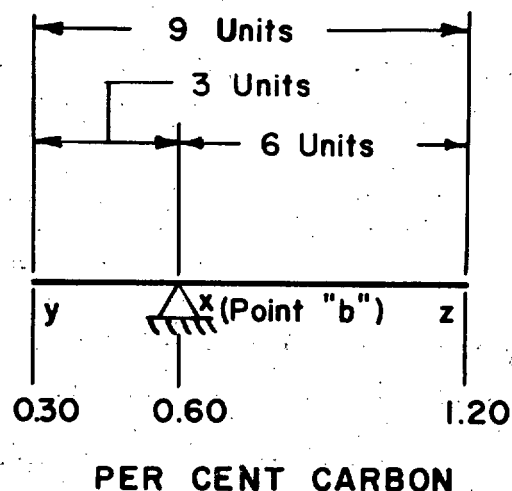
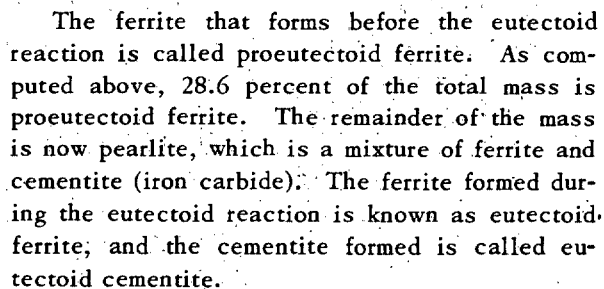


FIGURE 6. Lever Diagram

The percentage of ferrite in the total mass is $\frac{nq}{mq} = \frac{0.10}{0.68} \times 100 = 14.7$ percent. The percentage of austenite in the total mass is $\frac{mn}{mq} = \frac{0.58}{0.68} \times 100 = 85.3$ percent. The austenite contains 0.70 percent carbon and the ferrite 0.02 percent carbon.



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The percentages of eutectoid ferrite, and eutectoid cementite in the total mass can be found by applying the lever principle. Figure 8 illustrates the lever relationships of this calculation.

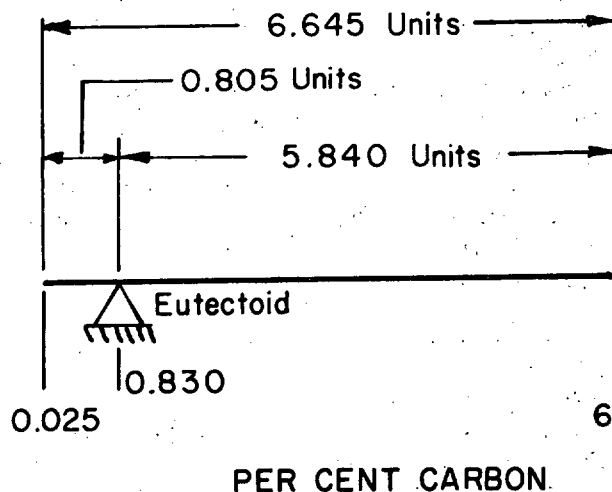


FIGURE 8. Lever Diagram

The lever for this reaction has its fulcrum on the 0.83 carbon ordinate and its terminal points on the 0.025 and 6.67 percent carbon ordinates.

Then, the percentages of ferrite and cementite in the pearlite are:

$$\text{Percent ferrite} = \frac{5.84}{6.645} \times 100 = 87.9 \text{ percent}$$

$$\text{Percent cementite} = \frac{0.805}{6.645} \times 100 = 12.1 \text{ percent}$$

Since 71.4 percent of the total mass is pearlite, the percent of eutectoid ferrite in the total mass is: $71.4 \times 0.879 = 62.8$ percent. The percent of eutectoid cementite in the total mass is: $71.4 \times 0.121 = 8.6$ percent. As shown by the foregoing calculations, the total amount of ferrite in the solidified steel is 28.6 percent + 62.8 percent = 91.4 percent. The total amount of cementite in the steel is 8.6 percent.

The preceding example demonstrates the reactions involved when a hypoeutectoid steel is cooled from above its melting point to below the

A_1 temperature under equilibrium conditions. At room temperature the 0.60 percent carbon steel was found to consist of two phases, cementite (iron carbide, Fe_3C) and ferrite. The ferrite was observed to exist in two forms: as proeutectoid ferrite, which formed as the steel was cooled from the A_3 temperature to the A_1 temperature; and as eutectoid ferrite which combined with the eutectoid cementite to form eutectoid pearlite. By applying the lever principle, the relative amounts of the two phases in the solid steel were estimated to be:

$$\text{Total ferrite} = 91.4\% \text{ (28.6\% proeutectoid ferrite + 62.8\% eutectoid ferrite).}$$

$$\text{Total cementite} = 8.6\%$$

Any alloy of the iron-iron carbide system can be analyzed in a similar manner. Actually, the lever diagram shown in Figure 8 and the associated calculations are the relationships and calculations which would be developed for the final transformation of an alloy of eutectoid composition (0.83%C). As indicated, the eutectoid alloy would, after the final transformation, be composed entirely of the eutectoid, pearlite, consisting of 87.9 percent eutectoid ferrite and 12.1 percent eutectoid cementite.

Inspection of the equilibrium diagram Figure 4 indicates that any hypoeutectoid alloy will transform, under equilibrium cooling, in the same manner as the 0.60 percent carbon steel cited in the sample analysis. When these steels cool to the A_3 temperature ferrite begins to form from the austenite; as cooling continues, more ferrite forms and the austenite becomes increasingly rich in carbon. The composition of the austenite of course follows the A_3 curve so that when the temperature reaches 1333°F the remaining austenite contains 0.83 percent carbon, the eutectoid composition. This austenite then transforms to the eutectoid, pearlite. Hypoeutectoid alloys, when solidified under equilibrium conditions, are composed of proeutectoid ferrite and the eutectoid, pearlite. The relative amount of each constituent in an alloy is determined by the amount of carbon in the alloy. It is evident from the equilibrium diagram that as the carbon content decreases the proeutectoid ferrite content of

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hypoeutectoid alloys increases, and the pearlite content decreases proportionately.

The hypereutectoid steels contain carbon in excess of 0.83 percent to 1.7 percent. These alloys, when cooled under equilibrium conditions, transform into proeutectoid cementite and pearlite. The proeutectoid cementite begins to form when the alloys are cooled to the A_{cm} temperature, which, as shown, varies with carbon content. With continued cooling the austenite rejects more and more carbon in the form of cementite so that as the temperature decreases the amount of proeutectoid cementite increases. The change in composition of the austenite with decreasing temperatures is indicated by the A_{cm} curve. When the temperature reaches 1333°F the remaining austenite contains 0.83 percent carbon, the eutectoid composition, which transforms to the eutectoid, pearlite. As indicated in Figure 4, the proeutectoid cementite content of hypereutectoid alloys increases with increasing carbon content and the pearlite content decreases proportionately.

Equilibrium diagrams are maps of the transformations that occur in alloy systems under equilibrium conditions. As previously mentioned, the temperatures shown on an equilibrium diagram at which some transformation takes place are called critical temperatures or critical points. The loci of these critical temperatures are identified as the A_1 , A_3 , A_{3-1} and A_{cm} lines or curves. The letter A derives from the word arrest, since at these temperatures an arrest occurs in the heating or cooling curve. The temperature interval between the A_1 and A_3 critical points for a particular alloy is designated as the critical range. The A_3 is called the upper critical temperature and the A_1 is the lower critical temperature.

The rate at which an iron-carbon alloy is heated or cooled affects the critical temperature of the alloy. In practice, strict equilibrium conditions are not maintained during heating or cooling because equilibrium could be achieved only if the heating or cooling rate was extremely slow, or more accurately, infinitely slow. In commercial enterprises equilibrium rates are not practical. Heating at nonequilibrium rates tends to raise the critical temperatures, while cooling at

nonequilibrium rates lowers the critical temperatures from the equilibrium critical temperatures. Generally the greater the rate of heating or cooling the greater is the deviation from the equilibrium critical temperatures. The critical points on heating are identified by the symbol A_c , for example, A_{c1} , A_{c3} , A_{c1-3} . The letter "c" derives from the French word for heating, "chauffage". The symbol A_r denotes critical points on cooling. Again the "r" derives from a French word, this time, "refroidissement" for cooling. When it is necessary to identify the critical points for equilibrium (e) conditions, the symbol A_e is occasionally used, as A_{e1} , A_{e3} , etc.

12. The Theory of Heat Treatment. The heat-treatment of steels is essentially a process of controlled departure from equilibrium heating and cooling. When a steel is cooled, under equilibrium cooling conditions, from above the A_3 critical temperature, the austenite remaining when the A_1 temperature is reached transforms to pearlite. With more rapid cooling, the faster the cooling rate the farther the transformation temperature (A_{r1}) is depressed below the A_{e1} temperature.

The eutectoid, pearlite, that forms when austenite is cooled below the A_{r1} temperature is a lamellar product made up of alternate plates of ferrite and cementite. The pearlite formed under equilibrium cooling is a coarse lamellar product. The process of transformation of pearlite from austenite involves diffusion of carbon and since the diffusion rate is a function of temperature, faster cooling rates with attendant lower transformation temperatures produces pearlite with a finer lamellar structure. A finer dispersion of phases tends to promote greater strength and hardness and to reduce the ductility of the steel. With very rapid cooling the austenite transformation occurs at a low temperature and the resulting structure is not pearlite but a structure known as martensite. Therefore, by controlling the cooling rate, the temperature of the austenite transformation, and hence, the structure and properties of the steel are controlled.

Isothermal Transformation Diagrams: The time-temperature relationships for austenite transformations are graphically presented in isothermal transformation diagrams, commonly referred to as

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T-T-T curves, or more precisely, Time-Temperature-Transformation diagrams. T-T-T diagrams have been developed for various plain carbon and alloy steels. These diagrams are a plot of the times of the beginning and end of austenite transformations as a function of temperature.

The data that are required to plot a T-T-T diagram are developed through a series of isothermal transformation studies. The purpose of an isothermal transformation study is to determine the austenite transformation(s) that occur in a steel held at a constant temperature for increasing periods of time. To accomplish this objective small thin pieces of the steel under study are heated above the upper critical temperature and held at temperature long enough for homogeneous austenite to form. Each specimen, in turn is removed and quenched into a lead or salt bath which is held at the desired study temperature. Thin specimens are used so that cooling to the bath temperature can be assumed to be instantaneous. Each specimen is held in the isothermal bath for a different period of time, which may be seconds, minutes, or hours, and then quenched in brine or water to transform any remaining austenite to martensite. After the brine quench, the structure of each specimen is examined to determine what transformation product or products, if any, had formed during the isothermal cycle, and what percentage of the total structure had transformed into each product. A plot of these data is called an isothermal transformation curve. The data obtained from a series of isothermal studies are used to develop T-T-T diagrams in which the time for the beginning and ending of transformations are plotted as functions of temperature. The basic method is illustrated in Figure 9.

Isothermal transformation studies provide information on the transformation rates encountered at various temperatures and also the transformation products that form at the various temperatures. Depending upon the transformation temperatures, and the composition of the steel, austenite will transform into one or more of the following constituents: proeutectoid ferrite; proeutectoid cementite; pearlite; upper bainite; lower bainite; and martensite.

Figures 10 and 11 are the isothermal transformation diagrams for eutectoid steel and a hypoeutectoid steel, respectively. Generally, for carbon and low alloy steels, the temperature ranges over which austenite transforms into the various constituents, under isothermal cooling, are as indicated in Figure 10.

Referring to Figure 10, pearlitic microstructures are formed from about 1300°F to 1000°F. Pearlite, as previously discussed, is a constituent with a lamellar structure of alternating plates of ferrite and cementite. The lamellar structure formed at the higher transformation temperatures is relatively coarse but as the transformation temperatures decrease the lamellae become more closely spaced. When the transformation occurs at about 1000°F the lamellar structure is very fine and difficult to resolve with an optical microscope.

The transformation of austenite to pearlite is a process of nucleation and growth. In homogeneous austenite nucleation apparently occurs almost exclusively at the grain boundaries. When the austenite is not of uniform composition, but contains residual iron carbide particles and carbon concentration gradients, pearlite can nucleate within the grains as well as at the grain boundaries.

The generally accepted theory is that the pearlite nucleus is a small lamella of cementite which, assuming the austenite is homogeneous, forms at an austenite grain boundary. As the nucleus grows into the grain it absorbs carbon atoms from the surrounding austenite. When the carbon concentration of the surrounding austenite has been sufficiently reduced, ferrite nucleates and grows along the surface of the cementite plate. Because ferrite can dissolve only about 0.02 percent carbon, carbon atoms are rejected by the ferrite as it forms. As a result there is a build-up of carbon at the ferrite-austenite interface. The carbon-concentration continues to increase until the concentration level is sufficiently high and a new cementite nucleus forms. The sideways nucleation is repeated while, simultaneously, growth occurs at the edges of the ferrite and cementite plates. The alternating lamellae of cementite and ferrite originating from a single cementite nucleus is called a pearlite colony.

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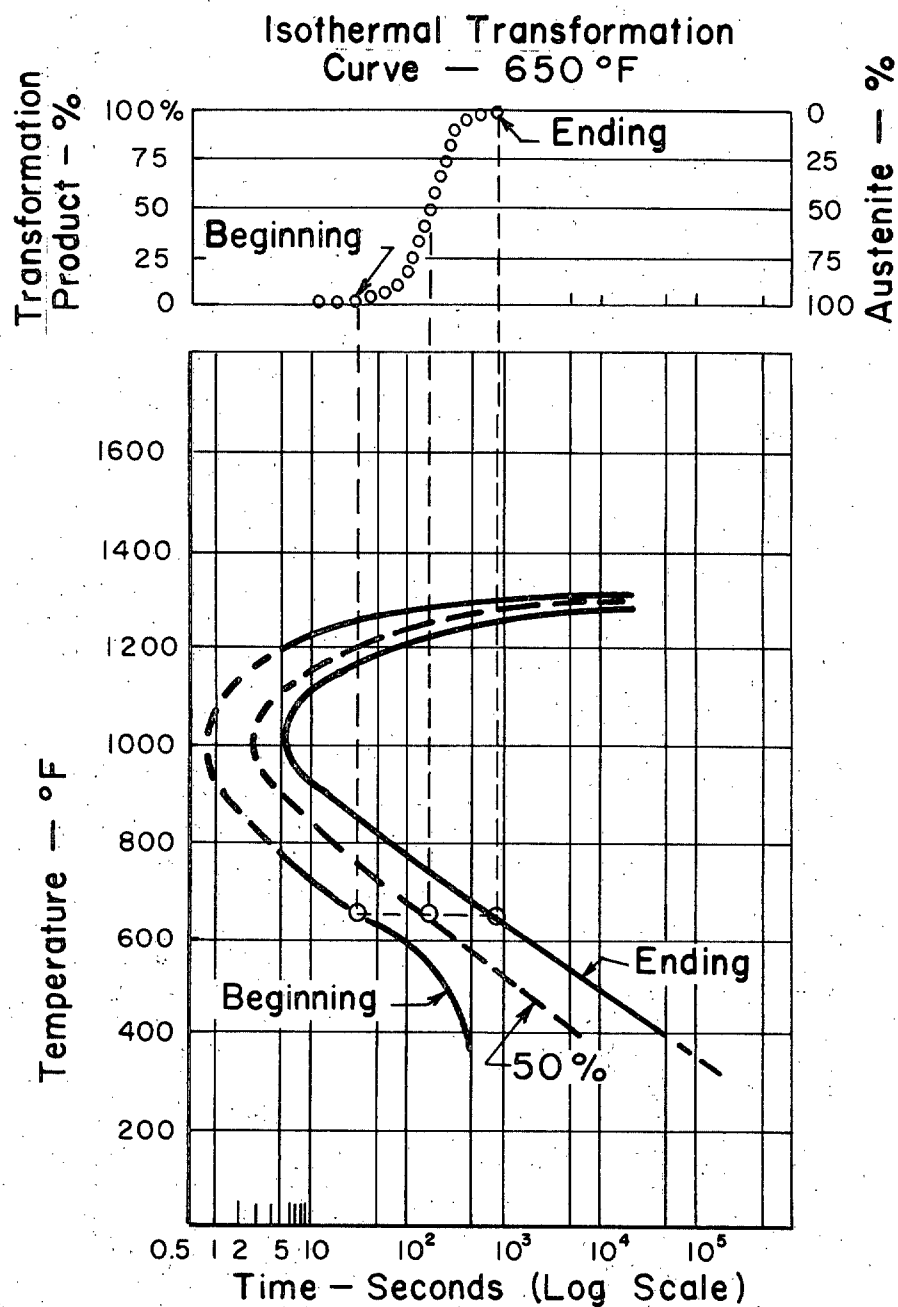


FIGURE 9. The Use of Transformation Curves to Develop Isothermal Transformation Diagrams

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A = Austenite

F = Ferrite

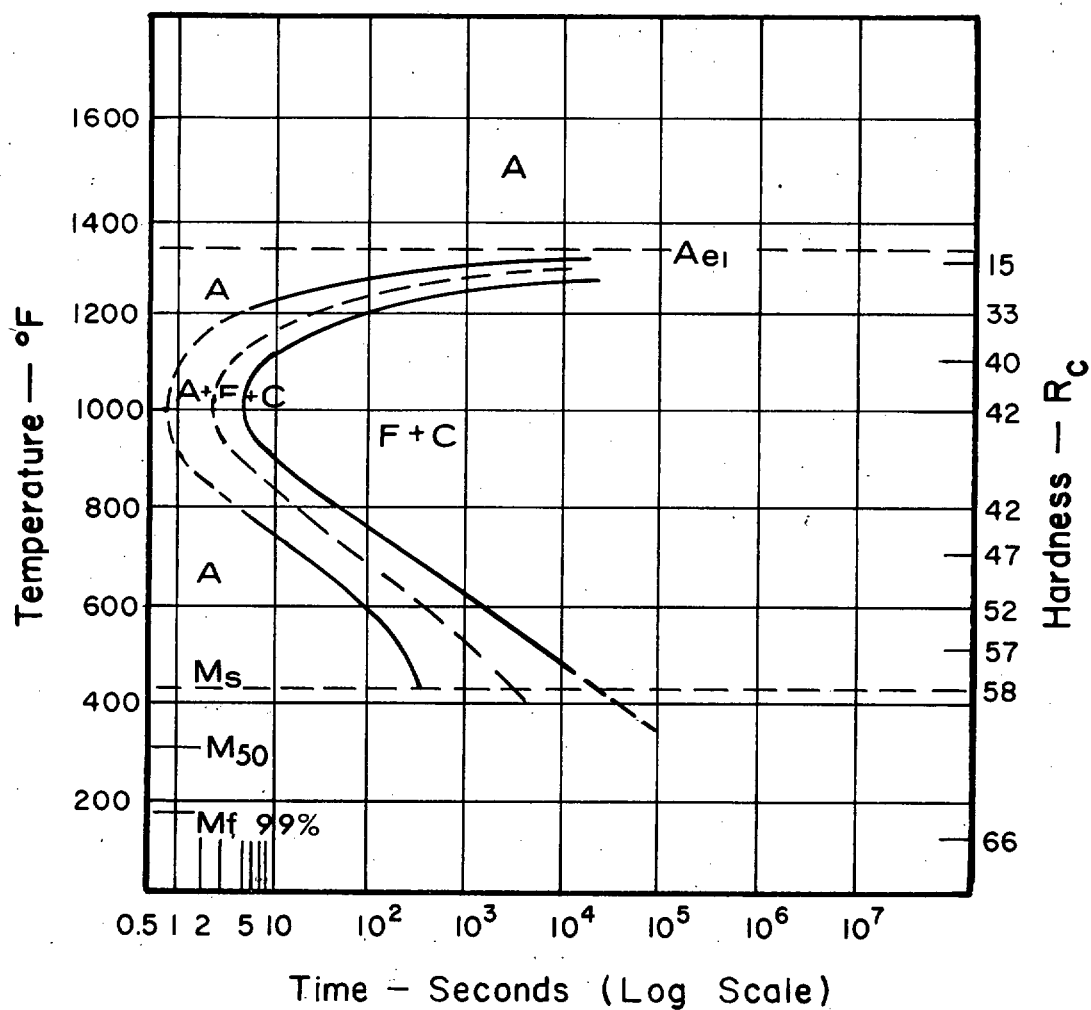
C = Carbide (Fe_3C) M_s = Martensite Start

FIGURE 10. The Isothermal Transformation Diagram of an Eutectoid Carbon Steel

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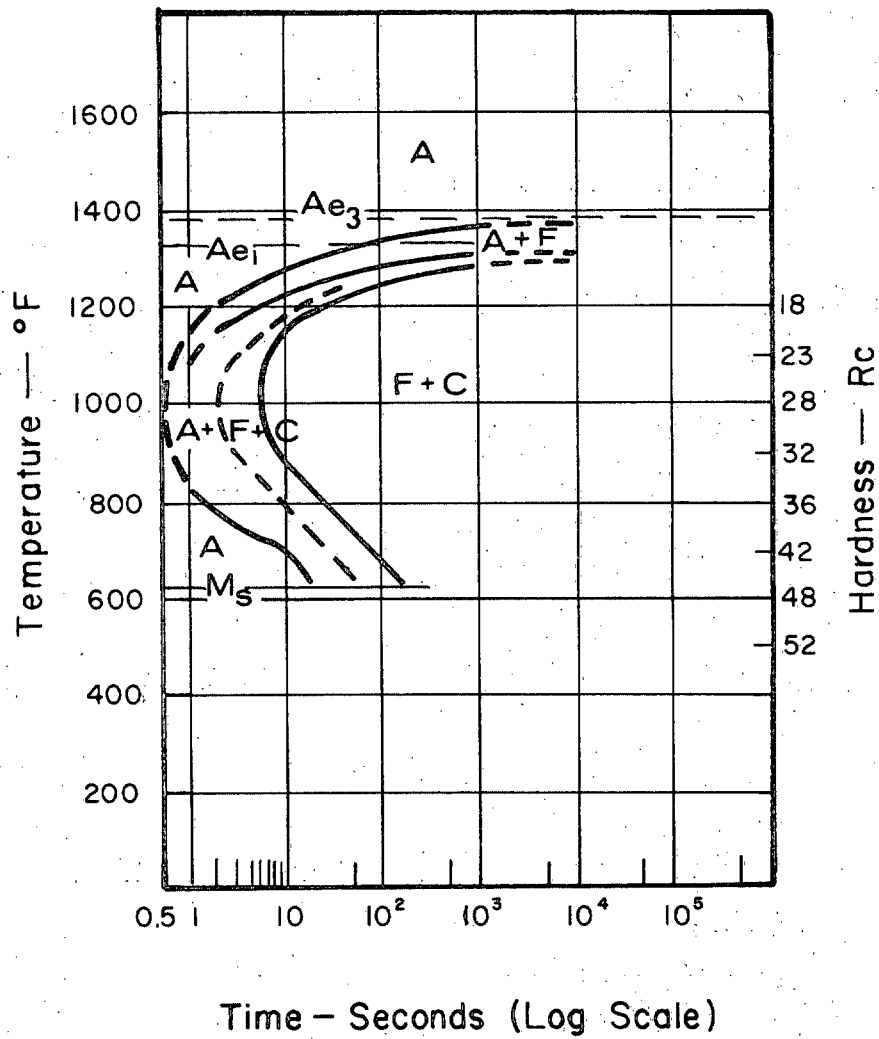


FIGURE 11. The Isothermal Transformation Diagram of a Hypoeutectoid Carbon Steel

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With decreasing temperatures, from A_{e1} down to about 1100°F the rate of nucleation and the rate of growth of pearlite colonies both increase. As a result, at lower transformation temperatures the spacing the pearlite lamellae becomes smaller and the metal becomes harder. Pearlite formed just below the A_{e1} temperature, at about 1300°F , is coarse pearlite with a lamellar spacing in the order of 10^{-3} mm and a hardness of about Rockwell C-15. The pearlite formed at about 1100°F is fine pearlite with a spacing in the order of 10^{-4} mm and a hardness of about Rockwell C-40. The fine pearlites formed at the lower transformation temperatures besides being harder than the coarse pearlites formed at higher temperatures are tougher and more ductile.

At temperatures near the low end of the pearlite transformation range another constituent forms from austenite. In plain carbon steels this constituent is formed only by isothermal transformation treatments and does not form when the steel is cooled continuously from above the critical temperature. The new constituent, known as bainite, forms from about 1050°F down to about 400°F . Steels transformed in the range where the bainite and pearlite transformation temperatures overlap have structures containing both pearlite and bainite. As the isothermal transformation temperatures are lowered, bainite becomes the predominant constituent and pearlite disappears. Like pearlite, bainite is a mixture of ferrite and cementite but the two phases are not arranged in lamellar form as in a pearlitic structure. The transformation of austenite to bainite is also considered to involve a process of nucleation and growth accompanied by carbon diffusion. Bainite apparently grows from a ferrite nucleus into a plate-like structure with each plate composed of a ferrite matrix in which carbide particles are embedded. Bainite, when viewed as a metallographic section, has a characteristic acicular (needlelike) appearance. Bainite formed at the higher temperatures in the transformation range has a feathery appearance and is commonly referred to as upper-bainite. The bainite that forms at lower temperatures assumes a more pronounced acicular structure identified as lower bainite.

As with pearlite, the hardness and toughness of bainite both increase as the temperature of

transformation is lowered. Pearlite is usually tougher than upper-bainite of similar hardness, while lower bainite will compare favorably with tempered martensite on the basis of toughness.

The transformations of austenite to pearlite or bainite are time and temperature dependent. By contrast the transformation of austenite to martensite is an athermal transformation, which means that the reaction is dependent primarily upon temperature and is essentially independent of time. The martensite transformation then is considerably different than the pearlite and bainite transformations. In the latter transformations, as indicated in Figure 10, neither pearlite nor bainite forms immediately upon reaching an isothermal reaction temperature. An incubation period is required before the transformation begins and the steel must be held at temperature for a sufficient period of time for the reaction to be completed. By contrast, when austenite reaches the M_s (martensite start) temperature the austenite begins to transform to martensite instantly. Further, if the steel is held at that temperature the small amount of martensite that is formed instantly is all that will form. Until the steel is cooled to a still lower temperature, the transformation is arrested.

At some temperature below the M_s temperature the transformation of austenite to martensite will be essentially completed. This temperature is identified as the M_f (martensite finish) temperature. At temperatures between M_s and M_f fractional transformation will occur. It is possible to quench a steel to, say, the temperature at which 50 percent of the austenite will transform to martensite and then isothermally transform the remaining austenite to lower bainite.

The transformation of austenite to martensite does not involve the diffusion of carbon. The instantaneous transformation of a small volume of austenite to form a martensite needle involves a shear displacement of the iron atoms in the austenite crystal lattice. The martensite thus formed has a body-centered tetragonal crystal structure. In this form it is identified as alpha martensite. Alpha martensite consists of ferrite and carbon (C) or finely divided iron-carbide (Fe_3C) in a metastable (unstable) structure which is considered to be a transitional structure between the

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face-centered cubic structure of austenite and the body-centered cubic structure of ferrite. The instantaneous athermal transformation of austenite to martensite at relatively low temperature does not allow the carbon atoms to diffuse out of the lattice and they remain in solution in the highly stressed transition lattice. The tetragonal crystal structure of alpha martensite transforms to the body-centered cubic structure, beta martensite, upon slight heating or long standing. Essentially the trapped carbon escapes or is thrown out of the crystal lattice allowing the stressed lattice to shrink down to the body-centered cubic structure.

Alpha martensite has an acicular structure similar to lower bainite. It is the hardest and most brittle of the microstructures that can be obtained in a given steel. The hardness of alpha martensite is a function of carbon content, ranging from a theoretical maximum of Rc 65 in eutectoid alloys to Rc 40 or less in low carbon steels.

Alpha martensite is usually tempered to increase its ductility and toughness although these changes are usually accomplished at the expense of hardness and strength. In tempering, the steel is heated to some temperature below the critical temperatures and cooled at a suitable rate. The microstructure and mechanical properties of tempered steel depend upon the temperature and duration of the tempering cycle. The carbide particles agglomerate, become progressively larger, as the tempering temperature and time at temperature are increased. Usually an increase in temperature and/or the time at temperature results in a lowering of the hardness and strength of a steel while its ductility and toughness are increased.

To develop a martensitic structure a steel must be austenitized and then cooled at a rate sufficient to prevent the formation of ferrite, pearlite or bainite. Most steels must be cooled very rapidly if the formation of pearlite is to be avoided. This fact is illustrated in Figure 9 which indicates that the transformation of austenite to pearlite begins in one second or less between the temperatures of 1100°F and 950°F. In this range, often referred to as the pearlite nose of the curve, the transformation is complete in less than ten seconds.

An isothermal transformation diagram shows the changes in microstructure that occur when a steel is cooled instantly to some reaction temperature and held at that temperature long enough for the reactions to go to completion. The diagram for a given steel shows what structure or structures are formed by isothermal transformation at any selected temperature, the time that the material must be at temperature before a reaction starts, and the time required to complete the reaction.

Fine grained austenite transforms to pearlite more rapidly than does coarser grained austenite. This is explained by the fact that as grain size decreases the proportion of grain boundary material to the total mass increases. As previously discussed, pearlite nucleates at the grain boundaries in homogeneous austenite. Consequently, transformation to pearlite begins more quickly and progresses faster in fine grained austenite than in coarse grained austenite.

Figures 10 and 11 illustrate the effect of carbon on the isothermal transformation reactions in plain carbon steels. For the steel with the higher carbon content (Figure 10) the transformations are shown to start later and to progress more slowly than do comparable reactions in the lower carbon steel (Figure 11). In effect, higher carbon content shifts the isothermal transformation curves to the right, that is, transformations start later and proceed more slowly as carbon content is increased.

Most of the common metallic alloying elements also tend to retard the start of isothermal transformations and to increase the length of time required to complete them.

Compared to isothermal transformations, transformations under continuous cooling take longer to start and begin at lower temperature. In effect, the isothermal transformation curve is shifted downward and to the right. This is illustrated by the reactions of a plain carbon steel of eutectoid composition. In actual practice, the steel can be fully hardened by cooling at a rate of 250°F per second. However, the isothermal diagrams for such steel, Figure 12, indicates that a cooling rate of at least 400°F per second is required to prevent the cooling rate curve from intersecting

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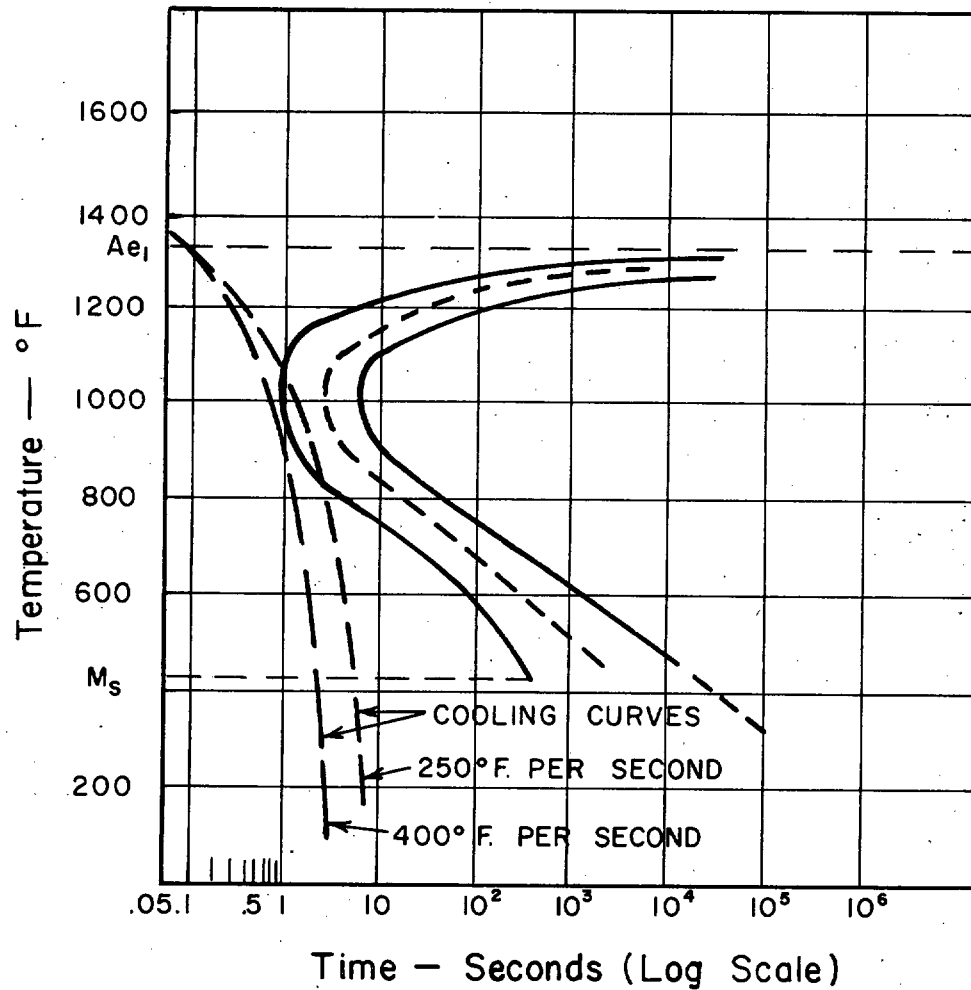


FIGURE 12. The Isothermal Transformation Diagram of an Eutectoid Carbon Steel with Cooling Curves Shown

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the transformation start curve at the pearlite knee. Theoretically, when the two curves intersect transformation to pearlite should begin and should continue until the cooling curve passes out of the pearlite field.

13. Hardenability. If a steel is to be hardened to a martensitic structure it must be austenitized and then cooled at a rate that is fast enough to prevent the formation of any of the other transformation products, such as, pearlite, ferrite or bainite. The slowest rate that avoids all other transformations is called the critical cooling rate for martensite. As would be expected, different steels have different critical cooling rates, in fact there is considerable variation in this respect.

Steel with relatively slow critical cooling rates are high hardenability steels, conversely, steels that must be cooled rapidly to obtain a martensitic structure are low-hardenability steels. Hardenability, then, is actually a measure of the capacity of a steel to transform to martensite, that is, to harden. Hardenability is also a measure of the depth to which a steel will transform to martensite, or harden, under given cooling conditions. Low hardenability steels respond to only a limited depth, and are called shallow hardening steels. With steels of high hardenability it is possible to harden thicker sections to greater depths.

The most common method of cooling a steel to obtain a martensitic structure is by quenching, that is, rapidly cooling the steel from above the critical temperature by immersion in some medium that is capable of cooling it at the required rate. The cooling rate is determined by the hardenability of the steel and the size of the piece being quenched. Brine, water, and oils are the most common quenching media, listed in the order of decreasing severity of quench:

In a piece of steel of any appreciable size the cooling rates at the surface and at the center are different. The difference in these rates increases with the severity of the quench. Low hardenability steels, because of this difference in cooling rates, respond, or harden, to only a limited depth when quenched. High hardenability steels harden to greater depths.

The most widely used hardenability test is the Jominy end-quench test. The popularity of this test is attributed to its convenience; only a single specimen is required and in one operation it is exposed to a range of cooling rates that vary from a rapid water quench at one end of the specimen to a slow air quench at the other end. The test specimen is a bar, four inches long and one-inch in diameter. It is heated to an austenitizing temperature and held at temperature long enough to develop a uniform austenite structure and then placed in a fixture and quenched. Quenching is accomplished by a gentle stream of water that is directed at and allowed to impinge on only one flat end of the specimen. The test bar is thereby subjected to a series of cooling rates which vary continuously from a rapid water quench at one end to a slow air cool at the other end. After quenching two flat surfaces are ground on the specimen. These are located 180° apart, run the full length of the specimen and the depth of grind is at least 0.015 inch. Starting at the quenched end, Rockwell C hardness measurements are taken at 1/16 inch intervals along the length of the bar for at least 2 1/2 inches. The results are plotted to show hardness versus distance from the quenched end.

The procedures for conducting the Jominy end-quench test are established in Federal Test Method Standard 151, Method 711. The Jominy end-quench hardenability test is the most generally accepted and widely used hardenability test yet developed. Its popularity led to the development of the "H" grade steels. These alloy steels are distinguished from the usual AISI-SAE grade designation by the suffix "H" to denote steels produced to a hardenability specification. For example, 4340 is the standard AISI-SAE grade designation for a nickel-chromium-molybdenum steel, while 4340H identifies the same steel produced to a hardenability specification.

Minimum and maximum end quench hardenability curves have been established for the "H" steels. The establishment of these curves, known as hardenability bands, permits the use of steel specifications in which hardenability tolerances are specified directly. In this type of steel specification, hardenability is established as the primary requirement, and chemical composition,

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grain size, etc., assume less importance and are not as stringently controlled as for standard steels.

The practical application of hardenability data to procurement specifications is of vital interest to the buyer of alloy steels. Federal Standard No. 66, "Steels: Chemical Composition and

Hardenability" gives the hardenability bands for the standard "H" steels and explains how these data can be used. ASTM specification A304, the SAE Handbook, and the ASM Metals Handbook, Volume 1, also present and explain the use of hardenability bands and other types of hardenability data.

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Chapter 3

Wrought Products

WROUGHT PRODUCTS

14. General. Steel making, from the reduction of iron-rich ores in a blast furnace to the casting of ingots, was discussed in Chapter 2. Steel in ingot form is usually a coarse-grained, heterogeneous, brittle material, and is in some cases quite porous. To convert the relatively brittle cast ingot material into a tougher, more ductile, wrought product the steel must be plastically deformed, or worked.

The production of finished wrought steel forms usually involves a sequence of operations that gradually convert the ingot into finished form, Figure 13. The working of metals is divided into two basic classifications, hot working, and cold working. Hot working is the plastic deformation of a metal at a temperature above the recrystallization temperature of the metal. Cold working is the plastic deformation of a metal at a temperature lower than the recrystallization temperature of the metal.

15. Hot Working. During hot working the individual grains in a piece of steel deform in much the same manner as the whole piece. That is, the grains tend to elongate in the same direction as the piece of steel elongates. At hot working temperatures, however, the deformed grains tend to break-up and re-form into new grains, a process known as recrystallization. The size of the new grains depends upon the temperature at which the steel is worked, with grain size increasing as temperature increases. Hot working also closes blow holes (porosity) and, if the surfaces are not oxidized, the pores will weld shut. Inclusions, such as oxides, sulfides, and other compounds are drawn out by

hot working to form stringers which align in the direction of principal deformation.

16. Cold Working. Cold working, as related to the production of wrought forms is usually accomplished by cold rolling or cold drawing. Cold rolling which results in only a slight reduction in the thickness of the steel, say 1 to 2 percent, is called temper rolling. With greater reductions, the operation is known as cold rolling or cold reduction. Cold working produces two effects; the surface of the steel is improved by comparison to hot worked material, and the ultimate and yield strengths of the steel are increased while ductility and toughness decrease. In effect the material strain hardens. Both effects are dependent upon the magnitude of the reduction during the cold working operation.

17. Wrought Forms.

a. General. The conversion of an ingot into a wrought form usually involves a series of operations. Because of the physical characteristics of ingot material the first operations are usually hot working operations conducted at relatively high temperatures, about 2200°F to 2350°F. For standard wrought forms, such as, plate, sheet, strip, structural shapes, bar, etc., the ingot is usually first rolled on a primary mill to convert it to a bloom, billet or slab. Rolling is a process of shaping materials by passing it between two rolls that are revolving in opposite directions at the same peripheral speed, Figure 14. The rolls are spaced so that the distance between them is less than the thickness of the material being worked, thus, in passing through the rolls the thickness of the

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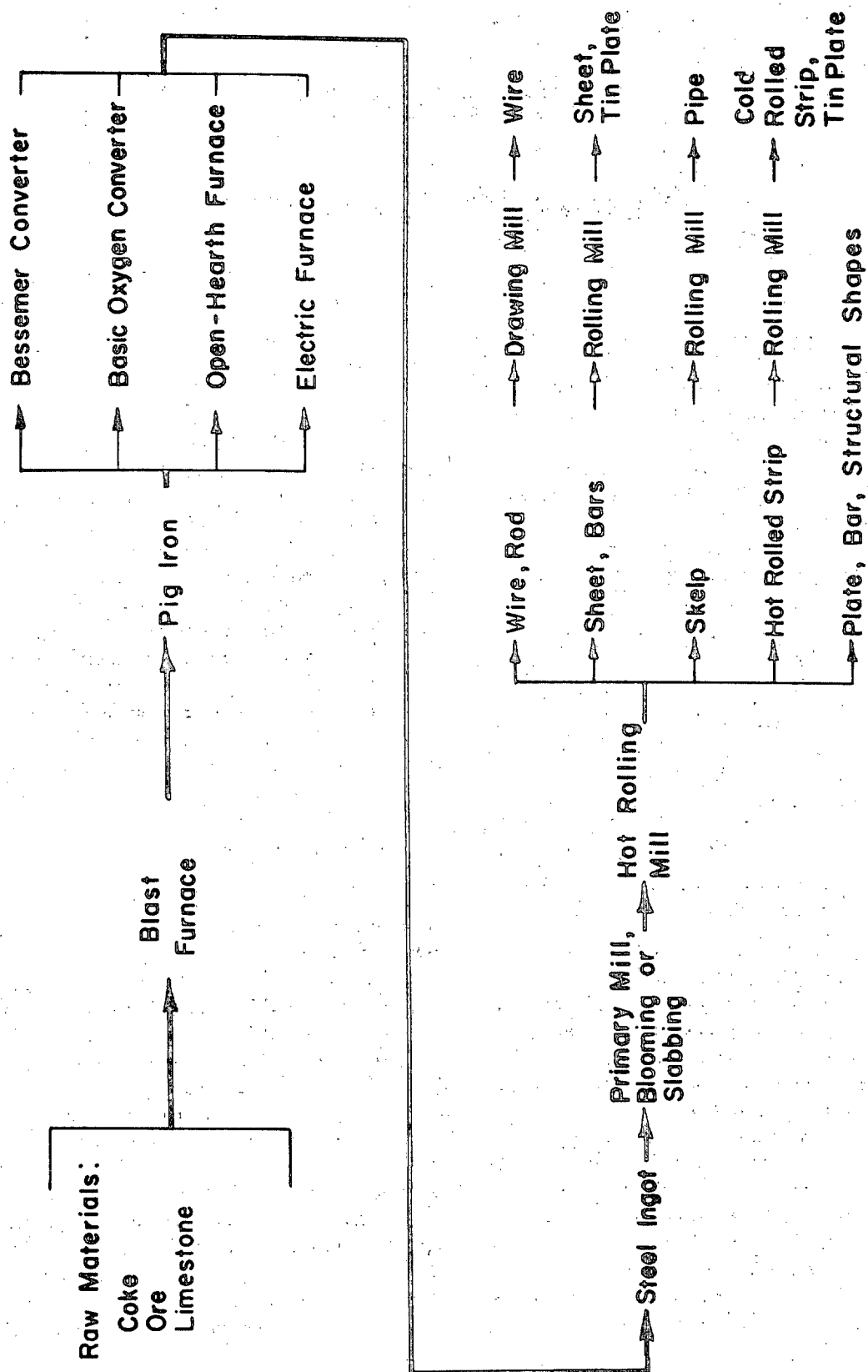
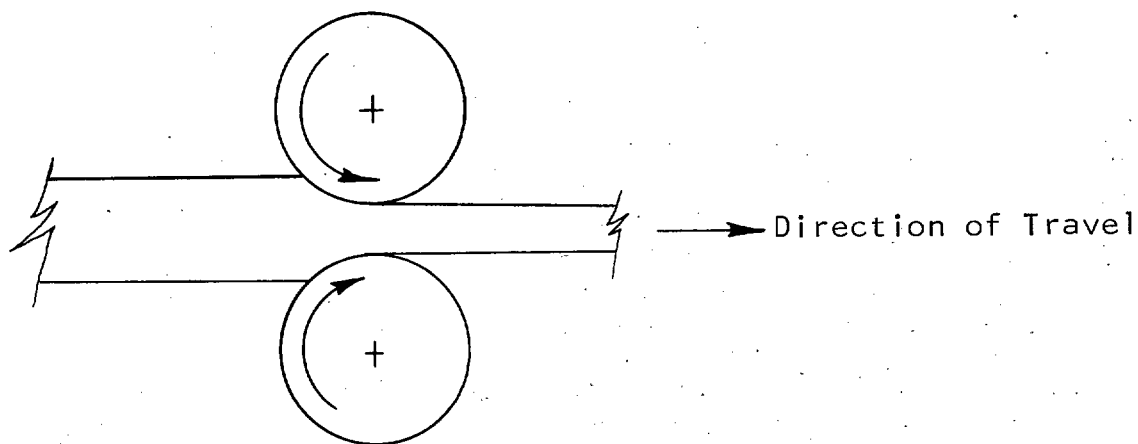


FIGURE 13. Flow Chart - Steel Wrought Products

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material is reduced. The ingot is gradually converted to a bloom, billet or slab by a series of operations or passes through the rolls. If necessary the ingot is turned between passes to develop the proper shape. The shapes produced on the primary mills are identified by size and geometry as follows:

(1) Billets are generally round or square with a minimum diameter or thickness of 1-1/2 inches. The cross sectional area of billets range from 2-1/4 sq. inches to 36 sq inches.

(2) Blooms usually have a square or rectangular cross-section. If rectangular, the width is limited to no greater than twice the thickness. The cross-sectional area is usually 36 sq inches or greater.

(3) Slabs have a rectangular cross-section with a width greater than twice the thickness. The minimum thickness of slabs is 2 inches and the minimum cross-sectional area is 16 sq inches.

It is possible to roll ingots directly through the bloom, slab, or billet stage into finished steel products in one continuous operation. Usually, however, the blooms, billets, or slabs

are cooled, and stored for some period of time between the primary and subsequent operations.

During this period the products are inspected and surface defects are removed by machining or other methods to condition the material for further processing.

Ingots may be converted directly to wrought products by forging. Forging is discussed later in the chapter and the present discussion will be limited to wrought forms produced by rolling.

Finished rolled wrought forms can be classed as flat rolled products and shapes. Flat rolled products are formed between smooth rolls. Rolls with grooved surfaces are used to produce shapes. Flat rolled products include plate, sheet, strip, and bar. These products characteristically have a high width to thickness ratio.

Finished flat rolled steel products are divided into two major categories, hot rolled products and cold rolled products. Hot rolled products are rolled to final thickness at elevated temperatures, usually above 1300°F. Cold rolled products are actually only cold finished since the ingot is reduced to nearly the final thickness by hot rolling and only the final reduction or reductions are accomplished by cold rolling.

MIL-HDBK-723A**30 NOVEMBER 1970****b. Available forms.**

(1) General. Following are brief descriptions of the basic wrought forms in which carbon and alloy steels are available. When applicable, general size ranges are listed but there is no attempt to define standard sizes, conditions, and tolerances for the various forms. This information was deliberately omitted because:

(a) When standard sizes are listed the erroneous inference is often drawn that all alloys are available in all sizes at all times and in limitless quantity. Because such conditions do not exist standard size data are actually of academic interest rather than of practical value.

(b) Standard sizes, tolerances, and other related information are included in available publications, including but not limited to the following: Bulletin R22-46, National Bureau of Standards; Steel Products Manual, American Iron and Steel Institute; Federal Standard 48; SAE Handbook; and the specifications and standards listed in Chapter 5.

(c) The producers and suppliers of steel products should be consulted regarding the availability of wrought products. They are the most valid source of information regarding wrought products and the sizes, finishes, and compositions in which each is available. The sizes of the various commodities that are produced and stocked vary with demand and the stock lists and data sheets provided by the producers and suppliers are periodically revised to reflect the ever changing conditions.

(2) Plate. Plates are hot rolled, flat finished steel products that are rolled either directly from ingots or from reheated slabs. In terms of thickness and width, carbon and alloy steel plate is defined as follows:

<u>Width (inches)</u>	<u>Thickness (inch)</u>
Over 8 to 48 inclusive	0.2300 and thicker
48 and over	0.1800 and thicker

(3) Hot Rolled Bars. Hot rolled carbon and alloy steel bars are rolled in a variety of sections such as rounds, squares, round cornered

squares, flats, spring flats, hexagons, octagons, and special bar shapes (angles, channels, tees, zeos, with a maximum sectional diameter of 3 inches or less).

The general size limits for hot rolled carbon and alloy steel bar are as follows:

Rounds, 1/4" to 8-1/2", inclusive;

Squares, 1/4" to 5-1/2", inclusive;

Round cornered squares, 3/8" to 8", inclusive;

Hexagons, 1/4" to 4-1/16", inclusive;

Flats, 13/64" and over in specified thickness, and up to 6", inclusive, in specified width;

Flats, 0.230" and over in specified thickness, over 6" to 8", inclusive, in specified width;

Bar size shapes, including angles, channels, tees and zeos when their greatest sectional diameter is less than 3";

Ovals, half-ovals and half-rounds;

Special bar sections.

(4) Cold Finished Bars. Cold finished carbon and alloy steel bars are produced from hot rolled steel by several cold finishing processes. Cold finishing improves the surface finish, dimensional accuracy and alignment of the bars. Cold finishing processes, which can be used singly or in combination, include cold drawing, cold rolling, turning, grinding, straightening and polishing. Bars produced by cold finishing are generally restricted to rounds, squares, flats, and hexagons.

Cold rolling was discussed previously but cold drawing was not. Cold drawing is a process that consists essentially of pulling a hot rolled bar through an opening in a die. The die opening is similar in shape to the cross-section of the bar but of smaller size, thus the section size of the hot rolled bar is reduced by the drawing operation. Before drawing the bars are descaled, washed in clear water, and dipped in a hot lime solution which retards rusting and aids lubrication.

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Turning and polishing is a cold finishing operation by which hot rolled round bars are reduced to the desired size by turning in a lathe, or a special purpose turning machine, and finished by polishing. The rough surface metal is removed and a bright, smooth, surface is produced by the polishing operation. The sizes of bars made by this operation generally range from 3/4 inch to 9 inches.

Other processes used on hot rolled rounds are turning, grinding, and polishing. Except that the bar is ground before it is polished there is little difference between this operation and the turning and polishing operation. Bars made by turning, grinding, and polishing range from 3/4 inch to 9 inches.

For small diameter bars a high quality surface is produced by a combination of cold drawing, centerless grinding and polishing operations performed in the sequence indicated. Bars up to 1-15/16 inch diameter can be made in this manner.

(5) Hot Rolled and Cold Rolled Sheet and Strip. The distinction between hot rolled and cold rolled sheet and strip lies in the methods used to attain the finished thickness. The cold rolled commodities develop superior surface finishes. Size ranges are indicated in the following tables:

Hot Rolled Carbon Steel Sheets

Thickness (inch)	Width (inches)
0.2299 to 0.1800	12 to 48 inclusive
0.1799 to 0.0449	over 12

Cold Rolled Carbon Steel Sheets

Thickness (inch)	Width (inches)
0.0142 and up	over 12
0.0142 to 0.0821 incl.	over 2

Hot Rolled High Strength Low Alloy Steel Sheets

Thickness (inch)	Width (inches)
0.2299 to 0.1800 incl.	12 to 48 inclusive
0.1799 to 0.0710 incl.	over 12

Cold Rolled High Strength Low Alloy Steel Sheets

Thickness (inch)	Width (inches)
0.0142 to 0.0821 incl.	2 to 12 inclusive
0.0142 and thicker	over 2

Hot and Cold Rolled Alloy Sheets

Thickness (inch)	Width (inches)
0.2299 and thinner	24 to 48 inclusive
0.1799 and thinner	over 48

Hot Rolled Carbon Steel Strip

Thickness (inch)	Width (inches)
0.0255 to 0.2030 incl.	to 3-1/2 incl.
0.0344 to 0.2030 incl.	over 3-1/2 to 6 incl.
0.0449 to 0.2299 incl.	over 6 to 12 incl.

**Cold Rolled Carbon Steel Strip
(0.75% carbon maximum)**

Thickness (inch)	Width (inches)
0.2499 and thinner	over 1/2 to 23-15/16 incl.

Hot Rolled High Strength Low Alloy Steel Strip

Thickness (inch)	Width (inches)
0.0255 to 0.2030 incl.	to 3-1/2 incl.
0.0344 to 0.2030 incl.	over 3-1/2 to 6 incl.
0.0499 to 0.2299 incl.	over 6 to 12 incl.

Cold Rolled High Strength Low Alloy Steel Strip

Thickness (inch)	Width (inches)
0.2499 and thinner	1/2 to 12
0.2499 and thinner	12 to 23-15/16 when a special edge or special finish is specified

Hot Rolled Alloy Steel Strip

Thickness (inch)	Width (inches)
0.2030 and thinner	to 6 incl.
0.2299 and thinner	over 6 to 23-15/16 incl.

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Thickness (inch)	Width (inches)
0.2499 and under	to 23-15/16 incl.

(6) Structural Shapes. Structural shapes is the general term applied to rolled flanged sections used in the construction of bridges, buildings, ships, railroad rolling stock, and for numerous other constructional purposes. They are designated as wide flange sections, beams, channels, angles, tees, zees, and include center sills, bulb angles and miscellaneous sections for carbuilding.

Angles, channels, tees and zees are classified as structural shapes only when their greatest sectional dimension is 3 inches or more. Smaller sizes are classified as bar shapes.

The method of designating the size of structural sections is as follows:

Wide-flange sections: by depth, width across flange, and weight per foot, in that order.

Beams and Channels: by depth of section and weight per foot.

Angles: by length of legs and thickness in fractions of an inch; or by length of legs and weight per foot. The longer leg of an unequal angle is commonly stated first.

Tees: by width of flange, overall depth of stem, and weight per foot, in that order.

Zees: by depth, width of flanges and thickness in fractions of an inch; or by depth, flange width and weight per foot.

Size designations have been listed by the U. S. Department of Commerce Simplified Practice Recommendation R216-46 covering Hot Rolled Carbon Steel Structural Shapes. Another excellent reference is the Steel Construction Manual of the American Institute of Steel Construction.

(7) Miscellaneous Flat Forms. Carbon steel is also available in flat rolled form with various coatings, for example; galvanized sheet and strip (zinc coated); tin plate (tin coated); and

long terre and short terre sheets and plate (coated with a lead-tin alloy).

(8) Wire. Carbon and alloy steels are, in some compositions, available in the form of wire. Wire is not restricted to a round cross section, it is in addition produced in many common shapes, such as, square, hexagon, octagon, oval, half-oval, triangular, and flat. Wire is drawn from hot rolled rod. The size limits for wire range from 0.001 inch to 4 inches diameter for round wire and from a few thousandths of an inch of thickness to 3-1/2 inches for square, hexagonal, and octagonal wire.

(9) Tubular Products. Steel is also available in a wide variety of tubular forms, such as, standard pipe, aircraft quality tubes, conduit pipe, and tubular poles, to name a few classifications. Tubular products are classified as welded and seamless, according to the methods of manufacture.

HEAT TREATMENT OF STEEL

18. General. The predictable changes to the microstructure that can be effected by heating and cooling solid steel at selected rates under controlled conditions is the basis for the heat treatment of steel. In Chapter 2 the theory of heat treatment was introduced during the study of equilibrium and isothermal transformation diagrams. Some of the practical aspects of steel heat treatment are introduced in the following discussions of annealing, normalizing, quench and tempering, martempering, and austempering.

19. Annealing.

a. General. Steel is annealed for various reasons, i.e., to reduce the hardness, to relieve stresses, to develop a particular microstructure and associated physical and mechanical properties, and to improve machinability and formability. To accomplish these purposes various procedures are used, each of which is identified by a descriptive term, such as, full annealing, isothermal annealing, and process annealing. Unless the term is qualified, annealing when applied to steel implies full annealing.

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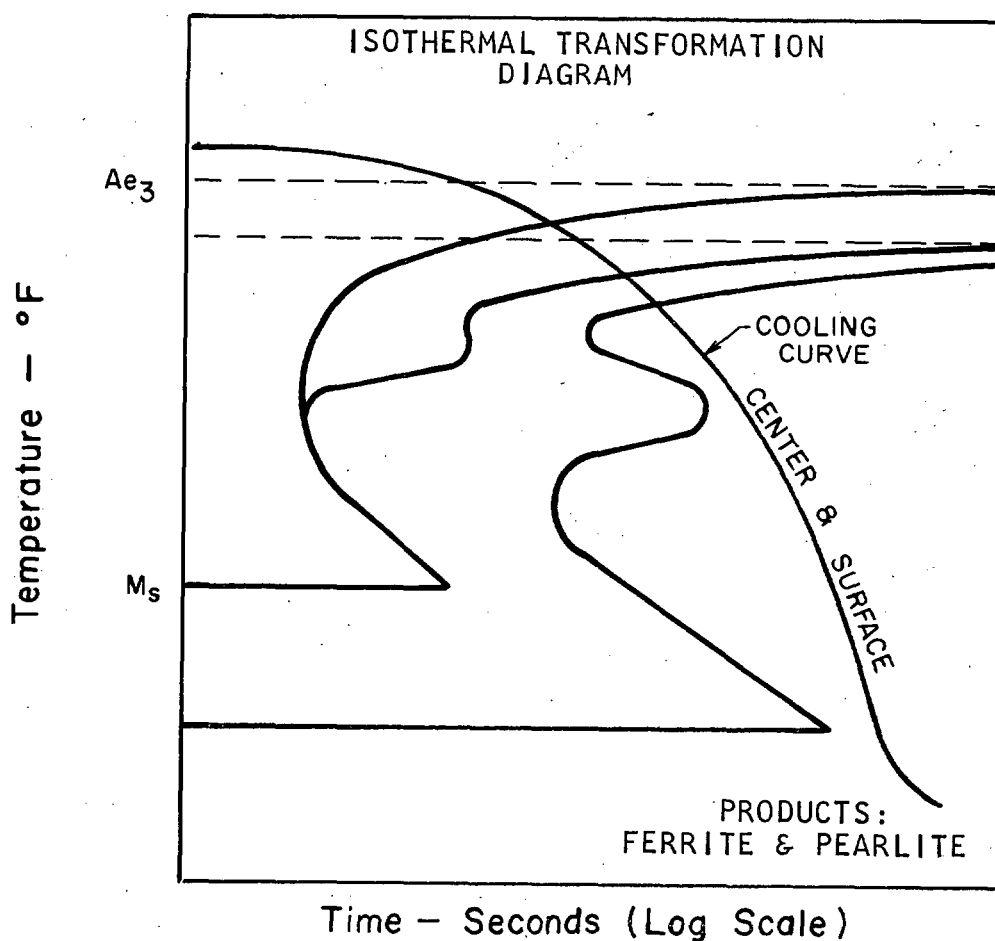


FIGURE 15. Schematic Representation of the Full Annealing Cycle

b. Full annealing. Full annealing is a relatively simple heat treatment. The steel is heated to a temperature above the A_{c3} critical temperature and held at temperature long enough to allow the solution of carbon and other alloying elements in the austenite. The steel is cooled from the annealing temperature at a slow rate so that the transformation is completed in the high temperature region of the pearlite range. This process is shown schematically in Figure 15.

Full annealing produces a structure of relatively soft coarse pearlite. Depending upon the composition of the steel, ferrite or carbide may also be present.

Full annealing is a simple process but it is also a slow process. The steel must be cooled very slowly from the annealing (austenitizing) temperature to a temperature below that at which the transformation is completed.

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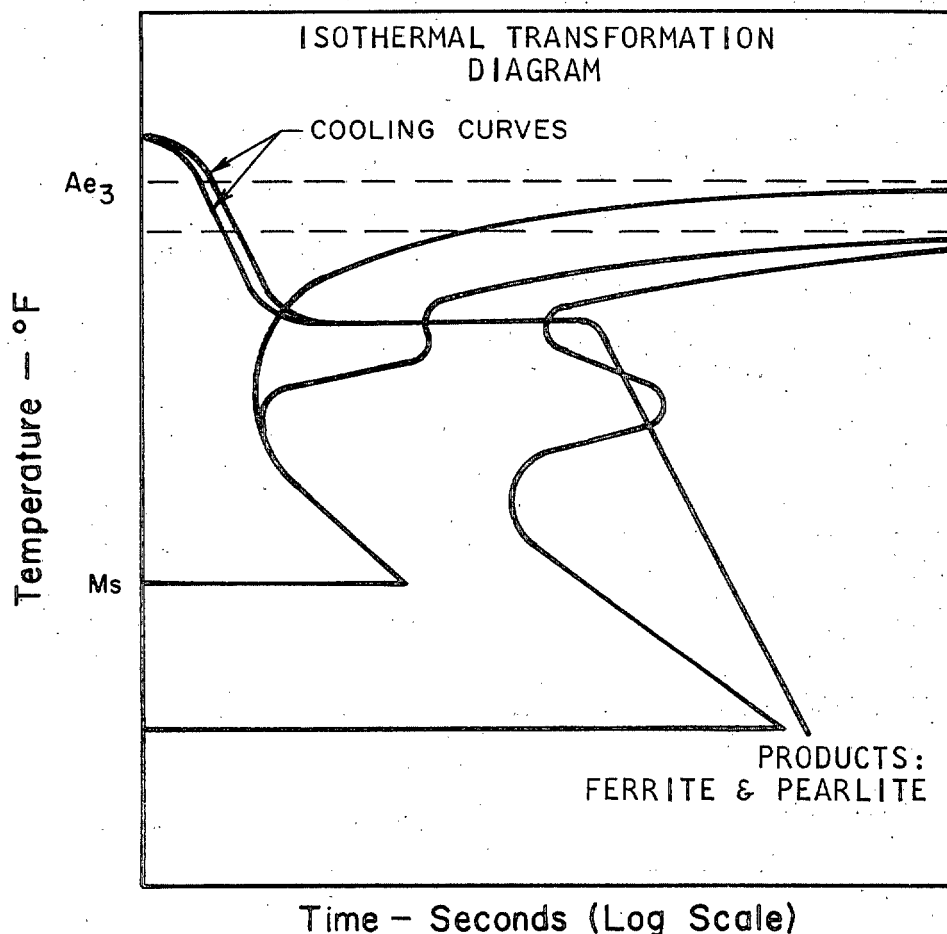


FIGURE 16. Schematic Representation of the Isothermal Annealing Cycle

c. *Isothermal annealing.* Annealing to a coarse pearlitic microstructure can be accomplished by cooling steel from the austenitizing temperature to the proper temperature for the transformation to occur. It is held at that temperature until the transformation is completed. This process is depicted in Figure 16.

d. *Spheroidize annealing.* Steels may be heated and cooled to produce a structure of globular carbides in a ferrite matrix (a spheroidized structure) by various procedures. One such method consists of holding the steel at a temperature just below the A_{e1} (holding between A_{c1} and A_{c3} for at least part of the time is

generally involved). To achieve full spheroidization of the carbides by this method the steel usually must be held at temperature for long periods of time. Heating and cooling the steel alternately to temperatures slightly above and slightly below the A_{e1} temperature will also produce a spheroidized structure. Also, if the carbide is not completely dissolved during austenitizing and the steel is slowly cooled in a manner similar to full annealing, or if it is isothermally treated as in isothermal annealing, a spheroidized structure can be developed. A spheroidized structure is sometimes desirable to develop minimum hardness and maximum ductility to facilitate forming, or, in high carbon

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steels, to improve the machining characteristics of the steel.

e. Process annealing. The annealing of cold worked steel to restore its ductility and to reduce its hardness by recrystallization at subcritical (below A_{c1}) temperatures is called process annealing. Process annealing consists of heating steel to some temperature below, and usually near, A_{c1} , holding it at temperature for an appropriate time after which it is slowly cooled, usually in air.

20. Normalizing. Normalizing is that process of heat treatment which consists of reheating steel above its critical temperature and then cooling it in air. Steels are normalized for two basic purposes, to refine the grain, and to develop a more uniform microstructure. It is used as a preliminary treatment to quenching and tempering to develop a more uniform microstructure and facilitate the solution of carbides and alloying elements. Normalizing is also used when the as-normalized properties are those desired in the finished part, in which case normalizing is the final treatment. When necessary, normalizing can be followed by tempering, usually at 1000°F to 1300°F, to reduce hardness and to improve toughness.

21. Hardening by Quenching and Tempering.

a. General. Hardening by quenching and tempering is the heat treatment commonly used to develop martensitic structures with the desired combination of toughness and strength. The process is divided into three separate operations; heating, quenching, and tempering.

b. Austenitizing. The first step in the hardening process is to austenitize the steel by heating it to a temperature above the critical range. The material should be held at temperature long enough for the carbon and other alloying elements to dissolve but not long enough for excessive grain growth to occur.

c. Quenching. Quenching is the rapid cooling of the steel from the austenitizing temperature to a temperature below the M_s (Martensite start) temperature. The cooling rate must be rapid enough to prevent the formation of other

transformation products such as pearlite, bainite, ferrite or cementite. Common quenching media include oils, water, brine, and forced air. The choice of cooling medium is dependent upon the desired cooling rate which is determined by the composition (hardenability) of the steel, and the size and shape of the section being quenched. Quenching sets up high thermal and transformation stresses which may cause distortion and cracking of the part. Consequently it is usually desirable to keep these stresses at a minimum by cooling at a rate that is just slightly faster than the critical cooling rate as determined by the hardenability of the steel and the size and shape of the piece being quenched.

Brine quenching is the most severe, followed in order by water and oil quenching. Agitation of the quenching medium is important because it produces more uniform cooling and accelerates the rate of cooling.

d. Tempering. Tempering is the name applied to the process of heating quench hardened or normalized steel to a temperature below the transformation range, holding it at temperature for a suitable time and cooling it at an appropriate rate. The martensite formed on quenching is very hard, brittle and highly stressed. Tempering is employed to relieve these stresses and to improve the ductility of the steel, usually at the expense of strength and hardness. The stress relief, and the recovery of ductility are brought about by the precipitation of carbide from the supersaturated unstable alpha martensite and through diffusion and coalescence of the carbide as tempering proceeds.

Tempering is usually carried out at temperature between 350°F and 1300°F and the usual time at temperature ranges from 30 minutes to 4 hours. For many carbon and low alloy steels ductility and toughness increases upon tempering at temperatures up to 400°F. In the approximate temperature range of 450°F to 700°F notch toughness decreases as tempering temperatures are increased, consequently quench hardened steels are rarely tempered in that temperature range. Tempering in the range of 200°F to 400°F is used when it is important to retain

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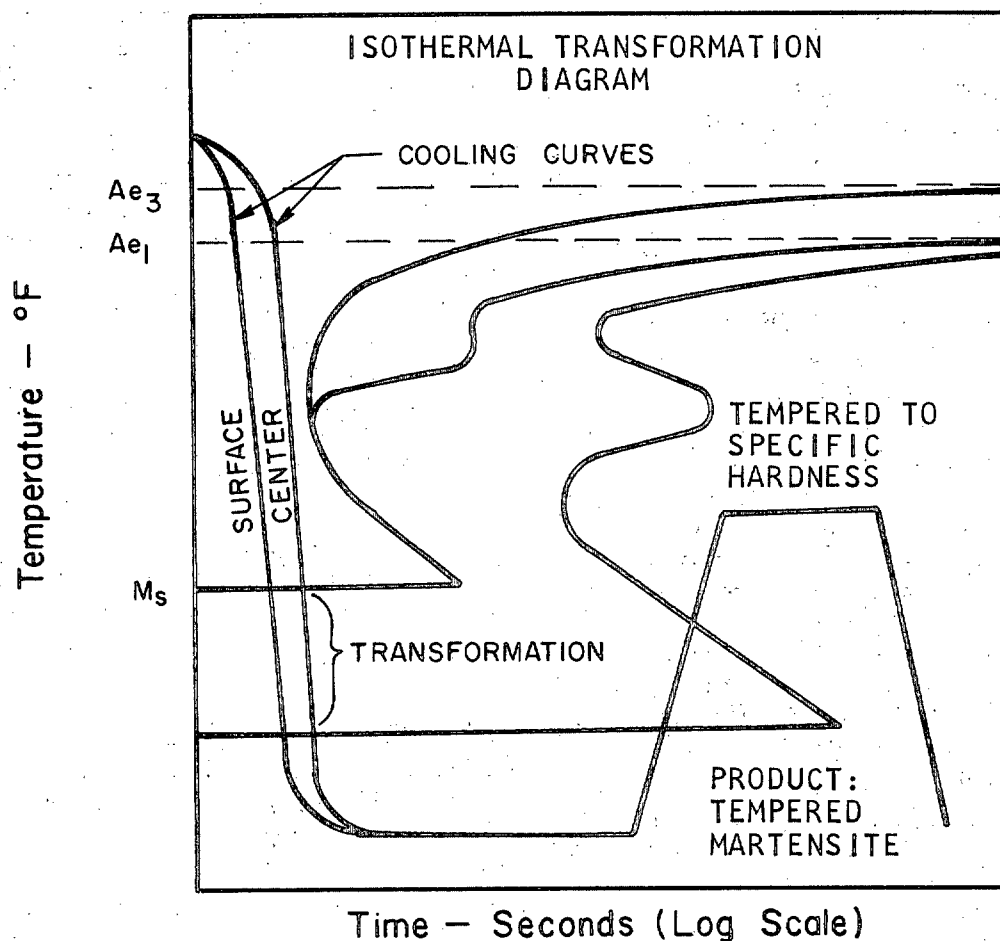


FIGURE 17. Schematic Representation of the Quench and Temper Cycle

hardness and strength and effect a modest improvement in toughness. In the higher temperature range of 700°F to 1250°F tempering causes an appreciable increase in toughness and ductility of the steel and a simultaneous decrease in hardness and strength.

As discussed in Chapter 2, the maximum as-quenched hardness of a steel is primarily dependent upon carbon content regardless of what other alloying elements are included in the composition. Steels with the same carbon content but with otherwise different compositions temper at different rates and the tempering

cycles must be adjusted accordingly. The tempering procedure for a fully hardened steel can be varied, within limits, to develop different combinations of hardness and toughness.

22. Heat Treatment of Selected Steels. The conventional quench and tempering process is shown schematically in Figure 17. Military Specification Mil-H-6875, "Heat Treatment of Steels (Aircraft Practice, Process for)" establishes heat treating practices for selected steels commonly used in construction of aircraft and missiles. The processes covered by this specification are: normalizing, annealing (full), process annealing (stress-relieving),

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hardening by quenching, and tempering. In addition to specifying temperatures or temperature ranges for the various heat treatments for each alloy, the specification establishes requirements for equipment, operating and test procedures, and certification of equipment.

ASM Metals Handbook, Volume II, "Heat Treating, Cleaning, and Finishing" gives particulars for the heat treatment of many carbon and low alloy steels. In addition to temperature data the Metals Handbook provides comprehensive coverage of the practical aspects of heat treating steels. The SAE Handbook and other sources listed in the bibliography also provide specific information regarding the heat treatment of the various carbon and low alloy steels.

Tables I through V, give representative heat treatment temperatures for selected steels. The data presented in these tables are for general cases and the temperatures and times listed can, and should be adjusted to compensate for differences in equipment, chemical composition, the size and shape of the parts being treated, and other variables. The data presented in these tables are intended only as examples of the heat treatments applicable to the selected steels. These tables should not be used to establish heat treatment processes for the steels listed. Specification Mil-H-6875 and other approved references, or preferably, a Materials Engineering organization should be consulted for that purpose.

TABLE I. STRESS RELIEF TEMPERATURES

Material	Stress Relief Temperature (°F)	Soak Time at Temperature
Low-Alloy Steels (after heat treat at 150 to 180,000 psi)	700 ± 25	1 hr*

*Allow 1 hr per in. of cross section for heatup time.

TABLE II. ANNEALING CYCLE FOR LOW-CARBON AND LOW-ALLOY STEELS

Material	Alloy	Annealing Temperature (°F)	Furnace Cooling Cycle at 50°F/hr* From (°F) To	Soak Time (hr)	Heatup Time
Low-Carbon	1018	1575 to 1650	1575 1300	1 hr for sections to 1 in. thick. Add 1/2 hr for each additional 1 in. of thickness.	1 hr per in. of material thickness.
	1020	1575 to 1650	1575 1290		
	1025	1575 to 1650	1575 1290		
	1030	1550 to 1625	1550 1200		
	1035	1550 to 1625	1550 1200		
Low-Alloy	4130	1450 to 1550	1450 900	1 in. of thickness.	
	4140	1450 to 1550	1450 900		
	4340	1450 to 1550	1450 900		
	5150	1500 to 1600	1500 900		
	6150	1550 to 1650	1550 1000		

*After reaching the lower temperature, the rate of cooling is unimportant.

MIL-HDBK-723A**30 NOVEMBER 1970****TABLE III. NORMALIZING CYCLE FOR LOW-CARBON AND LOW-ALLOY STEELS**

Material	Alloy	Normalizing Temperature (°F)	Soak Time (hr)	Heatup Time
Low-Carbon	1015	1650 to 1700	1 hr for sections to 1 in. thick. Add 1/2 hr for each additional 1 in. of thickness.	1 hr per in. of material thickness.
	1020	1650 to 1700		
	1025	1625 to 1675		
	1030	1625 to 1675		
	1035	1600 to 1650		
Low-Alloy	4130	1600 to 1750		
	4140	1550 to 1700		
	4340	1550 to 1700		
	5150	1550 to 1700		
	6150	1600 to 1750		

TABLE IV. AUSTENITIZING CYCLE FOR LOW-CARBON AND LOW-ALLOY STEELS

Material	Alloy	Austenitizing Temperature (°F)	Soak Time		Heatup Time
			Thickness (in.)	Time (hr)	
Low-Carbon*	1025	1575 to 1650	1/2 or less	1/4	1 hr per in. of material thickness.
	1030	1550 to 1600	1	1/3	
	1035	1525 to 1575	2	1/2	
Low-Alloy	4130	1500 to 1600	3	3/4	
	4140	1550 to 1600	4	1-1/4	
	4340	1500 to 1550	5	1-1/2	
	5150	1475 to 1550			
	6150	1550 to 1625			

*The amount of strengthening by austenitizing and quenching is insignificant.

TABLE V. TEMPERING CYCLE FOR LOW-ALLOY STEELS

Alloy	Tempering Temperature (°F)				
	125,000 psi	150,000 psi	180,000 psi	Soak Time	Heatup Time
4130	950 to 1150	800 to 1000	700 to 900	1 hr per in. of material thickness	1 hr per in. of material thickness
4140	1050 to 1250	950 to 1150	800 to 1000		
4340	1075 to 1225	975 to 1075	850 to 975		

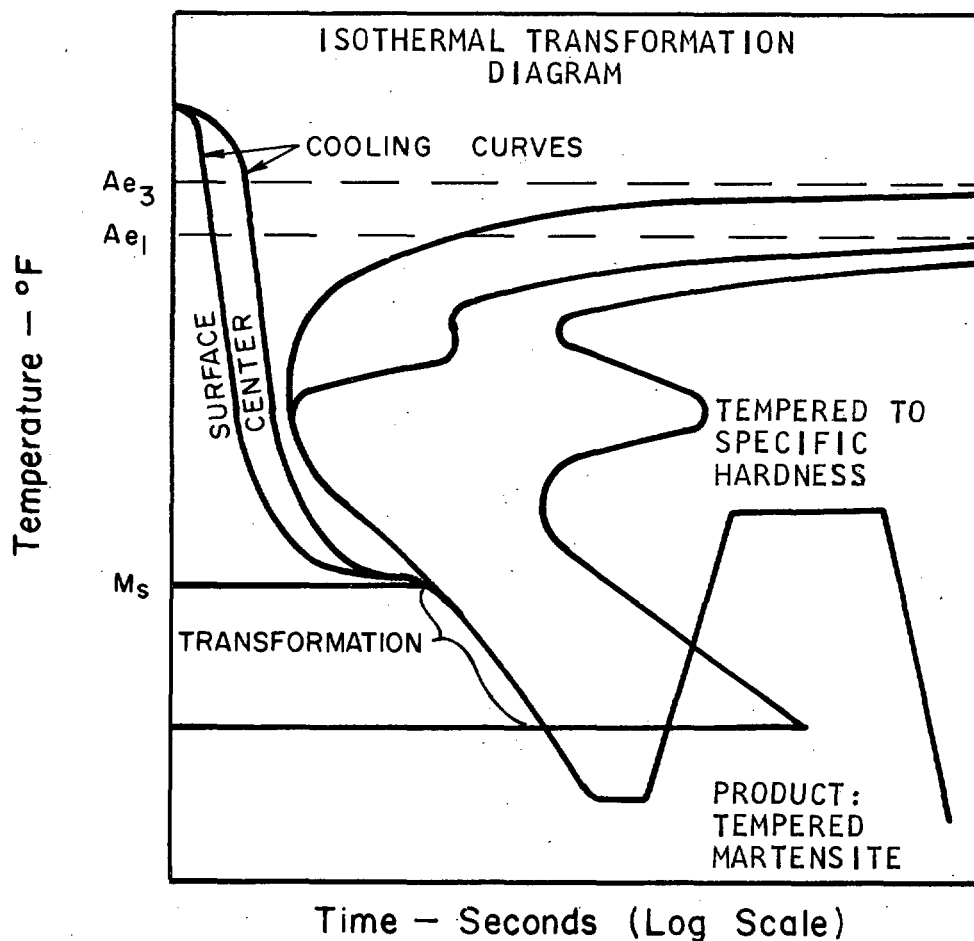


FIGURE 18. Schematic Representation of the Martempering Cycle

23. Controlled Atmospheres. Controlled atmospheres are often used to protect the surfaces of steel parts during heat treatment. Unless such precautions are taken, scaling, carburization, or decarburization may result. Scaling, or oxidation, mars the surface, represents a loss of metal, and may affect the cooling rate when the part is quenched. Carburization is the addition of carbon to the surface material by heating it in contact with a carbonaceous material. Decarburization is the loss of carbon from the surface of the part as a result of heating the part in contact with some medium that reacts

with carbon. Decarburization results in a soft surface and can seriously affect the fatigue life of a steel part.

Controlled atmospheres are generally used when temperatures exceed 1200°F. The temperature, time at temperature, and the carbon content of the steel are important factors which must be considered in selecting an atmosphere for a given application. Various atmospheres are used depending upon the material, the treatment, available equipment, and the disposition of the parts after heat treatment. Parts that are machined after heat treatment to a

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depth sufficient to remove the affected material usually do not need to be heat treated in a controlled atmosphere.

24. Martempering. The transformation of austenite to martensite during rapid cooling of a steel through the martensite transformation range produces high stresses and can cause distortion and cracking. Martempering is a process that is useful in reducing these high stresses. It is an interrupted quenching process in which a steel is quenched from the austenitizing temperature into hot oil or a molten salt bath at a temperature near, but slightly above, the M_s temperature of the alloy, Figure 18. The steel is held in the quenching medium long enough for its temperature to stabilize, after which time it is removed and allowed to cool slowly in air.

The transformation of austenite to martensite occurs during the period when the steel is cooling slowly in air. Because of the slow cooling rate a relatively uniform temperature is maintained throughout the mass of the steel, and the severe thermal gradients that are characteristic of conventional quenching are not developed. Consequently, martensite forms at a uniform rate throughout the piece and the stresses developed during transformation are much lower than for conventional quenching. The lower stresses developed by martempering in turn lessen the distortion of the treated part.

Martempering is usually reserved for steels of medium hardenability such as those that are conventionally hardened by oil quenching. A modified martempering process can also be used to advantage. It consists of quenching from the austenitizing temperature to a temperature slightly below the M_s . The higher cooling rates obtained by the lower temperature quench in effect allows the treatment of steels of lower hardenability than can be treated by the standard martempering process.

25. Austempering. Austempering is the name applied to the heat treatment whereby austenite is transformed isothermally to lower bainite, Figure 19. Lower bainite, as mentioned in

Chapter 2, compares favorably to tempered martensite with respect to strength and hardness, and for a comparable hardness, exhibits superior ductility. Austempering is an alternate method of heat treating steels to develop high strength and hardness in combination with good ductility and toughness.

The austempering process consists of:

- a. Heating the steel to a temperature within its austenitizing range.
- b. Quenching the steel in a constant temperature bath at the desired transformation temperature in the lower bainite region.
- c. Holding the steel in the bath for a sufficient period of time to allow the austenite to transform isothermally to bainite.
- d. Cooling the steel to room temperature in still air.

Austempering is an isothermal transformation process carried out at relatively high temperatures so that, compared to conventional quenching, transformation stresses are reduced, and distortion is minimized. Austempering is usually substituted for conventional quenching and tempering to obtain higher ductility or notch toughness at a given hardness, and/or to decrease the distortion and cracking associated with normal quenching.

26. Surface Hardening of Steel.

a. General. In many industrial applications it is necessary to develop a high surface hardness on a steel part so that it can resist wear and abrasion. This can be done by hardening a high carbon steel; however, the high hardness is then accompanied by low ductility and toughness. In many applications the poor ductility and toughness cannot be tolerated throughout the entire part and another solution to the problem must be found.

Low carbon steels can be treated to develop a hard surface or case while the interior of the steel, or core, is unaffected and retains its normal ductility and toughness. Surface hardening or case hardening processes for steels may

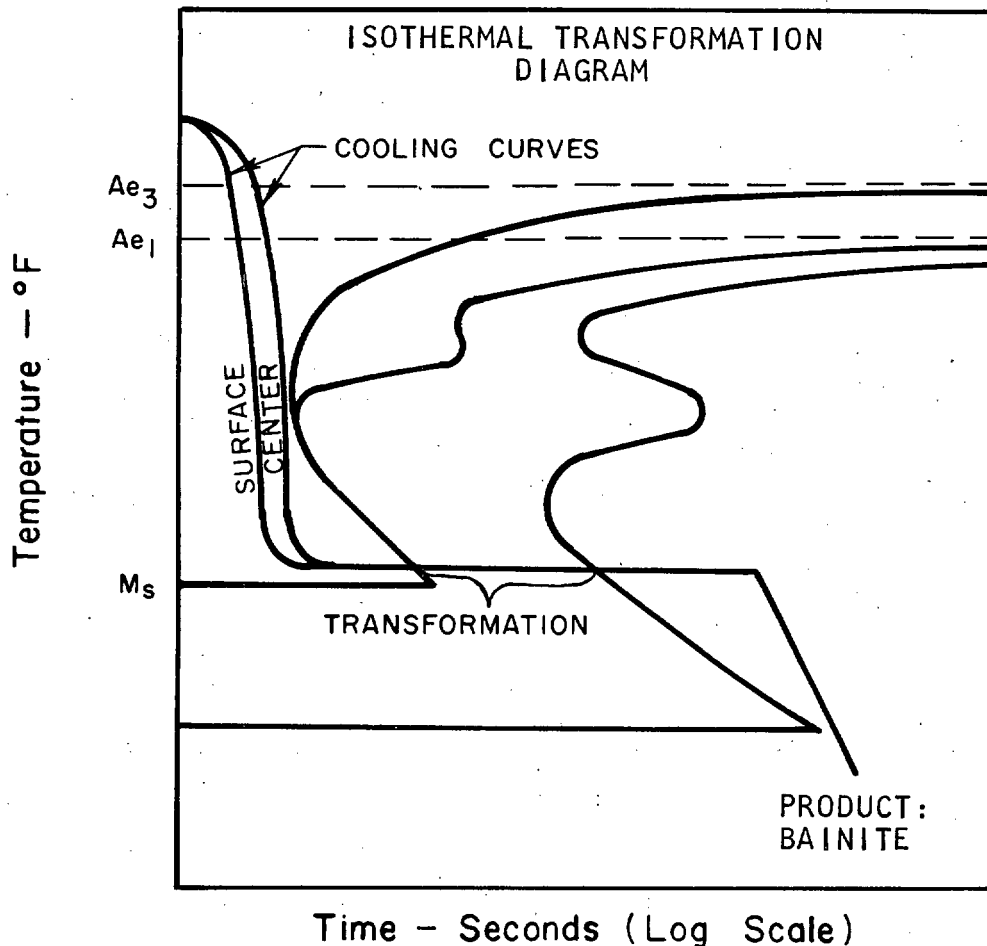


FIGURE 19. Schematic Representation of the Austempering Cycle

be divided into two broad classifications: (1) those in which the composition of the surface material is changed; and (2) those in which the composition of the surface material is not changed. Carburizing, nitriding, carbonitriding, and cyaniding are processes that fit into the first classification. Flame hardening and induction hardening are included in the second classification.

b. Carburizing. Carburizing is usually applied to plain carbon or low-alloy steels with less than 0.20% carbon. The low carbon steel

is heated in contact with a carbonaceous material to develop a case or surface layer on the steel that has a high carbon content. Upon quenching, the high carbon case becomes very hard while the low-carbon core remains relatively soft. This process produces parts with hard, wear-resistant exterior surfaces, and soft, tough cores. Three methods of carburizing steel are:

(1) Pack Carburizing - in which the steel parts are placed in containers and carbonaceous solids are packed around them. The carbonaceous material is usually charcoal, or coke mixed with a suitable energizer such as barium

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or sodium carbonate. The carbon monoxide gas which forms is actually the carburizing medium. The chemical reaction is:



The carbon atoms diffuse into the steel, which for carburizing is heated above the critical range, hence the carbon goes into solid solution in the austenite. The temperature range for pack carburizing is from 1500°F to 1750°F; the temperature selected is usually about 100°F above the A_{c3} point of the alloy being treated. The depth of core and the carbon concentration gradient of carburized parts are governed by the carburizing temperature, time, the carbon potential of the pack, and the original composition of the steel.

(2) Gas Carburizing - in which the steel parts are exposed to carburizing gases. This process is more controllable than pack carburizing and generally more versatile and efficient. The usual operating temperature range for gas carburizing is from 1550°F to 1750°F.

(3) Liquid Carburizing - in which the steel parts are immersed in a molten salt bath containing sodium cyanide. Low temperature salt baths, 1550°F to 1650°F, are best suited for cases 0.003 to 0.030 inches deep. High temperature baths are used to produce deeper cases, 0.020 to 0.120 inches deep, and in some instances cases up to 0.250 may be produced.

Many carbon and low-alloy steels are used for carburizing, although the general practice is to use steels containing about 0.15 or 0.20 percent carbon.

The heat treatment of a carburized steel will depend upon the carburizing temperature, the composition of the core and the case, and the properties that must be obtained. In some instances the steel may be quenched directly from the carburizing temperature and then tempered. Another method is to slowly cool the steel from the carburizing temperature, reheat it to a temperature slightly above the A_{3-1} temperature, quench, and temper. Double reheat and quench operations are also employed with some steels.

In some instances it is necessary to develop a case in only local areas and not over the entire surface of a part. Carburization can be prevented in local surface areas by protecting those areas by copper plating them or covering them with a copper bearing lacquer. Another effective method is to machine the part after carburizing to remove the case from those areas where a soft surface is desired.

c. Nitriding. Nitriding is a nitrogen case-hardening process. For successful nitriding it is necessary to use alloy steels containing aluminum, chromium and molybdenum which combine with the nitrogen to form hard nitrides. The nitriding medium is commonly ammonia gas and the operating temperature is in the vicinity of 950°F. Core depths are usually 0.015 to 0.020 inch. It is unnecessary to quench or temper the steel after nitriding; consequently, parts are usually fully machined and hardened before nitriding.

d. Carbonitriding. Carbonitriding is a case hardening process in which carbon and alloy steels are exposed to a gaseous atmosphere from which they absorb carbon and nitrogen simultaneously. The process is a modified gas carburizing process in which ammonia is introduced into the gas carburizing atmosphere. Operating temperatures range from 1300°F to 1650°F. Case depths of 0.003 to 0.030 inch are developed. Many carbon and alloy steels with carbon contents up to 0.25 percent are carbonitrided. Nitrogen increases the hardenability of the case. Thus full hardness can be achieved by less severe quenching, and distortion is minimized.

e. Cyaniding (liquid carbonitriding). This process is similar to liquid carburizing except that the molten salt bath contains higher percentages of sodium cyanide, ranging from 30 percent to 97 percent. The steel absorbs both carbon and nitrogen from the molten bath and by selection of bath composition and operating temperature it is possible to regulate, within limits, the relative amounts of carbon and nitrogen in the case. Operating temperatures

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range from 1400°F to 1600°F. Usually, thin cases, less than 0.010 inch deep, are produced by this process.

f. Flame hardening. Flame hardening is a surface hardening process that consists of heating the surface area to be hardened to a temperature above the upper critical temperature of the alloy with a high temperature flame. The heated surface is then quenched in a suitable manner. The process produces a hard surface with a soft tough core.

g. Induction hardening. In this process the surface of the steel is heated by induced current to a temperature above the upper critical temperature. The part to be hardened is placed in coil, usually of water cooled copper tube, that does not contact the steel. A high frequency current is passed through the coil and the surface of the steel is heated by induced current. The current is shut off and the steel is immediately quenched. The heating time is fast, from 1 to 5 seconds, and there is no time for serious oxidization, decarburization or grain growth to occur. This process also develops a hard surface over a soft tough core.

Steels used for flame and induction hardening must have a carbon content of 0.40 percent or greater.

THE FORMING OF STEEL

27. General. Carbon and low-alloy steels in the form of ingots, billets, blooms, bar, sheet, strip, plate and rod are formed to desired shapes by various hot and cold forming methods. Some of the more common methods are discussed briefly in this section.

28. Forging.

a. General. Modern forging methods encompass the various hot working operations by which metals and alloys are hammered or pressed to the desired shape. The material is shaped by impact or pressure either on anvils, in open dies or in closed dies. Large forgings are often made directly from the ingot, smaller forgings are made from billets, blooms, bar, and rod.

b. Hammer or smith forging. Hammer or smith forging consists of hammering the heated metal with hand tools (blacksmithing) or between flat dies on a steam hammer. Hand forging, as practiced by blacksmiths, is the oldest forging process, and is still in use today. Hand forgings are necessarily limited in size, complexity of shape, and dimensional accuracy. The skill of the blacksmith is the all important factor in the process. Currently the process is generally restricted to repair work and to the production of limited quantities of small parts. Larger forgings are hand shaped with open dies on steam hammers and pneumatic hammers. Although the use of the steam or pneumatic hammers permits the forging of larger parts, the process, smith forging, is dependent upon operator skill and is limited as to the shape and accuracy of the forgings produced.

c. Drop forging (impact die forging). Drop forging or impact die forging differs from smith forging in the type of dies used. Open faced dies are used to produce smith forgings while closed impression dies are used in drop forging. Closed impression dies consist of two die blocks in which cavities or impressions of the required configurations are machined. One die block is mounted to the anvil of the forging machine, the other attaches to the ram. The heated metal is placed between the die blocks and is caused to flow and conform to the shape of the cavities by the impact of repeated blows on the metal. Proper flow and shaping of the metal is controlled by a gradual change of shape through a succession of forming steps. Each step is carried out in a different die cavity. The cavities are designed to be used in succession so that forming of the part is a progressive operation. The number of steps and the number of different die cavities, or impressions, required of course vary according to the size and shape of the final forging. For small forgings a set of die blocks may contain all of the different impressions required to produce the part. For larger parts more than one set of dies may be required. Drop forgings are produced on steam drop hammers.

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d. Press forging. Press forging consists of a slow squeezing of the metal between dies as opposed to the rapid impact blows of hammer forging. Press forging is used for all types of forging operations, from open to closed die. Hydraulic and mechanical presses are used in press forging.

e. Upset forging. Upset forging machines are designed to operate horizontally with a vertical die parting plane as opposed to the vertical operation and horizontal die parting of hammer and press forgings. The operation consists of gripping a bar of uniform section between gripper dies. The gripper dies form a cavity into which the free end of the bar protrudes. Pressure is applied to the free end of the bar by a ram which upsets the bar until it conforms to the shape of the die cavity. For some products the upsetting operation may be completed in one die cavity. For most shapes the forming is accomplished in successive operations in a series of cavities. Upset forging is a versatile hot forming method by which a wide variety of parts are produced. In addition to upsetting, the upset forging machines may be used for piercing, trimming or punching.

29. Hot Extrusion. In this process, hot plastic metal is forced through an orifice in a die. Since the extruded metal assumes the shape of the orifice, some shapes that cannot be produced by rolling can be made as an extrusion. Squeezing toothpaste from a tube is analogous to the extrusion of metal. The advantages of the hot extrusion process, as related to steel, are: shapes can be produced by extrusion that are not possible by rolling; and the directionality of mechanical properties is minimized. Die wear is a problem and affects the tolerances of steel extrusions.

30. Hot Drawing or Cupping. Hot drawing is the operation in which heated steel is pushed through a die to change its cross section or shape. One common hot drawing process is cupping. A round disk, cut out of a steel plate of suitable thickness, is heated to forging

temperature and placed on a ring die. A plunger forces the metal down through the die to form a cup shaped part. The operation may be repeated using dies of reduced diameter until the desired cup shape is obtained.

Drawing may also be performed on a hot draw bench. In this horizontal operation a tubular part, closed on one end, is forced through a series of dies of continually decreasing diameter. Cylinders are often formed by cupping followed by hot drawing.

31. Hot Spinning. Hot spinning is an operation by which plate in the form of a circular blank is formed to a dish shape on special spinning machines or on lathes adapted to the process. The flat blank is held or attached to a mandrel so that the blank and mandrel can be rotated as a unit. A roller is brought to bear against the rotating blank. The steel is formed to the shape of the mandrel by adjusting the pressure on the roller and manipulating its position.

32. Hot Pressing. Hot pressing is also used to produce large dish shaped heads of various sizes and designs from steel plate. Other shapes are also produced by this method in which a plate blank is formed to the desired shape by squeezing it between forming dies in a large press. Again successive operations may be required to produce the final shape.

33. Cold Heading. Nails, rivets, and small bolts are made by this method. Coiled bar or rod is automatically fed into the machine which upsets it to the desired shape.

34. Press Work. The forming operations performed on presses range from simple bends produced on a press brake to the complex compound-curvature-forming involved in the production of automotive parts. Many different types and sizes of presses are used, most of which may be adapted to different operations, depending upon the types of dies used. The tools most used in press operations come under the general heading of punches and dies. The punch refers to that part of the assembly which is attached to the ram of the press while the die is usually stationary and rests on the bed of

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the press. The die usually has an opening or is shaped to mate with the punch and the two must be aligned for proper operation. The material is worked between the punch and the die. Common press operations include: shearing - blanking, notching, perforating, etc; bending - forming, angle bending, folding, etc; drawing - tubes, cupping, forming flanges, embossing, etc; and squeezing - coining, upsetting, cold forging, hot pressing, etc:

35. Explosive Forming. Explosive forming is a high energy rate forming method which is rapidly gaining prominence. It is a versatile method that can be adapted to large or small parts and can be used effectively when production quantities are limited. The energy released by detonating an explosive charge is transferred through some suitable medium, such as water, to the workpiece. The very fast rates at which metal is deformed by explosive forming methods often permits more severe forming between process anneals than can be accomplished by standard methods.

36. Roll Forming. Coiled strip is formed into tubular and various other shapes by passing it through a series of mating rolls which progressively form it to the desired shape.

37. Other Forming Processes. Carbon and low-alloy steels may be hot worked and cold worked by other processes too numerous to list here. Forming characteristics vary with composition, condition, and the severity of the forming. The ASM Metals Handbook, Volume 1, 8th Edition, presents a comprehensive discussion of metal forming and the selection of steels for forming.

MACHINING OF STEEL.

38. General. The methods used to machine carbon and low-alloy steels include all of the common operations such as turning on lathes, milling, drilling, sawing, grinding, broaching, shaping, planing, etc. The machinability of steel varies with composition and condition or temper. The Machining Data Handbook compiled by Metcut Research Associates, Inc., Cincinnati, Ohio, for Rock Island Arsenal, Rock Island, Illinois, (Contract DA-11-070-AMC-224(w)) is an

excellent source of detailed information for various machining operations as applied to steels and many other materials.

39. Machinability. Machinability has been defined as "a complex property of a material that controls the facility with which it can be cut to the size, shape and surface finish required commercially". The predominant factor governing the machinability of carbon steels, as would be expected, is carbon content. Low carbon steels, 0.15 percent carbon or less, have low tensile and shear strengths in the annealed condition. As a result they are soft and gummy and machine poorly. Cold drawing increases strength and hardness and serves to improve the machining characteristics of these steels.

Steels containing from 0.15 to 0.30 percent carbon usually machine satisfactorily in the as-forged, as-rolled, normalized, or annealed condition.

The medium-carbon steels, containing up to 0.55 percent carbon, usually machine best if they have been annealed to produce a microstructure that is a mixture of pearlite (lamellar) and spheroidite. If the material is not partially spheroidized its hardness will be too high for optimum machinability. Steels containing 0.55 to 0.60 percent carbon should be completely spheroidized to develop the best machining characteristics.

Selection of the 1000 series carbon steels is seldom based on machinability alone, although relative machinability may be a consideration. For example 1022 may be preferred to 1020 because of better machinability in those applications where either alloy is otherwise satisfactory.

The 1100 and 1200 series free machining carbon steels have improved machining characteristics as compared to equivalent 1000 series steels. The resulfurized carbon steels (1100 series) may contain up to 0.33 percent sulfur, although for most of the compositions the sulfur is held to within 0.08 to 0.13 percent. The sulfur combines with manganese to form MnS. The sulfides promote favorable machining conditions by causing the chips to

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break up and also serve as a built in lubricant that prevents the chips from sticking to the tool.

The series 1200 steels are resulfurized and rephosphorized. Sulfur serves the purposes noted above and phosphorus tends to increase the strength and hardness of the ferrite which also promotes chip breakage.

The machinability of the alloy steels varies with composition and temper. Generally alloy steels are more difficult to machine than carbon steels of equal carbon content. In addition, the machining and heat treatment of alloy steels must be coordinated for efficient production. The effects of heat treatment on surface finish, size, the distortion from quenching, etc., must be considered in scheduling the operations.

JOINING OF STEEL AND WROUGHT IRON

40. General. In general, wrought iron, carbon, and low alloy steels can be readily and effectively joined by the various methods commonly used in the metal fabricating industry. The various joining methods may be grouped as follows:

- a. High temperature methods; various fusion welding and resistance welding processes.
- b. Intermediate temperature methods; brazing and soldering processes.
- c. Room temperature methods; mechanical fastening.

The welding methods commonly used to join wrought iron, carbon and low alloy steels include oxyacetylene welding, shielded metal-arc welding, gas shielded-arc welding, submerged-arc welding, forge welding, flash welding, induction welding, electroslag welding, friction welding, stud welding, spot, seam and projection welding.

Intermediate temperature methods include torch brazing, furnace brazing and induction brazing as well as the various soldering methods.

Room temperature mechanical methods include lock seaming, riveting and fastening with screws, nuts and bolts.

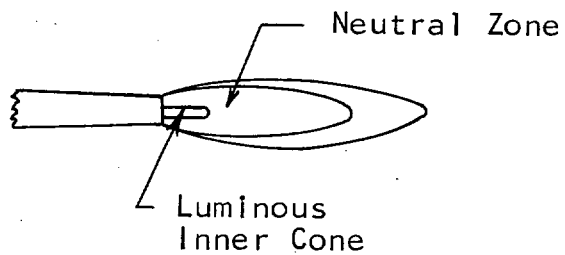
41. Oxyacetylene Welding. Oxyacetylene welding is a welding process in which coalescence is produced by heating a metal with an oxyacetylene gas flame or flames, with or without the application of pressure, and with or without the addition of filler metal. The acetylene gas and oxygen are mixed in the proper proportion in a mixing chamber which is generally a part of the welding tip assembly. The torch is designed so that the operator has complete control of the flame.

Oxyacetylene welding involves the melting of the base metal and also the filler metal, if any is used, with the heat produced by the burning of the gases at the tip of the welding torch. The molten metal, which includes base metal and any filler metal, intermix in a common molten pool and upon cooling coalesce to form one continuous mass. Properly adjusted the flame can also provide a protective atmosphere to cover the pool of molten metal. A mixture of one part oxygen to one part acetylene provides flame temperatures up to 5600°F, approximately twice the melting temperature of steel, and produces the high localized heating necessary for welding.

A range of welding tip sizes are available so that welding flames of various sizes can be produced, with selection dependent upon the specific application. Flame sizes range up to 3/16 inch or more in diameter and 2 inches or more in length. The inner core or blue flame is called the working flame. The closer the working flame is to the surface of the metal being welded, the more efficient is the transfer of heat from the flame to the metal. Changing the ratio of the volume of oxygen to acetylene alters the chemical action of the flame on the molten weld puddle. Generally, wrought iron and steels are welded with a neutral flame having approximately a 1:1 gas ratio. Increasing the oxygen flow produces an oxidizing action; conversely, increasing the acetylene flow produces a carburizing action on the molten pool. Three types of flame adjustment are shown in Figure 20.

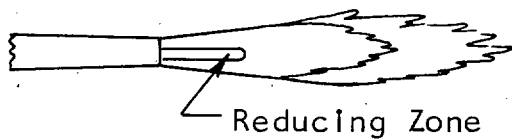
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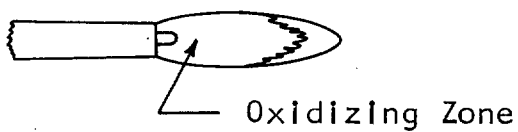
Neutral Flame

Clear, sharp luminous
inner cone with quiet flame



Carburizing or Reducing Flame

Long inner cone coupled
with feathery edges on flame



Oxidizing Flame

Short inner cone with
smaller overall flame

FIGURE 20. Characteristics of Neutral, Carburizing and Oxidizing Flames

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The cleanliness of the base metal at the weld joint is of utmost importance. Oil, dirt or oxides may cause blowholes, lack of fusion, slag inclusions or porosity.

The configuration of the edges of the material to be welded is determined by its thickness. Thin sheet (up to 3/16 inch thick) can be completely melted by the flame without edge preparation. Material from 3/16 to 1/4 inch thick requires a slight root opening for complete penetration; however, filler metal must be added to compensate for the root opening. The joint edges of material 1/4 inch or greater in thickness should be beveled. The angle of bevel for the oxyacetylene welding of wrought iron and steel varies from 35 to 45 degrees, which is equivalent to an included angle of from 70 to 90 degrees. A root face of 1/16 inch is recommended, however, thinner edges are occasionally used. Material 3/4 inch and greater in thickness should be double beveled when it is possible to weld from both sides of the joint. The root face can vary from 0 to 1/8 inches. See Figure 21.

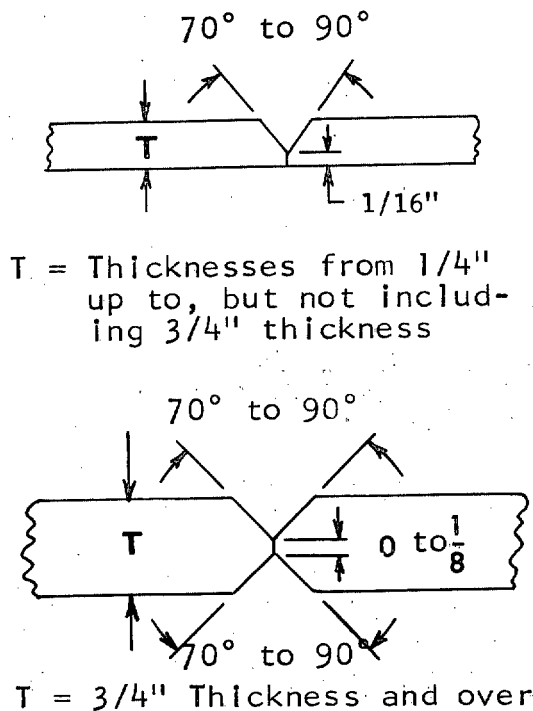


FIGURE 21. Edge Configurations for Oxyacetylene Welding

A bad characteristic of oxyacetylene welding is the steep temperature gradient that is produced across the weld joint and in the surrounding base metal. This temperature gradient often results in distortion unless precautions are taken to minimize its effect. The problem can often be minimized by first tack welding the assembly and then starting the final weld at that section of the assembly that is least subject to distortion. Peening, the proper use of braces, welding alternately on both sides of the joint, and the use of a backstep sequence in welding are all methods which may be used to control or minimize distortion. However, the most effective deterrent of all is to design weldments properly.

During welding, the temperature of the base metal ranges from the melting temperature and above in the weld puddle, to room temperature in areas remote from the heat source. Because the material adjacent to and in the weld is heated to a temperature considerably above the transformation temperature of the steel a coarse grain structure develops in the weld metal and adjacent base material. This condition can be corrected by a grain refining heat treatment after welding.

If a steel contains sufficient carbon, and if the rate of cooling after welding is rapid enough, the weld metal and material in the heat affected zone will harden. Hardening should be avoided because the affected material will lack ductility and will be susceptible to cracking. Hardening can be avoided in most hardenable steels by playing the torch over the weld and the adjacent heat affected zone for a short period of time after welding is completed, or by preheating the material before it is welded. Air hardening steels may require a post heat treatment, such as a stress relief treatment or an annealing treatment, to eliminate the hardened zone.

A variety of equipment is available for both manual and automatic oxyacetylene welding. Most oxyacetylene welding is performed manually. However, when production rates warrant, automatic or semi-automatic equipment can be used to great advantage. Figure 22 shows schematically the relationship of the basic tools required in manual oxyacetylene welding. Automatic

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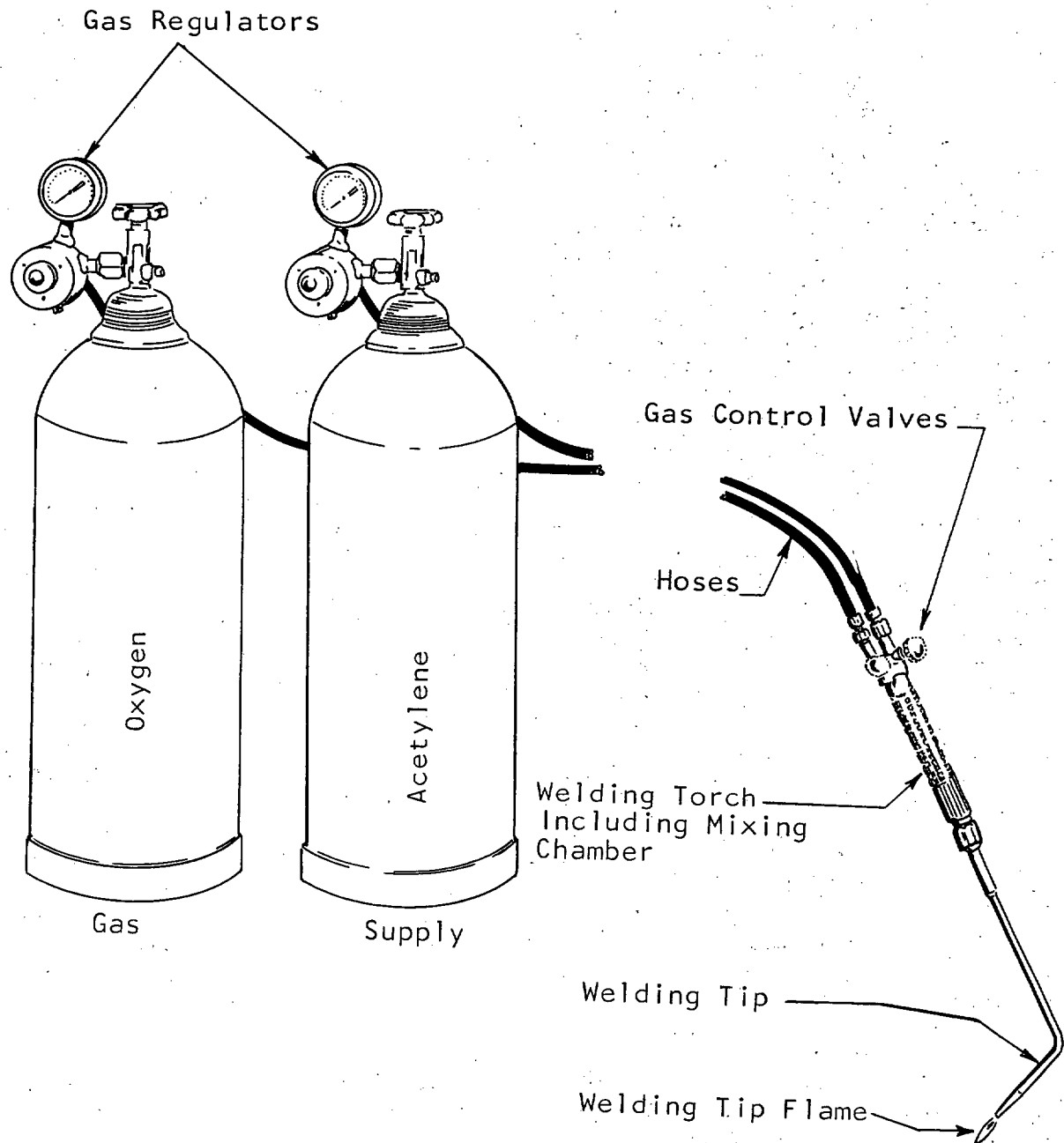


FIGURE 22. Oxyacetylene Welding Equipment

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systems employ special welding heads, regulators, valves and other accessories designed for automatic operation.

Low carbon, low alloy steels, and wrought iron are readily welded by the oxyacetylene process. For welding, carbon steels having more than 0.35% carbon are generally considered high carbon steels and require special care to preserve their particular properties. Low alloy steels with air hardening tendencies also require special attention during welding, even those with a carbon content less than 0.35%. For these steels the material in the joint area is usually preheated to a temperature of 300°F to 750°F to retard the rate of cooling in the weld zone. Retarding the cooling rate minimizes the possibility of hardening the weld metal and the material in the heat affected zone. It is also important to maintain a uniform temperature in the weld area when these steels are welded.

Multi-pass welding is used when it is desirable to obtain maximum ductility of a steel weld in the as-welded or stress-relieved condition. Improved ductility in the weld deposit results from grain refinement in the underlying weld beads when they are reheated during subsequent passes. The final deposit will not be refined unless an extra deposit is added and subsequently removed, or unless the last deposit is subsequently torch heated to a normalizing temperature.

Generally, the composition of the weld deposit should approach that of the base metal. This is particularly true when the weldment will be heat treated after welding to develop mechanical properties that are not possible in the as-welded condition. Steel rods and wire for oxyacetylene welding are designed to deposit metal of a desired composition. Allowances are usually made in the composition of the rod to allow for the recovery of certain elements in the weld deposit. Filler metal conforming to Type A, Mil-R-908 "Rods, Welding; Steel and Cast Iron"; Class 1 Mil-R-5632 "Rods and Wire, Steel, Welding"; and GA60 or GB60 of the AWS-ASTM Specifications for Iron and Steel Gas Welding Rods are suitable for welding wrought iron and low carbon steels. Filler metals con-

forming to Type B or Type C, Mil-R-908; and Class 2, Mil-R-5632 are suitable for welding low alloy steels.

42. Shielded Metal-Arc Welding Process.

Shielded metal-arc welding is a welding process in which coalescence is produced by heating the material with an electric arc which is struck between a coated metal electrode and the work. Shielding is obtained from the decomposition of the electrode coating. Pressure is not used and filler metal is obtained from the electrode. The shielded metal-arc process is primarily a manual process although automatic procedures have been developed.

Basically, the process consists of establishing an electric arc between a coated metallic electrode and the metal to be welded. Current flows through two leads and arcs across the gap between the end of a consumable electrode and the metal being welded. Transformation of electrical energy into heat energy at the gap provides the necessary heat. Figure 23 illustrates the metallic arc welding circuit.

During welding, the materials in the electrode coating are decomposed by the heat of the arc and perform a number of functions, namely: (a) they promote and help stabilize conduction across the arc; (b) they produce an envelope of gas which excludes oxygen and nitrogen in the air from contacting the molten weld puddle; (c) they add fluxing ingredients to the molten puddle for refining purposes; (d) In certain electrode designs, they add alloying elements to the weld deposit; and (e) they provide materials that help to control the bead shape. Figure 24 is a schematic presentation of the shielded metal arc process.

Actual welding consists of striking an arc by touching the work piece with the electrode and quickly withdrawing it to normal arc length, then guiding the electrode to produce simultaneous fusion to the electrode tip and base metal to form a solid bond on cooling. Intermixing of the deposited filler metal with melted base metal occurs to a greater or lesser degree depending on the techniques used.

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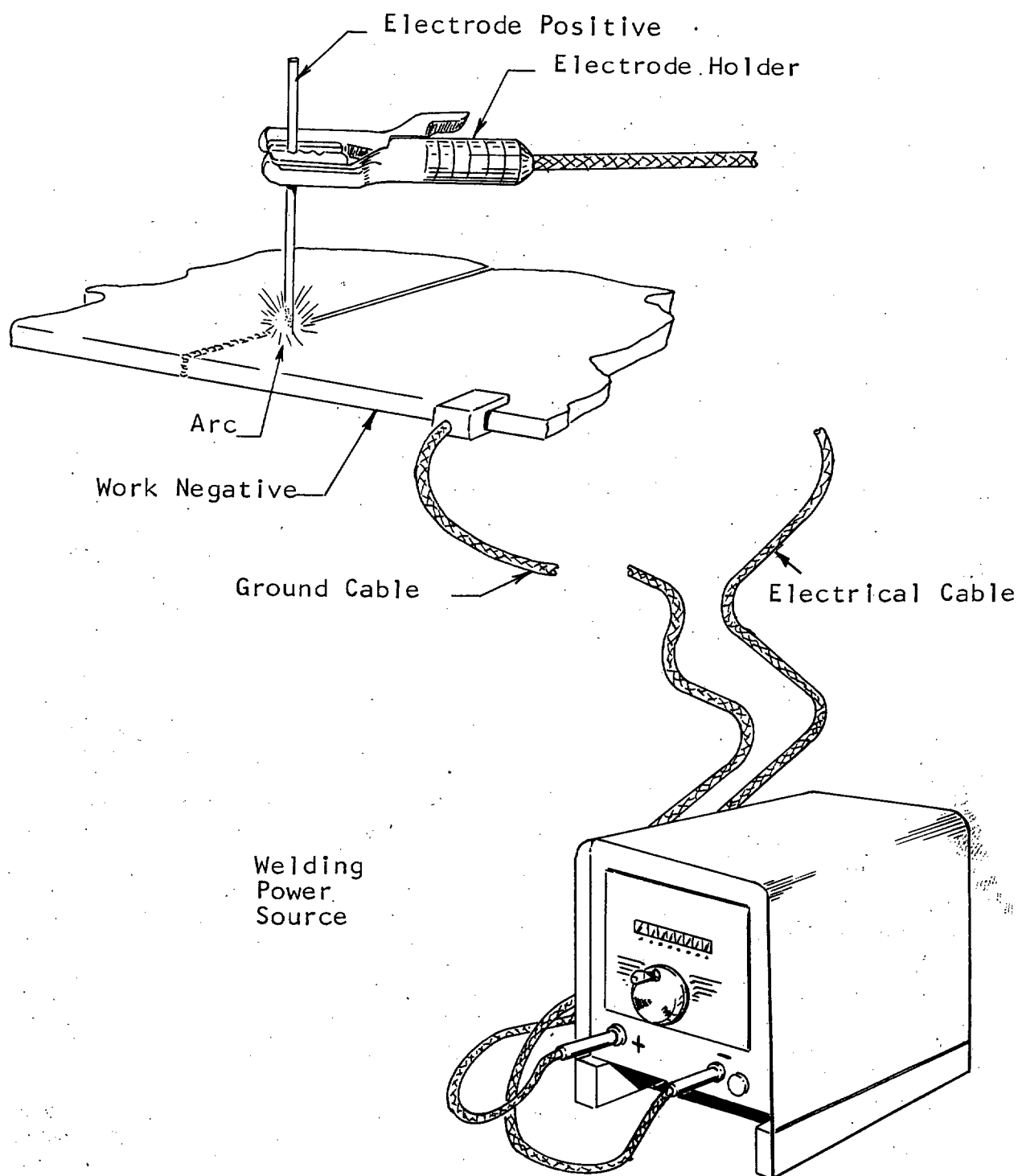


FIGURE 23. The Shielded Metal-Arc Welding Circuit (Reverse Polarity Operation)

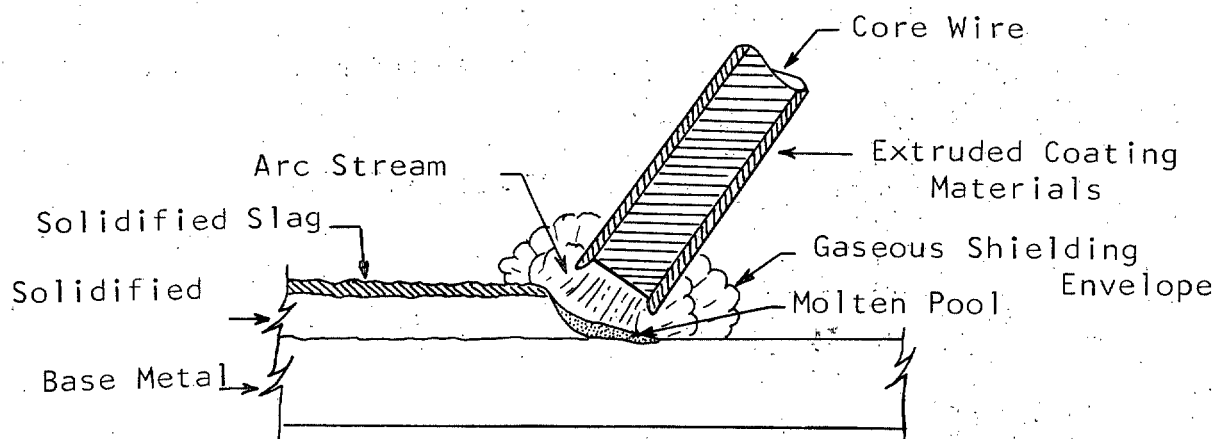
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FIGURE 24. A Schematic Diagram of the Shielded Metal-Arc Welding Process

Manual welding equipment includes a power source (as transformer, dc generator, ac generator or dc rectifier), electrode holders, cables, cable connectors, ground connectors, chipping hammers, wire brushes, helmets and weld gages.

Automatic shielded metal-arc welding equipment, in addition to a welding head, consists of such items as work positioners, head travel carriages, turning rolls, work skids with hold-downs, and portable power units.

Joint design is very important particularly in heavy sections and in the case of higher carbon and low alloy steels. In general, joint design should be in accordance with the latest practices for shielded metal arc welding as recommended by the American Welding Society.

Dirt, greases, oil, paint, and oxide should be removed from joint areas to prevent porosity and inclusions in the weld deposit.

In shielded metal-arc welding of wrought iron the best results are obtained when the welding speed and current are slightly below those used for mild steel of the same thickness. The slower speed permits the molten metal immediately behind the arc to remain molten longer, thereby allowing entrapped slag and gases to float out of the weld puddle. The use of a lower current also minimizes the possibility of burning through thinner sections. In practice, as little base metal as possible is melted to minimize the accumulation of slag in the weld. In multi-pass operations each weld bead should be thoroughly

cleaned of oxide before subsequent beads are deposited.

Electrodes selected for welding wrought iron should meet the requirements of Mil-E-15599, or the requirements of the E60XX series of classifications of the AWS-ASTM Specifications for Mild Steel Arc Welding Electrodes.

Low carbon steels up to 0.30 percent carbon content are readily welded by the shielded metal-arc process. These steels are normally welded without preheat, post-heat or special electrodes. Special precautions such as preheating to 200°F, maintaining a minimum interpass temperature of 200°F, and postweld stress relief are advisable when section thickness exceeds one inch.

When the carbon content is over 0.30% special precautions are necessary to avoid cracking in the weld deposit or in the adjacent heat affected zone. Preheating to, and maintaining a minimum interpass temperature of 300°F to 400°F is advisable for all thicknesses of material. A stress relief treatment should follow welding.

Carbon steels having a carbon content over 0.50% are seldom welded. However, satisfactory welds may be obtained if special precautions are taken to avoid cracking.

The selection of electrode type and the size of electrode to use in welding carbon steels depends upon the weld strength requirements, the composition of the steel being welded, the

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thickness of the steel, the joint configuration, and the welding position. Electrodes of the Mil-60XX series of Mil-E-15599 or the E60XX series of AWS-ASTM Specification for Mild Steel Arc Welding Electrodes are suitable for welding the low carbon steels. For welding the medium and higher carbon steels, low hydrogen type electrodes of the Mil-70XX series, meeting Mil-E-18038 and Mil-E-22200, and electrodes of the AWS-ASTM E70XX series are recommended.

It is usually advisable to preheat the low alloy steels prior to welding in order to avoid cracking. Preheating in the order of 400°F to 750°F is recommended depending upon hardenability. The areas to be welded should be preheated to the temperature noted in Table VI.

TABLE VI. PREHEAT TEMPERATURES FOR LOW-ALLOY STEELS

Carbon Content (%)	Hardenability Equivalency	Preheat and Interpass Temp. (°F Min.)
0.16 through 0.35	AISI-4130 and steels of equal or equivalent hardenability	400
0.34 through 0.43	Steels with hardenability higher than above	500 to 750

Exceptions to the preheating rule are a group of high-strength low-alloy steels such as HY80, HY100 and similar steels marketed by the steel industry. These steels are supplied in the quenched and tempered condition and combine high yield strength and good notch toughness with good weldability. To obtain 100% joint efficiency when welding these steels it is necessary to use the proper electrode and to cool the weld zone as rapidly as possible. Interpass temperatures must also be held to certain minimums if 100% joint efficiency is to be attained. As a result reheat treatment after welding is not necessary. Moderate preheating may be advisable when the thickness of the steel section exceeds one inch.

Preheating of face hardened armor steels is neither recommended nor desirable for the obvious reason that heat input should be held as low as practical to avoid tempering and softening wide areas of the hardened surface adjacent to the weld deposit.

For low alloy steels electrodes conforming to Mil-70XX, Mil-80XX, Mil-90XX and Mil-100XX of Mil-E-6843, Mil-E-15716, Mil-E-18038, and Mil-E-22200 are generally used when the weldment will remain in the as-welded condition or when the weldment will be stress relieved after welding. The type of electrode selected for use depends upon the steel being welded and strength requirements. Electrodes meeting the requirements for the E70XX, E80XX, E90XX and E100XX classifications of the AWS-ASTM Specifications are also widely used by industry.

When heat treatment after welding is required to develop mechanical properties higher than those attainable in the as-welded condition, specially designed electrodes with chemical compositions capable of responding to heat treatment must be used. Electrodes in this category are obtainable to Mil-E-8697 requirements. The selection of a particular electrode is based upon the alloy being welded and strength level required after heat treatment.

Electrodes used for welding the high-strength low-alloy structural steels include the Mil-110XX series, and Mil-120XX series of Mil-E-18038 and Mil-E-22200. When lower-than-base-metal strength can be tolerated, electrodes of the Mil-90XX series, Mil-E-18038 and Mil-E-22200, may be used. Corresponding electrodes of the AWS-ASTM classification are widely used by industry to weld these steels.

Because of its importance, reference should be made to the care of low hydrogen type electrodes. Low hydrogen type electrodes generally have less than 0.2 percent moisture in the coating to avoid introducing hydrogen to the weld zone. Usually, these electrodes are packed in hermetically sealed containers which should not be opened until the time of use. After opening the container, storing the electrodes in a holding oven at the temperature recommended by the manufacturer is advisable. Electrodes

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that have been exposed to moisture should be reconditioned according to the manufacturer's instructions or discarded.

It is generally advantageous to stress relieve the low alloy steels after welding. In addition to relieving residual stresses in the welded structure, the temperatures involved in stress relieving are such that any hardened material adjacent to the weld will be tempered, with a corresponding improvement in ductility.

43. Gas-Shielded Arc Welding Process.

a. General. The gas-shielded arc welding process is a process in which coalescence is produced by heating the metal with an electric arc which is struck and maintained between the end of a metal electrode and the part being welded. The arc and weld region are shielded by a protective gas. The shielding gas may or may not be inert; pressure may or may not be applied; and filler metal may or may not be added to the joint.

Gas-shielded arc welding is divided into two variations which may be classified as follows:

(1) Procedures using non-consumable electrodes, including both manual and mechanized operation, termed the gas tungsten-arc process.

(2) Procedures using consumable electrodes, also including both manual and mechanized operation, termed the gas metal-arc process.

b. The gas tungsten-arc welding process. This process, often referred to as the TIG process, uses a tungsten or tungsten alloy electrode as the source of welding heat. The heat for welding is produced by an electric arc maintained between the electrode tip and the metal being welded. Basic features of the process are illustrated in Figure 25. In manual welding, the filler metal, if required, is fed into the molten puddle in the vicinity of the arc in a manner similar to oxyacetylene welding. The molten metal, the adjacent base metal, and the electrode are protected from the atmosphere by an envelope of inert gas fed through the electrode holder. Generally, argon, helium, or mixtures of the two gases are used for shielding purposes; argon is most frequently used. The process utilizes both direct current reverse

polarity (DCRP) and direct current straight polarity (DCSP), however, direct current straight polarity is preferred for welding steels.

The basic components for manual welding include a power unit, an electrode holder (commonly called a torch) with gas passages and a nozzle for directing the flow of shielding gas, tungsten or tungsten alloy electrodes, gas flow regulating equipment, and usually a foot control for on-off switching purposes. Mechanized welding equipment may include electronic devices for checking and adjusting the welding torch level, work handling equipment, provisions for initiating the arc and controlling gas flow, and filler metal feed mechanisms.

c. The gas metal-arc welding process. This process, commonly referred to as the MIG process, uses a consumable electrode which is deposited as filler metal in the weld joint. The arc and weld puddle are shielded from the atmosphere by a gas, gas mixture or gas-flux mixture. In welding the carbon and low alloy steels, shielding is usually accomplished with mixtures of argon plus 2 percent oxygen; argon and carbon dioxide (CO_2); or CO_2 with flux additions. Direct current reverse polarity (DCRP) is used for welding steels.

The basic equipment required for semi-automatic MIG welding is shown in Figure 26. The equipment permits automatic feeding of the filler metal, and manual control of the welding gun. The process has been adapted to fully automatic operation with electronic devices controlling the equipment.

d. Process considerations.

(1) **Carbon Steels.** Both the gas tungsten-arc and gas metal-arc processes are used to weld carbon steels. The gas tungsten-arc process is usually limited to the welding of thinner sections with or without the addition of filler metal. The gas metal-arc process, because of its high deposition rate, is generally used to weld heavier section thicknesses. Quite often the root pass of a multi-pass weld is made with the gas tungsten-arc process, while the remaining passes are made with some other welding process, such as the shielded metal-arc process. This procedure assures a clean, sound root bead.

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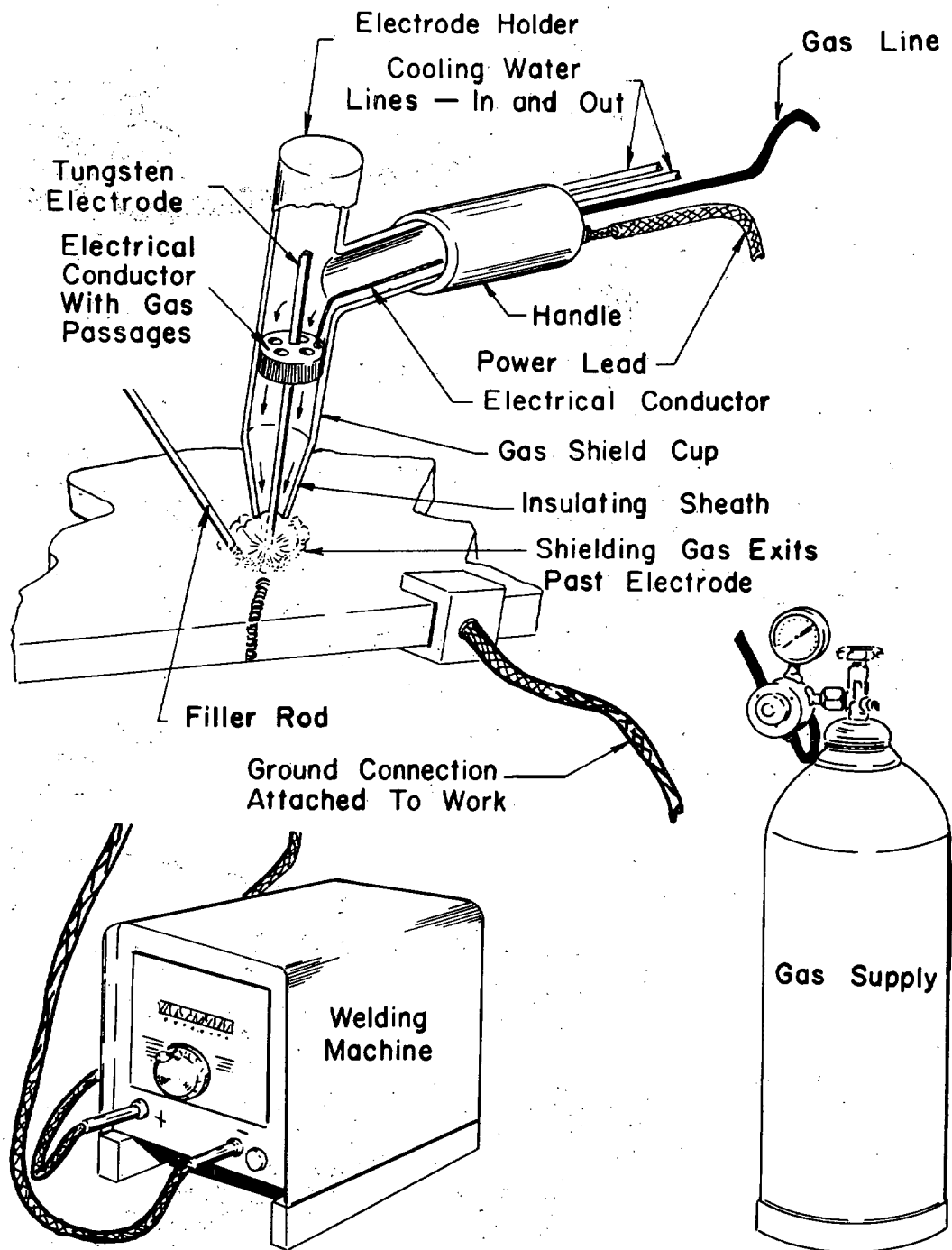


FIGURE 25. The Gas Tungsten-Arc (TIG) Welding Process

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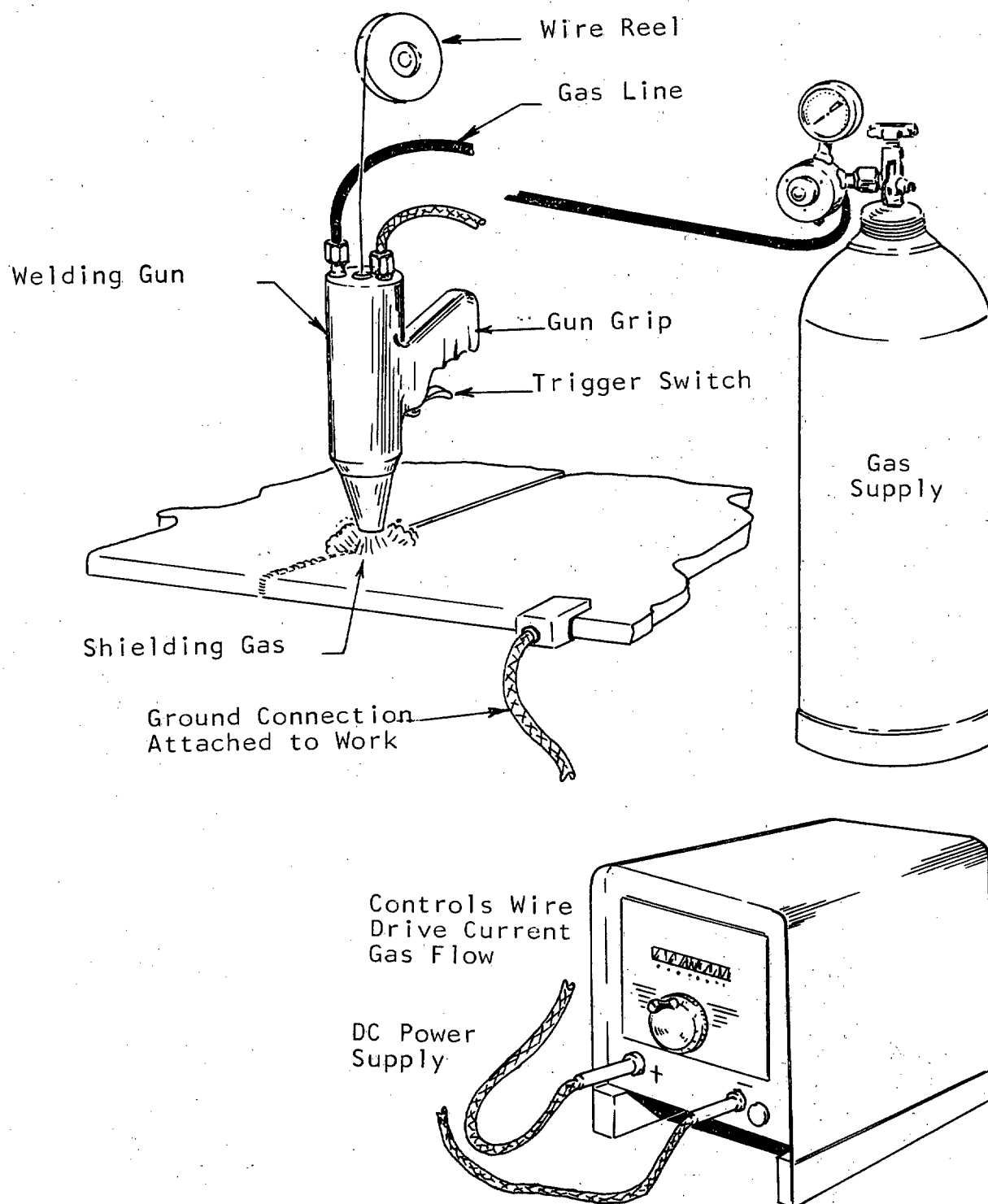


FIGURE 26. The Gas Metal-Arc (MIG) Welding Process

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Joint design and preparation should be in accordance with the best practices recommended by the American Welding Society. Cleanliness of areas to be welded is very important in gas shielded-arc welding. All greases, dirt, paint and oxides should be removed from joint areas to prevent excessive porosity and inclusions in the weld deposit.

In general, preheating practices applicable to shielded metal-arc welding of carbon steels also apply to gas shielded-arc welding.

Filler rods meeting Class 1 requirements of Mil-R-5632 are used with the gas tungsten-arc process in the welding of low and medium carbon steels. A number of welding wires are available which are designed specifically for gas metal-arc welding of the low and medium carbon steels. These wires usually contain deoxidizers or other scavenging agents to prevent porosity or other damage to the weld metal from the oxygen, nitrogen or hydrogen that may be in the shielding gas or which may reach the weld from the surrounding atmosphere. Deoxidizing agents are essential in welding wires that are used with shielding gases containing oxygen. The deoxidizing elements generally used are manganese, silicon and aluminum.

(2) Low Alloy Steels. The gas tungsten-arc and gas metal-arc processes are both used for welding the low alloy steels; however, the gas tungsten-arc process is generally selected when optimum mechanical properties are required for highly stressed parts. Joint design and preparation are similar to that used in shielded metal-arc welding.

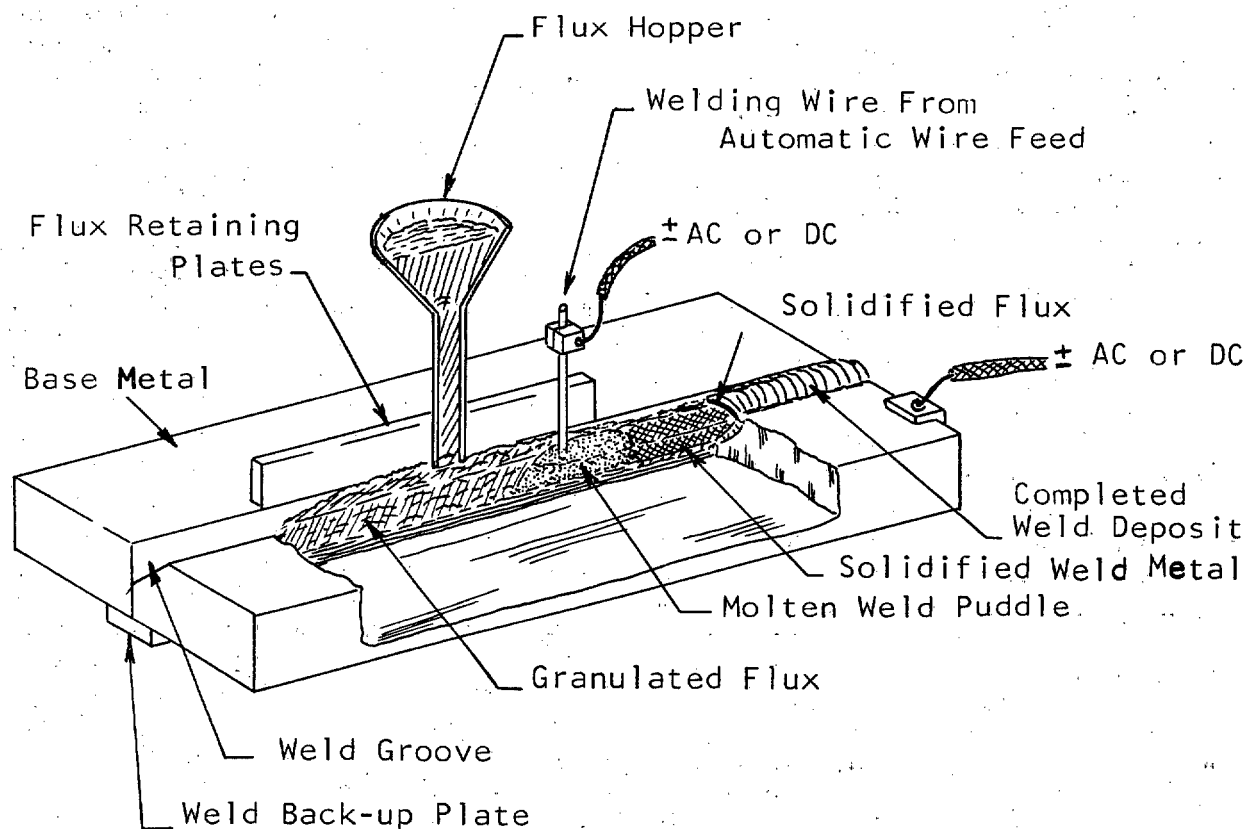
Preheating practices generally parallel those used for shielded metal-arc welding.

Several compositions of filler wire have been developed for use in gas metal-arc welding the low-alloy steels. Selection is usually based on composition of the steel to be welded and weld strength requirements. Generally the composition of the wire is similar to the base metal to be welded except that, in some cases, the carbon content is lowered in order to obtain improved ductility in the weld. Usually the lower carbon content is compensated for by increasing

the alloy content of the wire. This often improves weld ductility and notch toughness without sacrificing tensile strength. Filler metal meeting Class 2 requirements of Mil-R-5632 may be used to weld low alloy steel structures which will be heat treated after welding to develop high mechanical properties.

44. Submerged Arc Welding. Submerged arc welding may be defined as a process in which the heat for coalescence is produced by an electric arc or arcs struck and maintained between a bare metal electrode, or electrodes, and the work under a shielding blanket of granular, fusible material. Pressure is not used and filler metal is obtained either from the electrode or from supplementary welding rod. The basic feature of the submerged arc welding process is the flux, a finely crushed mineral composition, which makes possible the special operating conditions involved in this process. In submerged arc welding the electrode is not in contact with the material being welded; the current is carried across the gap by the flux. The flux, when cold, is a nonconductor of electricity, but in the molten state it becomes a highly conductive medium. The flux is laid either manually or automatically ahead of the weld zone. It serves as a shield to protect the material from the atmosphere, and also as the conducting medium. The insulating effect of the molten flux blanket enables intense heat to be generated in the weld zone where the electrode and base metal are rapidly fused. Since the atmosphere is excluded, bare welding wire can be fed directly into the weld zone. The fused flux cracks off or can be readily removed upon cooling. Figure 27 shows the essential elements of the submerged arc process.

Alternating current transformers are the most widely used sources of power because of the high welding current required for submerged arc welding. However, standard motor-generator or rectifier-type dc welding power supplies can be used. Remote control adjusters, actuated by controls on the operator's panel, are generally part of the equipment. Both automatic and semi-automatic equipment can be obtained.

MIL-HDBK-723A**30 NOVEMBER 1970****FIGURE 27. The Submerged Arc Welding Process**

Electrodes are normally coiled, although straight lengths are sometimes used. Steel rods and wire supplied for carbon and low alloy steel welding are generally lightly coated with copper to improve the contact surfaces and to prevent rusting.

Alloy weld deposits are produced by (a) the use of an alloy steel wire or rod, (b) the use of a composite electrode, as a sheath enclosing a core of alloying elements, and (c) the use of a flux containing the alloying elements in conjunction with a low carbon steel electrode. Bare welding electrodes conforming with requirement of Mil-E-18193 may be used in conjunction with certain fluxes for welding many low carbon and low alloy steels.

The fluxes used in submerged arc welding are granulated, fusible, mineral materials of

various compositions and particle sizes. Alloying elements may be included in their composition to be introduced into the molten weld metal during welding. The choice of flux depends upon several factors: (a) the welding procedure employed (b) the joint configuration, and (c) the composition of the base metal to be welded. Fluxes conforming with requirements of Mil-F-18251 and Mil-F-19922 are intended for use in conjunction with Mil-E-18193 electrodes.

The deep penetrating effect of the concentrated heat generated during submerged arc welding permits the use of small welding grooves. Consequently a smaller amount of filler metal is used in making a joint. Generally, the fused metal consists of about two parts of base metal to one part of filler metal. Joints should be designed in accordance with the recommendations of the American Welding Society.

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Since the submerged arc process creates a large volume of molten metal which remains fluid for an appreciable time, some means must be employed to support and contain it until solidification takes place. This is accomplished by the use of temporary or permanent weld backing, Figure 27. As with other welding processes it is important that all paint, rust or scale, grease and dirt be removed from the areas to be welded.

Wrought iron can be readily welded using the same fluxes and electrodes that are used to weld low carbon steels. Slower welding speeds than those used in welding carbon steels are recommended to allow the greater volume of gases generated during welding to escape before the molten metal solidifies. Since the weld deposit is more like a low carbon steel than wrought iron, the second and subsequent passes, if required, can be made at normal speeds.

The submerged arc welding process is one of the leading welding processes used for joining low and medium-carbon steels. Moderately thick sections with a carbon content ranging up to 0.35 percent can be welded without precautionary measures such as preheating and post-weld heat treatment. Preheating is generally necessary when the carbon content is over 0.35 percent.

The low alloy steels are easily welded using the submerged arc process. Precautions are usually necessary, however, to avoid cracking in the weld and heat affected zone. The heat treatable low alloy steels may be welded provided the weld area is preheated and the rate of cooling is slow. One important factor in welding these steels is the proper selection of filler metals and fluxes which will deposit weld metal capable of response to heat treatment after welding. Since some of the fluxes contain alloying elements, it is advisable to follow the manufacturer's recommendations in the choice of fluxes and wire.

In welding certain quenched and tempered structural steels, the heat input must be closely controlled to assure the retention of strength and notch toughness in the heat affected zone.

Retention of a high level of strength and notch toughness in the heat affected zone of these steels depends on the rapid dissipation of heat to permit formation of desirable microstructures. Any practice that will retard cooling, such as preheating or high welding heat inputs, should be avoided whenever possible.

45. Forge Welding. The term "forge welding" encompasses a group of welding processes in which coalescence is produced by heating the material to be welded in a forge or other furnace after which welding is accomplished by applying pressure or by hammering. Forge welding processes include roll welding, hammer welding and die welding.

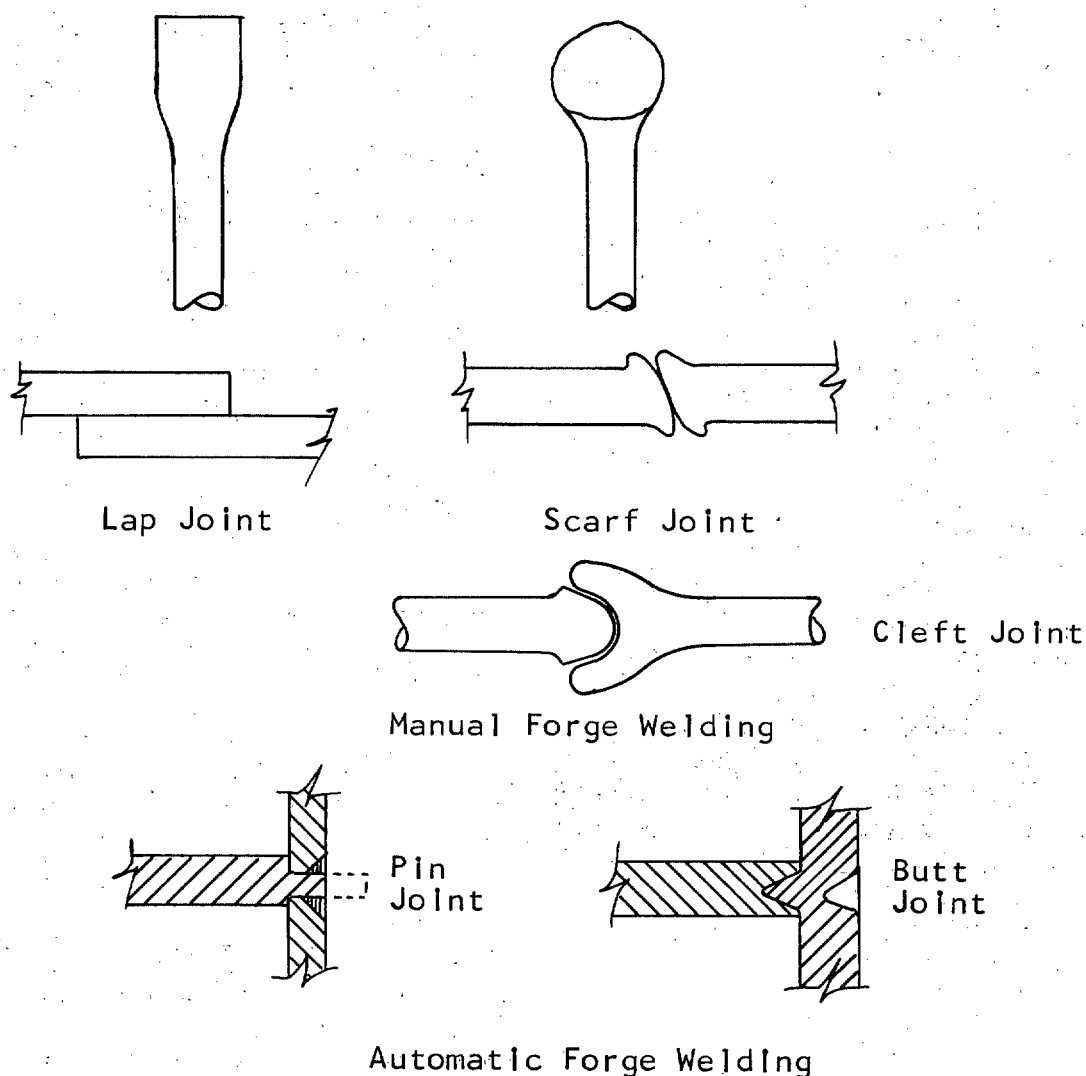
a. In hammer welding, the sections to be joined are heated in a forge or furnace until the surfaces to be joined are in a plastic condition. The surfaces are placed together and pressure is applied by means of hammer blows. The hammer blows may be applied manually with a sledge hammer or by more modern means such as with semi-automatic or automatic hammer welding equipment powered by hydraulic, steam or pneumatic equipment.

b. In die welding, the heated material is welded by pressing it between dies which are mounted in a suitable press.

c. Roll welding is used mainly to manufacture clad steel plates. After the material is heated it is passed through a set of rolls which apply the pressure to make the bond.

Several joint designs commonly used in manual and automatic forge welding operations are shown in Figure 28.

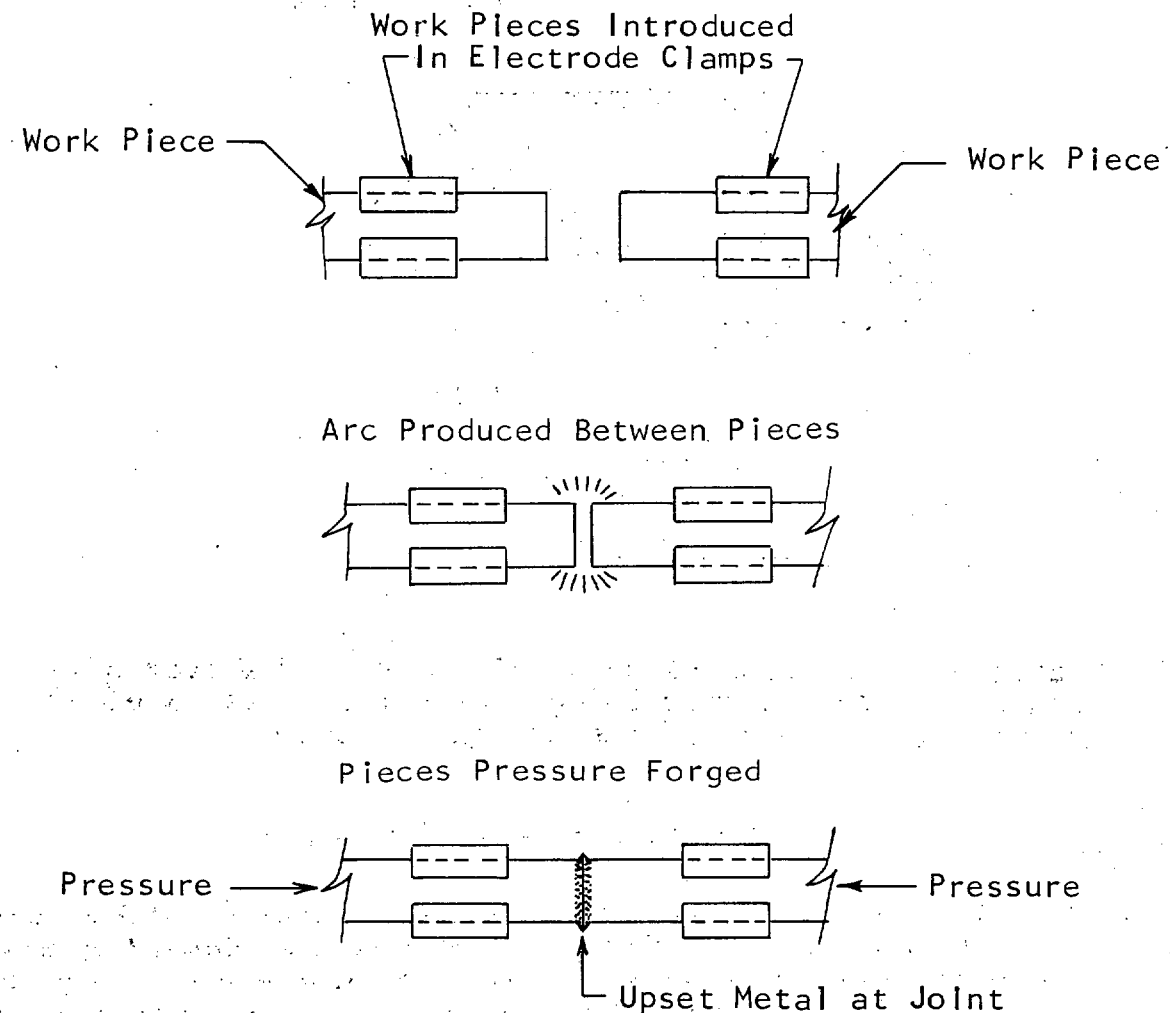
Wrought iron and low carbon steels are the materials most commonly forge welded. Temperatures somewhat higher than those required for steels are used in forge welding wrought iron. Since wrought iron is easily deformed at these temperatures the pressure applied must be carefully controlled to avoid excessive upsetting in the joint areas. The ductility of forge welded joints is notoriously low in the as-welded condition. Annealing after welding will refine the grain structure and improve ductility in the joint area.

MIL-HDBK-723A**30 NOVEMBER 1970****FIGURE 28. Joint Designs for Forge Welding**

46. Flash Welding. Flash welding is a method of resistance welding in which heat is developed by the resistance to the flow of electric current across a gap between two surfaces to be joined. The two surfaces are positioned sufficiently close together to allow the flow of an electric current across the gap. When the two surfaces are heated to the fusion point they are brought into tight contact under sufficient pressure to cause upsetting to effect a joint. At this point the current is shut-off and the joint is allowed to cool. Figure 29 shows the flash welding sequence.

Most equipment in use today is either semi-automatic or fully automatic with controls which start and stop the current supply, sequence the motion of the movable platen, and in some instances, apply preheat and postheat to the joint area.

Flash welding heats the abutting surfaces to a plastic temperature. At these temperatures low alloy steels and carbon steels with moderate or high carbon content will tend to harden upon cooling unless the cooling rate is retarded. This may be done by including a postheating

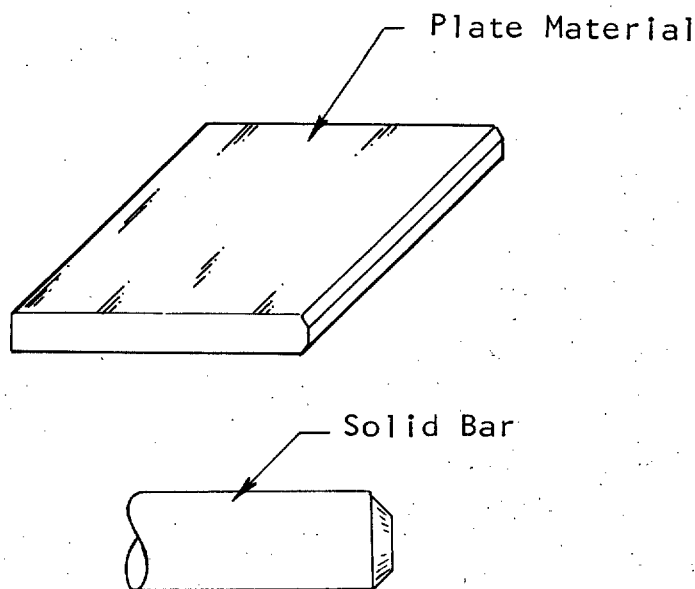
MIL-HDBK-723A**30 NOVEMBER 1970****FIGURE 29. The Flash Welding Sequence**

operation in the welding cycle. In some cases it is necessary to heat treat the entire welded assembly to obtain a uniform structure and hardness.

Most specifications governing the flash welding of steels, such as Mil-W-6873, require the establishment of flash welding schedules for each setup. This involves the preparation and testing of specimens to develop the proper equipment setup before production welding. All data necessary to insure satisfactory production parts are recorded on the weld schedule which governs production operations.

Probably the most important reason why flash welding finds limited application is the expensive testing requirements imposed on the process. Usually it is required that moderately or highly stressed parts be subjected to proof testing after welding (and heat treatment if required) to ensure joint integrity. This requirement together with the testing necessary to establish weld schedules greatly increases the cost of the process.

At times it is necessary to bevel one or both pieces of the joint, as shown in Figure 30, to facilitate flashing and obtain uniform heating

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Size of chamfer depends upon thickness or diameter of material, capacity of welding machine, and upon whether one or both mating surfaces are chamfered.

FIGURE 30. Joint Designs for Flash Welding

of both faces of the joint. This is particularly true with thicker materials. The surfaces of the parts contacting the electrodes and the surfaces to be joined should be free of dirt, grease, and oxides.

It is frequently necessary to remove all or part of the extruded or upset material after welding. They may be necessary in some cases only from the standpoint of appearance. Usually removal of internal flash from the joints of hollow shapes is not necessary.

47. Induction Welding. Induction welding is a welding process in which the heat for welding is produced by the resistance of the material to the flow of an induced electric current. Fusion may be accomplished with or without the application of pressure. The equipment for induction welding includes: (a) a source of alternating or pulsating current, (b) a device for transferring energy to the work piece, and

(c) precise methods of controlling the energy input, the duration of input, and the rate of cooling. The available sources for alternating current are high frequency motor generator sets, vacuum-tube oscillators and spark-gap oscillators. Heating for welding occurs very rapidly, in the order of a few hundredths of a second, requiring the use of precise control devices. Inductor coils of copper tubing or bar, are generally used to transfer the energy to the work piece. The coil is usually formed to the geometry of the piece being heated and may be of single or multiple turn design. When the configuration of the work piece precludes using a surrounding coil, other shapes are formed and placed adjacent to the work piece.

The process is well adapted to the joining of thin sheet where a very localized heat affected zone adjacent to the weld is desired. Induction welding is used extensively in the continuous forming of tube and pipe from strip steel.

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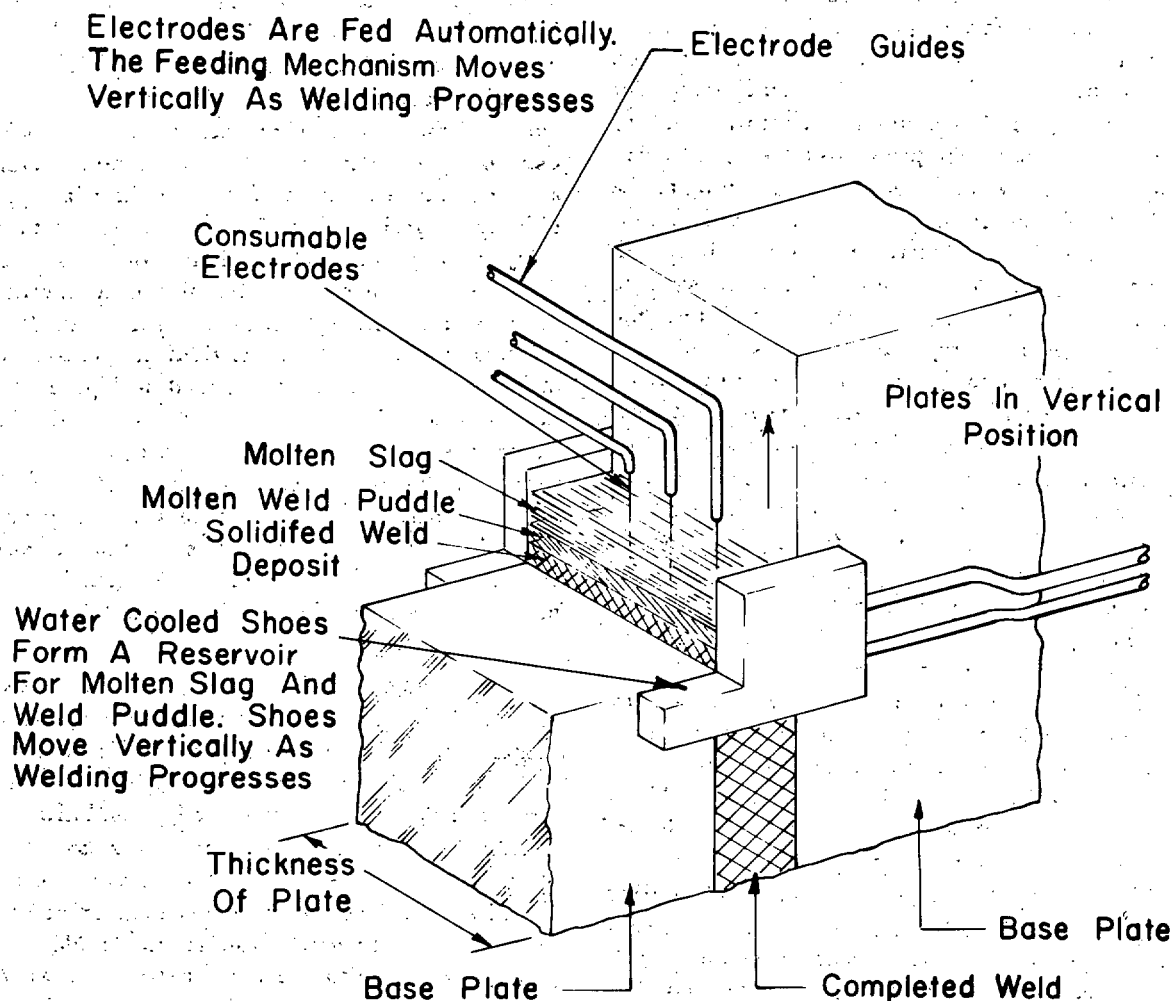


FIGURE 31. The Electroslag Welding Process

Postweld heat treatment may be performed by the welding equipment in cases where undesirable as-welded structures exist in the weld zone.

48. Electroslag Welding. Electroslag welding is a welding process which relies on molten slag to melt the filler metal and the base material to be welded. The weld pool is also shielded by the molten slag. The electrically

conductive slag is maintained in a molten condition by its resistance to the current which flows between the electrode and the work. The electroslag process has unique features which set it apart from other forms of electric welding. The principle involves the fusion of parent metal and continuously fed filler metal under a layer of high temperature electrically conductive molten slag. Figure 31 is a schematic diagram of the electroslag process.

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The electroslog process is applied mainly to the vertical welding of medium and heavy plate. Parts are assembled with a joint gap of approximately 1 to 1-1/2 inches. Joint edges need not be beveled. Square edges, either flame cut or machined, are satisfactory. A starting tab is necessary to build the proper depth of conductive slag before welding reaches the joint to be welded. A run-off tab is also required as a dam at the end of the seam. The arc is initiated, much like the submerged arc process, by starting an arc beneath granular flux dropped into the cavity. Arc energy, however, is used only initially to reduce the granular slag to a molten state. The molten slag then serves as a conductor through which current passes from the electrode to the work piece. Heat generated by the resistance to the flow of current through the molten slag and the weld puddle is sufficient to melt the edges of the base metal and the welding electrode into a pool beneath the slag. To obtain consistent energy dissipation a transverse motion, backwards and forwards, can be automatically imparted to the electrode wire as it is fed into the slag. For very heavy thicknesses, with suitable equipment, two or three wires may be fed into the same pool simultaneously. Water cooled copper shoes are used on each side of the joint to retain the molten metal and slag pool. As the pool of weld metal builds up the lower portion is continuously cooling to form a homogeneous weld with effective penetration of the base plates. Fresh flux must be added to the slag pool during welding to replace slag that solidifies into a thin layer on the surface of the weld as it cools. The thin layer on the surface can be easily removed.

Equipment for electroslog welding is usually designed and built to meet the special requirements of the user. The design generally depends on the range of thicknesses to be welded and degree of portability desired. The welding power is usually supplied by alternating current transformers, although direct current power sources may also be used.

The large quantity of heat generated during the electroslog welding operation preheats the

base metal ahead of the actual welding zone. This is beneficial in two respects: (a) preheating is not required, and (b) the heat as it dissipates in the adjacent base metal tends to minimize residual stress in the weld area. Because of the thermal characteristics of the process, the welds have a coarse dendritic structure and a wide heat affected zone exhibiting considerable grain growth. By using suitably alloyed electrodes, mechanical properties equal to or better than the base metal can be obtained in the weld, notch impact energy excepted. Heat treating above the lower critical temperature of the base metal is recommended if high notch-impact properties are required. Austenitizing treatments such as normalizing, and, quench and tempering, refine the grain structure of the weld and heat affected zone with resultant improvement in mechanical properties. Also, a subcritical stress relieving has been found to be beneficial in improving weld ductility.

Experience has shown that it is good practice to use electrode wire with a lower carbon content than the base metal when medium carbon and low alloy steels are welded with the electroslog process. Usually additional alloying in the electrode wire is relied upon to obtain strength in the weld deposit equivalent to the parent metal. When heat treatment after welding is required, electrode composition should compare favorably with the base metal composition in order to achieve the desired properties in the weld deposit. Three types of wire that have been used with the electroslog process include: solid wires; flux cored wires; and braided wires.

Materials that have been successfully welded by the electroslog process include the low tensile strength structural steels (45,000 - 72,000 psi), the medium tensile strength structural steels (65,000 - 85,000 psi), and high tensile strength structural steels (75,000 - 100,000 psi). These include both carbon steels and low alloy steels. Several high strength heat treatable low alloy steels such as HY80, AISI 41XX and AISI 43XX have been successfully welded.

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49. Friction Welding. Friction welding is a process in which mechanical energy is converted to thermal energy through friction. The most common method for friction welding is illustrated in Figure 32. Two cylindrical bars are aligned, one is rotated while the other is held stationary. The process is controlled by regulating the speed of the rotating member and the force at the rubbing surfaces to develop sufficient heat and metal displacement for welding.

Although the principles of friction welding are not new, application on a production basis is quite recent. However, the process has found wide acceptance and a number of friction welding machines have been developed with several speeds and adjustments to provide the necessary versatility.

The carbon steels and low alloy steels are readily welded by the friction welding process. The higher carbon steels and certain low alloy steels may require a postheat treatment depending upon the welding cycle employed and the intended service conditions. In general, the heat treatment of friction welded parts is much the same as flash welded parts.

50. Stud Welding. Stud welding is an arc welding process in which an electric arc is struck between a metal stud and another piece of metal. When the surfaces to be joined are properly heated they are brought together under pressure. Partial shielding may be obtained by the use of a ceramic ferrule surrounding the stud.

In stud welding, a stud welding gun is used to properly position the stud on the work piece. Manual pressure holds the stud on contact with the work piece so that the welding circuit is completed. After the circuit is completed the gun automatically withdraws the stud a short distance to create a gap and an electric arc. Then, simultaneously, the flow of electric current is stopped and the stud is plunged into the puddle of molten metal which has formed on the surface of the work piece. The process is similar to conventional arc welding because, in effect, the stud serves as a consumable electrode while the current is flowing. Figure 33 is a schematic diagram of the stud welding process.

The equipment used in stud welding consists of a source of dc welding current, a stud welding gun, ferrules for shielding the arc, and controls, including timing devices. The equipment is usually designed with portability in mind, although stationary equipment for large scale operations are in wide use today.

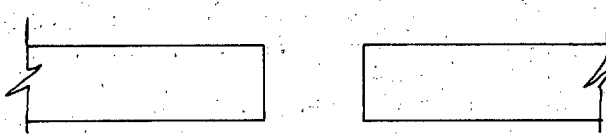
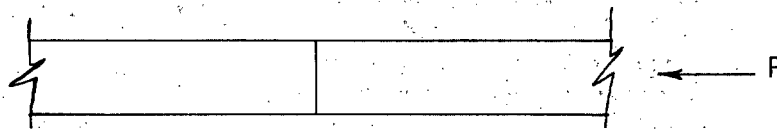
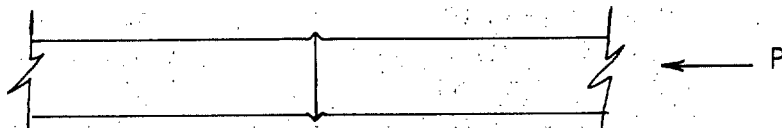
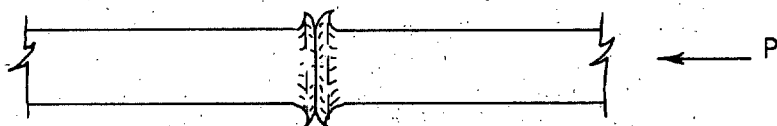
Welding studs are usually supplied with a quantity of welding flux either recessed within or permanently attached to the welding end of the stud. Generally, welding studs are made from low carbon steels with a carbon content ranging from 0.15 to 0.23 percent. Minimum tensile properties in the order of 60,000 psi ultimate strength, 50,000 psi yield strength, and 20 percent elongation in 2 inches are often specified.

In practice the same restrictions that apply to the metal-arc welding of carbon steels apply to stud welding. Carbon steels with a carbon content up to 0.30 percent may be welded without preheating. When the carbon content exceeds 0.30 percent, particularly in heavy sections, preheating is advisable in order to prevent cracking in the heat affected zone. In some cases, a combination of preheating and post-heating has proven beneficial.

Low alloy steels may be satisfactorily stud welded without preheating provided the carbon content is held to 0.12 percent maximum. Preheating is necessary when the carbon content exceeds 0.12 percent to avoid cracking in the heat affected zone.

The heat treatable high-strength low-alloy structural steels require more attention since these steels usually are sufficiently hardenable to form martensite in the heat affected zone. These steels are quite sensitive to underbead cracking and usually the weld area is low in ductility. Preheating to about 700°F is recommended when steels of this category are stud welded.

51. Spot Welding. Spot welding is a resistance welding process. Lapped work pieces are positioned between two electrodes to which pressure is applied to hold the work pieces together. Resistance to the electric current passed through the material between the electrodes produces sufficient heat to effect local

MIL-HDBK-723A**30 NOVEMBER 1970**Rotating
MemberRotating Member Brought
Up to Desired RPMRotating
MemberNonrotating Member Introduced to
Rotating Member and Pressure AppliedRotating
MemberPressure and Rotating Maintained
Until Required Heat Is Obtained at
InterfacesRotation is Stopped and Pressure Is
Either Maintained or Increased
For a Specified Period of Time**FIGURE 32. The Friction Welding Process**

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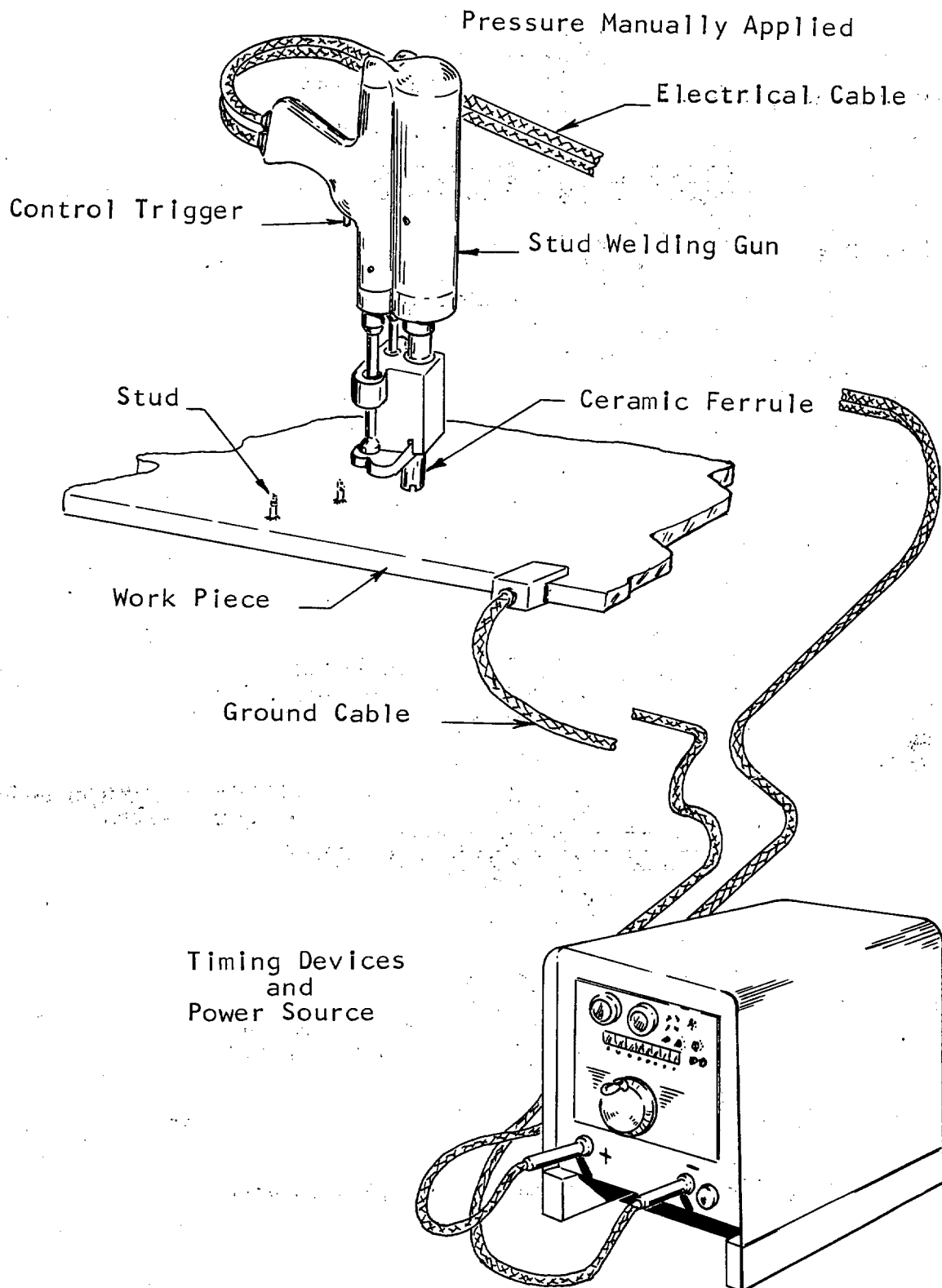


FIGURE 33. The Stud Welding Process

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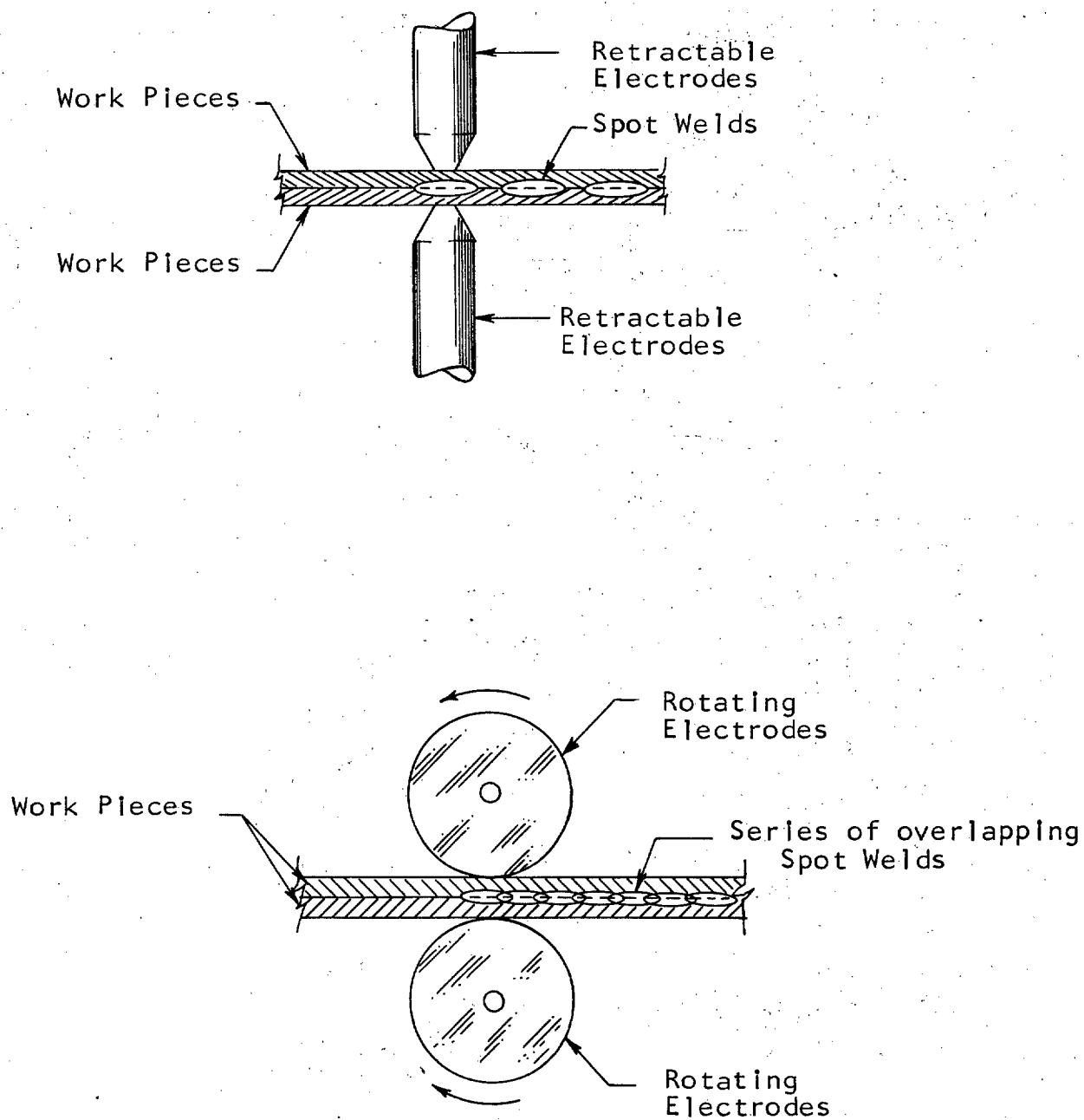


FIGURE 34. Spot Welding and Seam Welding Processes

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fusion of the work pieces. The size and shape of the individually formed welds are limited by the size and shape of the electrodes.

a. **Roll-spot welding.** A spot welding process in which circular, rotating electrodes are used to produce a series of aligned, spaced, spot welds.

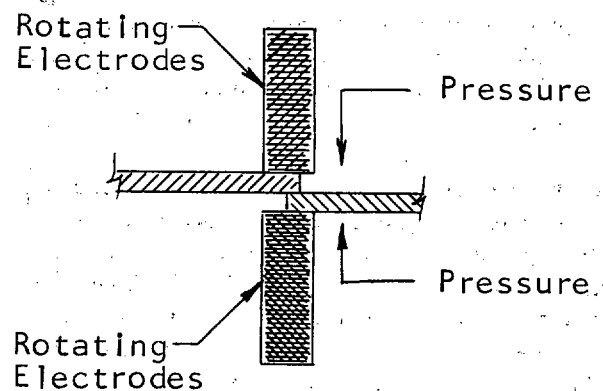
b. **Seam welding.** A spot welding process in which circular, rotating electrodes are used to produce a series of aligned, overlapping spot welds.

Figure 34 shows the characteristic differences between spot and seam welding. The important difference between spot and seam welding is that in spot welding the electrodes are withdrawn out of contact with the weld area after each individual weld or simultaneously made group of welds, whereas in seam welding at least one rotating electrode maintains continuous pressure on the weld area.

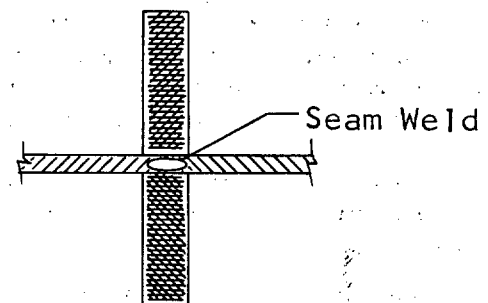
One widely used modification of the seam welding process is known as "mash welding". This produces a weld in which the overlap of the mating pieces comprising the joint is much less than for the conventional seam welded joint. High quality joints can be produced by mashing down the double thickness of an overlap to approximately the thickness of one member of the assembly. Figure 35 shows a mash seam weld set up. Low carbon steel sheet up to 1/16 inch thick can be successfully mash welded if the overlap distance is held to 1-1/2 times the stock thickness. Tack welding or clamping to maintain the overlap ahead of the electrodes is advisable.

Basically, a spot or seam welding machine consists of three principal elements:

(1) The electrical circuit including the welding transformer, and a secondary circuit including electrodes, which conducts the welding current through the work pieces.



Before Welding



Completed Joint

FIGURE 35. Mash Seam Welding

(2) A mechanical system consisting of the frame and apparatus for holding the work and applying the necessary welding force or pressure.

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(3) Equipment for controlling various functions of the process such as current initiation and duration, current magnitude and other process sequences.

The surfaces of the parts to be welded should be free from dirt, grease, paint, oxides or other films since these foreign substances tend to increase surface resistance, with resultant variation in the amount of heat generated at the weld area. Consequently, weld quality and consistency suffer. There are numerous methods of cleaning used in preparing steels for spot and seam welding. The most widely used include vapor degreasing, chemical cleaning, wire brushing and scraping.

Most specifications that govern the production of high quality spot and seam welds require the development of welding schedules which establish specific values for all of the welding variables before production welding is permitted to start. The suitability of the schedule is usually determined by the preparation and testing of a specified number of samples. A weld schedule is required for each material, or combination of materials and each combination of thicknesses that will be welded in production. The weld schedule should be strictly adhered to in production welding to maintain a high level of weld quality.

High quality spot or seam welds are dependent upon good design, the use of proper welding procedures and effective in-process controls. In designing the weld joint, consideration must be given to the spacing of spot welds with respect to one another to avoid shunting losses through prior welds. Minimum edge distances (location of weld with respect to sheet edge) must be established to prevent weld metal expulsion from between the joint members.

In high quality welding, representative samples from each welding machine are tested periodically to ensure that a high level of weld quality is being maintained during production. The usual practice for high quality spot and seam weld production is to compare samples with established quality standards on the basis of a number of factors which affect weld quality.

These factors, in general, are related to the weld structure and include the following:

(1) Penetration Requirements: Penetration into the base metal is ordinarily permitted to vary from 20 to 90 percent of the thickness of the member.

(2) Weld Symmetry: Welds should be symmetrical around the plane of the faying surfaces.

(3) Weld Diameter: Minimum weld nugget diameters are generally related to minimum shear strengths required.

(4) Interface Expulsion: Generally caused by excessive current and results in internal cavitation that usually reduces weld strength.

(5) Cracks and Porosity: Cracks and porosity within the weld nugget are caused primarily by excessive current and insufficient electrode force.

(6) Lack of Fusion: Lack of fusion at the weld interface may be due to insufficient current or weld time.

(7) Surface Appearance and Electrode Pick-Up: Electrode pick-up usually results from improperly cleaned electrode tips (or faces in seam welding). Excessive current may be a contributing factor.

(8) Surface Indentation: Excessive surface indentation results from the use of excessive heat or weld time, excessive electrode force or improperly contoured electrodes.

(9) Sheet Separation: Excessive sheet separation results from the same causes as excessive surface indentation. Sometimes edge cracks accompany excessive sheet separation.

Spot or seam welding of carbon steels is usually limited to low carbon steels with a maximum of 0.15 percent carbon content. Higher carbon contents require the use of special welding techniques involving a machine postheating cycle to avoid undesirable weld structures, cracking and extremely low ductility in the weld region.

Welding of low-alloy and high-strength low-alloy structural steels requires special welding techniques to reduce the hardness and avoid

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excessive brittleness in the weld area. Means can be provided in the machine for preheating and/or tempering the weld zone to improve ductility.

Some of the low-alloy high-strength structural steels may be welded without the benefit of preheating in the machine. In such cases welding is followed by tempering in a furnace at about 1100°F to eliminate any undesirable weld zone microstructures and to improve weld ductility.

52. Projection Welding. Projection welding is a resistance welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work pieces held together by electrode pressure. The resultant welds are localized at predetermined points by the design of the parts to be welded. The localization is usually accomplished by projections, bosses or inter-sections.

Projection welding is a modification of the spot welding process. Machines and process controls similar to those employed in spot welding are used. One big difference in equipment is the electrode employed in projection welding. The pointed or domed electrodes used in spot welding are replaced by electrodes with flat or recessed faces as shown in Figure 36. Projection welding electrodes are often designed to maintain alignment of the parts during welding and to act as work locators.

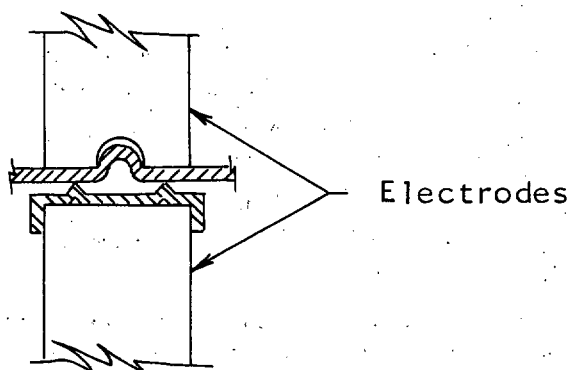


FIGURE 36. Projection Welding

Projections are formed in various ways such as by forming in a punch press or by machining. They may be of circular cross section or they may be square, oval or elongated depending upon the configuration of the parts to be welded. Parts with typical welding projections are shown in Figure 37. When the parts to be welded are of differing thickness, the projections are usually mounted on the thicker material, in order to maintain heat balance on both sides of the weld.

Projection welding lends itself well to the joining of relatively small parts that can be assembled in holding jigs prior to introduction into the welding machine. Examples include many types of studs, nuts, screws and stampings. Projection welding of steels is generally confined to the low carbon variety with less than 0.20 percent carbon content.

53. Residual Stresses.

a. General. When two pieces of steel are joined by welding, the weld metal and adjacent heat-affected base metal undergo considerable expansion on heating, and contract upon cooling to room temperature. If the two pieces are free to move they will be drawn closer together during contraction of the weld metal. If conditions are such that the pieces cannot move freely toward each other during contraction, then the weld area is said to be "under restraint". The forces set up by the restraining action create residual or "locked-in" stresses in the weld region. Generally the stresses are the highest in the metal near the center of the weld, which is the last to cool.

b. Stress relief. Although not always the case, residual stresses in welded structures are considered to be detrimental. There are two practical methods of reducing or eliminating residual stresses in welded structures: (a) thermally (stress relief heat treatment), (b) peening (hammer blows on the weld deposit).

Peening is frequently used to relieve residual stresses but its effectiveness is questionable because the method is difficult to control. Stress relief by thermal means is the more effective of the two. This is usually accomplished by heating the entire welded structure in a furnace or by local heating with a gas torch.

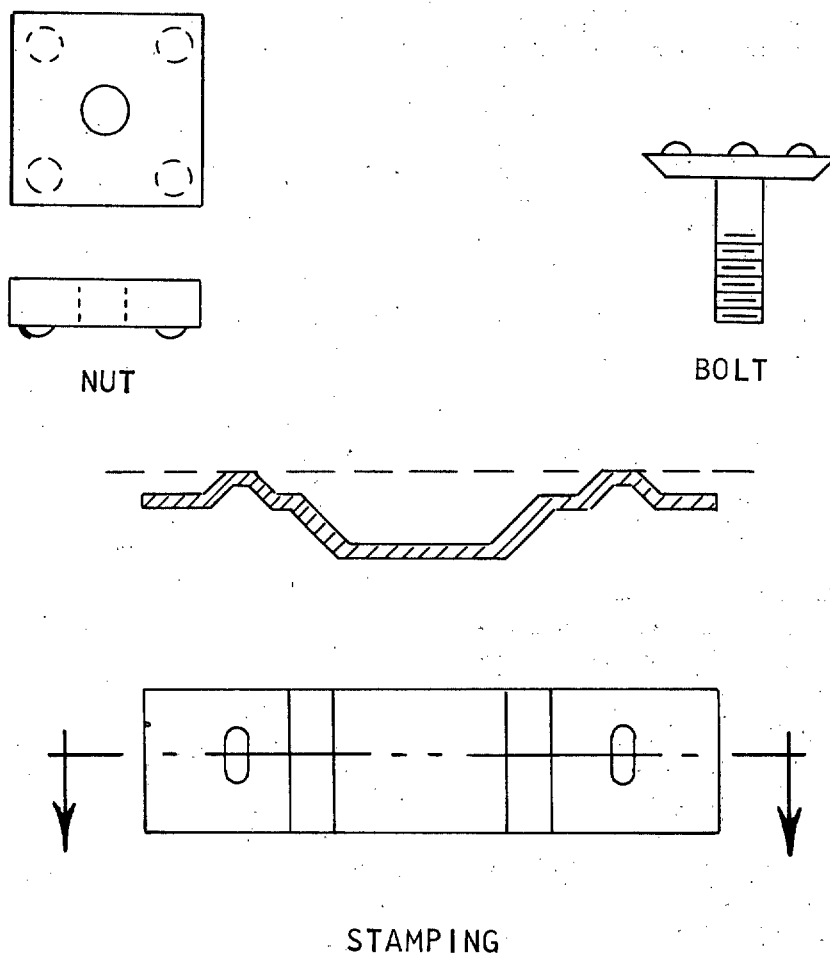
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FIGURE 37. Examples of Fasteners and Clips Designed for Projection Welding

In general, the stress relief of low carbon and low alloy steel welded structures is accomplished at temperatures ranging from 1100°F to 1200°F. Usual soaking time at temperature is one hour for each inch of thickness, with a one hour minimum. Cooling should be as gradual as possible.

c. Control of residual stresses. Much can be done to control residual stresses during the fabrication of welded structures, for example:

(1) The assembly and welding sequences should permit movement of the detail parts during welding. Joints of maximum fixity should be welded first.

(2) An intermittent sequence of welding such as "skip" or "backstep" welding is often advantageous.

(3) The introduction of bending stresses during welding should be avoided.

(4) Avoid overwelding, i.e., excessively large welds.

(5) Peening of all weld beads, except root and last bead, in multiple weld bead joints may be helpful.

d. Cracking. While the cracking conditions described below may occur in many of the low carbon and medium carbon steels, low alloy

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Cracking of welded joints results from the presence of localized stress which at some point exceeds the ultimate strength of the material. When cracks occur during welding, usually little or no deformation is apparent.

Probably the most troublesome form of cracking that occurs in the weld deposit is termed "hot cracking". Factors that lead to the formation of "hot cracks" in the weld deposit are high joint rigidity, the contour of the weld bead, a high carbon content and a high sulphur or silicon content. This type of cracking usually occurs in the last metal to freeze and is intergranular in nature. A convex bead is less susceptible to cracking than a concave bead. A stress concentration is developed at the thinnest and hottest part of a concave bead during cooling from the welding temperature, and a convex bead, because of its thicker center section, is less likely to crack.

Small star-shaped cracks are one type of hot crack associated with weld craters. Unless

special care is exercised, there is usually a tendency to form a weld crater when the welding operation is interrupted. Crater cracks may be starting points for longitudinal weld cracks, particularly when they form in a crater at the end of a weld bead. To avoid crater cracks it is necessary to fill the crater with additional metal before breaking off the welding operation. Preheating usually minimizes any tendency toward hot cracking by reducing stresses in the area.

A basic problem encountered in welding many of the low alloy steels is a type of cracking termed "underbead cracking". When underbead cracking occurs it is invariably located under the fusion zone in the heat affected zone of alloy steels. Figure 38 illustrates underbead cracking. Underbead cracking is attributed to the affect of dissolved hydrogen released from the austenite as it transforms. This type of cracking in alloy steels can be virtually eliminated by preheating and the use of a low hydrogen welding process. There is no tendency toward underbead cracking in low carbon steels.

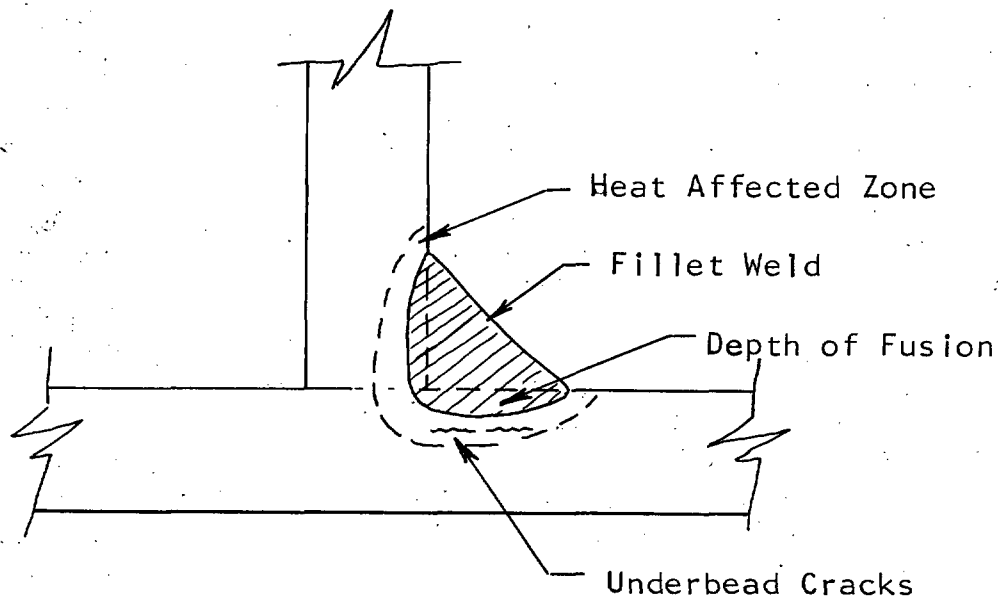


FIGURE 38. Underbead Cracking in a Fillet Weld

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Sometimes cracks occur within the heat-affected zone of the base metal. These cracks are usually longitudinal in nature and almost always associated with the hardened zone developed in hardenable steels, such as the medium carbon and low alloy steels. Hardness and brittleness in the heat-affected zone of the base metal are metallurgical effects produced by the heat of welding and are the chief factors which tend to cause cracking during welding. When base metal cracking is encountered with hardenable steels, improvement can be obtained by (a) using a suitable preheat, (b) increasing heat input which will tend to retard the cooling rate, and (c) selecting the most suitable electrode for the steel being welded.

54. Brazing. Brazing is a term used to describe a group of welding processes wherein coalescence is produced by heating to suitable temperatures above 800°F and by using a non-ferrous filler metal having a melting point below that of the base metal. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction. In the brazing process there is no melting of the metals that are being joined. The molten brazing alloy flows between the heated surfaces of the joint members by capillary action, or it is melted in place between the surfaces to be joined. The bond between the brazing alloy and base metal is obtained by slight diffusion of the brazing alloy into the heated base metal, by surface alloying of base metal with the brazing alloy, or by a combination of both.

Brazing processes have been classified according to the heating method used. Heating methods commonly employed in brazing carbon and alloy steels include the following:

a. Torch brazing - the most commonly used method. Gas mixtures may be air-gas, air-acetylene, oxyacetylene, or other oxy-fuel gases.

b. Furnace brazing - used extensively when parts can be preassembled or jigged and when atmosphere control is required. The atmosphere may be one of a number of types, combusted fuel gas, dissociated ammonia, high purity hydrogen, purified inert gases or vacuum atmospheres.

c. Induction brazing - used when parts are self jigging or can be fixtured easily, and when rapid, economic heating is required, as with large production runs of single items.

The brazing alloy classifications used for brazing carbon and low alloy steels include the

TABLE VII. BRAZING ALLOYS FOR CARBON AND LOW ALLOY STEELS

Brazing Alloy	Brazing Temperature Range (°F)	Remarks
BCu (Copper)	200 to 2100	Lap and butt joints commonly used.
RBCu-Zn-A (Copper-Zinc)	1670 to 1750	Overheating should be avoided because voids may form in joints as a result of entrapped zinc vapors.
BAG-1 (Silver Base)	1145 to 1440	Flows freely into capillary joints.
BAG-1A (Silver Base)	1175 to 1400	Low temperature applications. Free flowing.
BAG-2 (Silver Base)	1295 to 1550	Good "bridging" characteristics. Forms fillets readily.
BAG-5 (Silver Base)	1370 to 1550	Cadmium free. Applications involving "step" brazing.
BAG-18 (Silver Base)	1325 to 1550	Good "wetting" in controlled atmosphere or vacuum brazing without flux.

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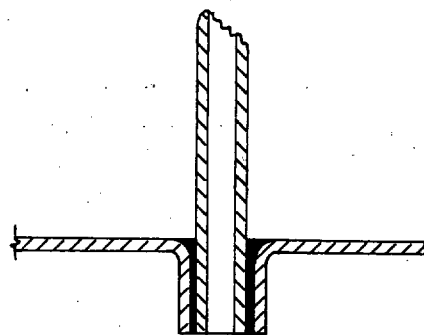
copper and copper-zinc alloys and the silver base alloys. It should be noted that the copper-phosphorus brazing alloys should not be used for joining ferrous alloys because the phosphorous content may cause the formation of brittle phosphides at the interfaces of the joint and brazing alloy. Cracking will occur through the brittle phosphide if the joint is stressed after brazing. Characteristics and usability of the filler alloys for brazing carbon and low alloy steels are presented in Table VII.

Brazing alloys can be obtained in strip, wire and powder form. Department of Defense and industry specifications governing the procurement of brazing alloys include QQ-S-561, Mil-B-15395 and AWS A5.8.

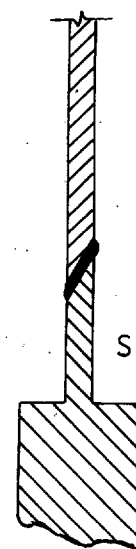
A variety of brazing fluxes are available. Selection is usually based on the temperature range to be used in brazing. Fluxes are specially compounded mixtures of fluorides, borides and wetting agents which melt below the melting temperature of the brazing alloy, clean the surface prior to alloy flow, prevent oxidation of the brazing alloy and base metal surface during brazing, promote flowing of the brazing alloy, and cause it to wet the surfaces being brazed. Fluxes should be removed as soon as possible after brazing is completed. Many fluxes are corrosive and may cause corrosion in the joint.

Basically there are two types of joints used in brazing; they are the lap joint and the butt joint. The lap joint provides the strongest joint of the two, since the overlap can be adjusted to develop strengths in the joint equal to or better than the parent metal despite the lower unit strength of the brazing alloy. Joint design and joint clearance should be selected in accordance with practices recommended by the American Welding Society. Figure 39 shows several typical brazed joint designs. Cleanliness of the surfaces to be joined is of prime importance in brazing, particularly when brazing will be accomplished by the controlled atmosphere furnace method without the application of fluxes.

When brazing the carbon and low alloy steels with copper or copper-zinc alloys there is some grain growth in the base metal because of the high brazing temperatures involved. The accompanying decrease in mechanical properties



Lap Joints



Scarf Joint

FIGURE 39. Examples of Brazed Joints

may not be objectionable for some applications. When necessary, the grain structure and mechanical properties of the material can be improved by reheating the brazed assembly above the critical range of the steel, provided the brazing alloy used has a melting temperature above the austenitizing temperature of the steel.

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55. Soldering. Soldering is defined as a joining process wherein coalescence between metal parts is produced by heating to suitable temperatures generally below 800°F and by using non-ferrous filler metals (solder) having melting temperatures below those of the base metals. The solder is usually distributed between the properly fitted surfaces of the joint by capillary attraction.

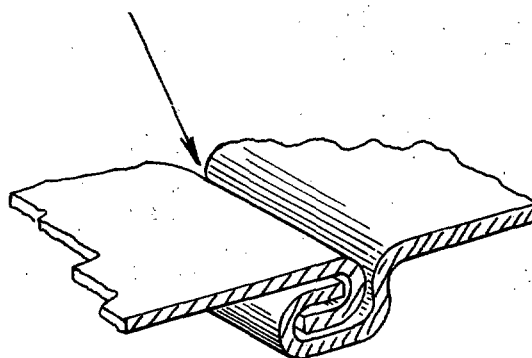
The more common heating methods employed in soldering include the soldering iron, or soldering copper as it is sometimes called, torch, oven or furnace, and induction coil.

The two basic types of joints used in soldering are the conventional lap joint and butt joint. Joint clearances of .002 to .005 inch are recommended, however, clearances ranging to .010 inch have been used. Higher strengths can be obtained with the lap joint. Joint strengths considerably higher than attainable with the conventional lap joint are possible by interlocking the parts to be joined and employing the solder only to seal the joint. Figure 40 shows typical interlock joint designs. In order to obtain maximum bond strength, the surfaces to be joined must be thoroughly cleaned. Foreign materials such as grease, oil, dirt, scale and finger marks should be eliminated to insure uniform and continuous contact between the solder and the base metal. Cleaning may be accomplished by degreasing, acid cleaning, or by wire brushing, shot blasting, filing, or grinding. Mechanical cleaning has the advantage over the other methods in that the surface is roughened thus creating little irregularities against which the solder can solidify. This results in increased gripping power.

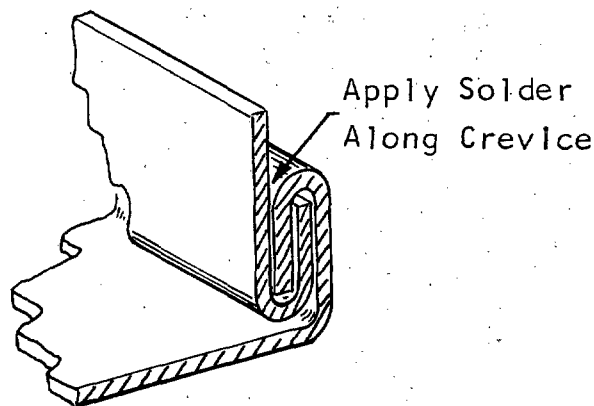
The most common solders are composed of tin and lead in varying amounts. Solders with special properties may also contain antimony, silver, bismuth or indium. Most of the common solders are included in Federal Specification QQ-S-571 and industry specifications ASTM B-32 and ASTM B284.

The main function of a flux is to promote good wetting action between the solder and the base metal. Fluxes may be highly corrosive, mildly corrosive, or noncorrosive depending on

Apply Solder Along Crevice



Interlock Butt Type Joint



Interlock Corner Joint

FIGURE 40. Interlock Solder Joints

the ingredients. They are available in either liquid or paste form. Fluxes, both liquid and paste, can be procured to Federal Specification O-F-506.

Flux residues that might corrode the base metal or prove harmful to the soldered joint must be removed or neutralized after the soldering operation is completed. This is particularly important in cases where the service environment might be humid. A noncorrosive type flux should be used in cases where, for reasons of joint design, all surfaces are not accessible to removal of flux residues after soldering.

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56. Inspection of Welds, and Brazed or Soldered joints. Weldment defects may be classified as being in three general categories: dimensional defects, structural discontinuities, and those associated with the properties of the weld or welded joint. The purpose of this section is to briefly describe some of the defects encountered in welding practice and the inspection methods used to establish the soundness and integrity of a weld or weldment. For a more complete treatment of the subject reference should be made to the Inspection Handbook for Metal-Arc Welding published by the American Welding Society.

The acceptance of weldments depends upon, among other things, the maintenance of specified dimensions whether it be the size and shape of welds or dimensions of a completed assembly. Any departure from the specified requirements should be regarded as a dimensional defect subject to correction before final acceptance of the weldment.

Welding involves the application of heat to local sections of the material. Expansion and contraction of the heated metal creates stresses of varying magnitude which persist after cooling. These stresses cause warpage and distortion in welded assemblies. Warpage or distortion is controllable, to a large degree, by the judicious use of peening, clamps, jigs, or fixtures and by proper welding sequence. Warpage or distortion is often corrected by a straightening operation which may involve the application of heat.

The size of a fillet weld is based on the length of the shortest leg in its triangular cross section. The effective throat thickness of a fillet weld is the shortest distance from the root to the face of the diagrammatic weld. For example, the effective throat thickness of an equal leg 45 degree fillet weld is 0.707 multiplied by the normal leg size of the weld, as shown in Figure 41. The size of a butt weld is based on the joint penetration plus the root penetration when so specified. The profile of a weld may have considerable effect upon its performance in service. Excess convexity tends to produce notches, while excess concavity may actually reduce the strength of a weld. Figure 42 illustrates acceptable and defective weld

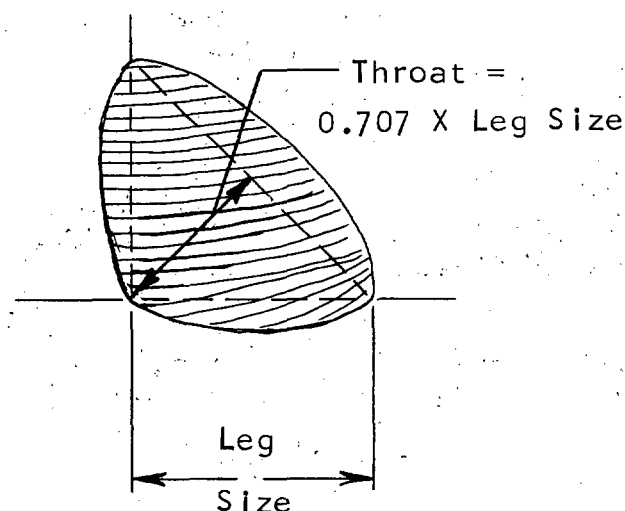


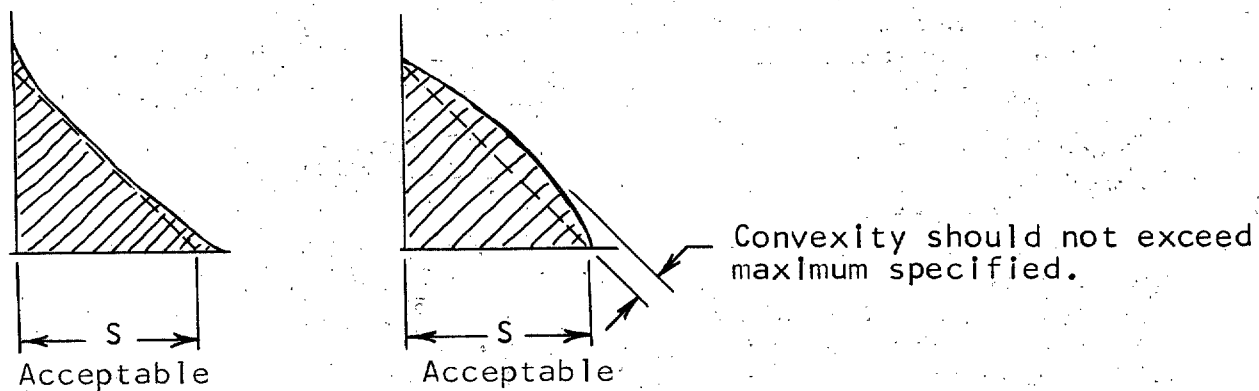
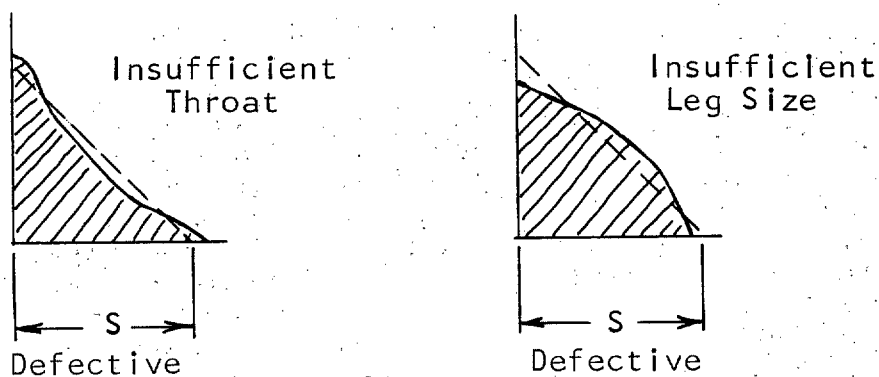
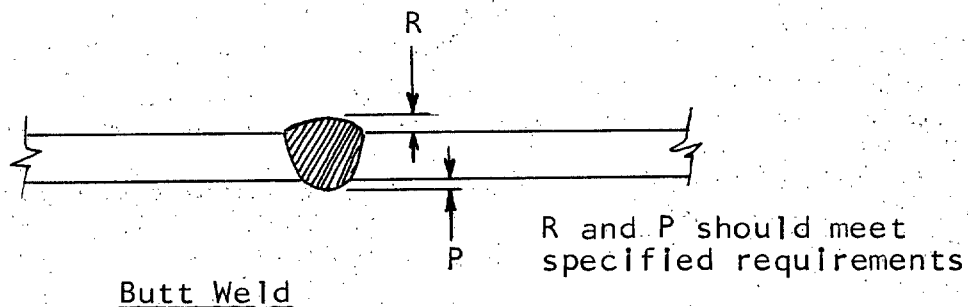
FIGURE 41. Effective Throat Thickness of an Equal Leg 45 Degree Fillet Weld

profiles. Weld size deficiencies may be detected visually and with the aid of suitable weld gauges. Weld size deficiencies can be corrected by selecting the proper size filler metal, and employing the proper welding technique. Undercut and overlap are the result of improper welding technique. These defects can be detected visually and are illustrated in Figure 43. Incomplete penetration of butt welds welded from one side may be detected visually provided the side opposite to the welding side is accessible for viewing. Incomplete root penetration in fillet welds and butt welds welded from both sides cannot be detected visually.

Cracks may occur in the weld deposit, adjacent parent metal, or both. Cracking in weld joints results from the presence of localized stress which at some point exceeds the ultimate strength of the material. Cracks open to the surface can be detected visually.

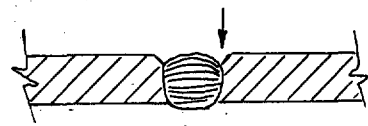
Low power magnifying glasses, magnetic particle inspection and penetrant inspection are methods used to detect external discontinuities.

Internal discontinuities that may be present in the weld zone include porosity, non-metallic inclusions, incomplete fusion and cracks. Inspection and test methods employed to detect

MIL-HDBK-723A**30 NOVEMBER 1970** S = Leg Size S = Leg SizeFillet Weld**FIGURE 42. Acceptable and Defective Weld Bead Profiles**

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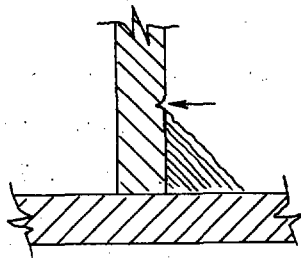


Undercut

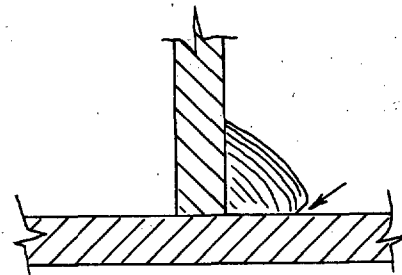


Overlap

Butt Weld



Undercut



Overlap

Fillet Weld

FIGURE 43. Undercut and Overlap in Fillet and Butt Welds

internal defects include radiographic examination, ultrasonic inspection, magnetic particle inspection, fraction test, bend test, and microscopic or macroscopic examination. Porosity and inclusions are usually the result of improper precleaning or poor gas coverage. Incomplete fusion can usually be traced to improper welding procedures.

Specific mechanical and chemical properties are required of all weld joints in any given weldment. The requirements depend on the specifications involved and any departure from the specified requirements should be judged as a defect. These properties may be determined by testing pre-fabrication or in-process test plates, although in many cases sample weldments taken from production are tested.

Resistance welds (spot, seam and projection) and brazed or soldered joints generally must meet the standards required by the contract or design drawings. Methods of inspection are usually dictated by the requirements.

The criteria for acceptance of carbon and low alloy steel weldments are generally a part of, or referenced in, most specifications, codes, standards and regulations controlling welding practices today. Some specifications contain two or more levels of acceptance based upon known service requirements or the intended function of the welded part. The following specifications, codes and standards largely control welding practices today. Included are specifications related to brazing and soldering practices.

MIL-HDBK-723A**30 NOVEMBER 1970**DEPARTMENT OF DEFENSE

Mil-W-41	Welding of Armor, Metal-Arc, Manual with Austenitic Electrodes, for Aircraft.
Mil-W-6858	Welding, Resistance, Aluminum, Magnesium, Non-Hardening Steels or Alloys, Nickel Alloys, Heat Resisting Alloys, and Titanium Alloys, Spot and Seam.
Mil-S-6872	Soldering Process, General Specification for.
Mil-W-6873	Welding, Flash, Carbon and Alloy Steel.
Mil-B-7883	Brazing of Steels, Copper, Copper Alloys, and Nickel Alloys.
Mil-W-8611	Welding, Metal-Arc and Gas, Steels, and Corrosion and Heat Resistant Alloys, Process for.
Mil-W-12332	Welding, Resistance, Spot and Projection, for Fabricating Assemblies of Low Carbon Steel.
Mil-B-12672	Braze-Welding, Oxyacetylene, of Built-Up Metal Structures.
Mil-B-12673	Brazing, Oxyacetylene of Built-Up Metal Structures.
Mil-W-21157	Weldment, Steel, Carbon and Low Alloy (Yield Strength 30,000 - 60,000 psi).
Mil-W-45223	Welding, Spot, Hardenable Steels.
Mil-W-46086	Welding, Homogeneous Armor, Metal Arc, Manual.
MIL-STD-278	Welding and Inspection of Machinery, Piping and Pressure Vessels for Ships of the United States Navy.
MIL-STD-1261	Welding Procedures for Constructional Steels.

NAVSHIPS 0900-000-1000 Fabrication, Welding and Inspection of Ship Hulls.

NAVSHIPS 0900-006-9010 Fabrication, Welding and Inspection of HY-80 Submarine Hulls.

MIL-HDBK-721(MR) Corrosion and Corrosion Protection of Metals
H-56 Arc Welding
INDUSTRY

ASME Boiler and Pressure Vessel Code.

AWS D1.0 Code for Welding in Building Construction.

AWS D2.0 Specifications for Welded Highway and Railroad Bridges.

ASA B31 Code for Pressure Piping.

API Standard 1104 Field Welding of Pipelines.

SAE AMS 2665 Silver Brazing.

SAE AMS 2666 Silver Brazing (High Temperature)

SAE AMS 2667 Silver Brazing (For Flexible Metal Hose)

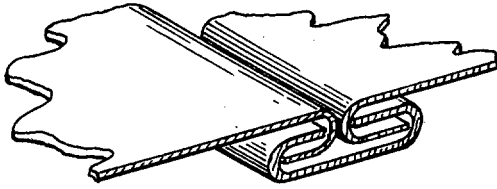
SAE AMS 2668 Silver Brazing (Flexible Metal Hose - 400°F Max Operating Temperature)

SAE AMS 2669 Silver Brazing (Flexible Metal Hose - 800°F Max Operating Temperature)

SAE AMS 2670 Copper Furnace Brazing (Carbon and Low Alloy Steels)

57. Mechanical Fastening. The number of mechanical fasteners and fastening methods other than those briefly described herein is almost infinite. The most common mechanical fastening methods employed include lock seaming, rivets, screws, nuts and bolts.

Low carbon steel sheet and strip in thicknesses of 1/16 inch and less lend themselves well to joining by lock seaming. Figure 44 shows a typical lock joint design. The open seam may be soldered if a leak tight joint is desired (Figure 40).

MIL-HDBK-723A**30 NOVEMBER 1970****FIGURE 44. Lock Joint Design**

Riveting is a common method used to join low carbon and low alloy structural steels. Its use, however, has been overshadowed somewhat by the higher joint efficiencies obtainable with joints of welded design. Rivet types and sizes in use are multitudinous. Rivet designs include universal heads, flat heads, and countersunk heads with solid or tubular shanks. Riveting may be accomplished either hot or cold depending upon the application. The chief advantages of riveting are that it affords a quick method of

joining and, as practiced cold, it avoids the hazards of heating (warping and distortion) that are encountered in welding.

A wide variety of screws are used in joining steel components. Screws are available in numerous sizes and designs including flat fillister heads, drilled fillister heads, oval fillister heads, slotted hex heads, hexagon socket heads, slotted hexagon shaped heads and slotted flat countersunk heads with either solid or drilled out shanks. Screws may be either carbon or low alloy steel and may be obtained with a cadmium, zinc or phosphate protective coating.

Nuts and bolts are commercially available in a wide assortment of sizes and types including round heads, square heads, hexagon heads, drilled heads, square and hexagon socket type heads with solid or drilled out shanks. They may be obtained with cadmium, zinc, black oxide or phosphate coating for added corrosion resistance.

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Chapter 4

Selection Criteria

INTRODUCTION

This chapter is concerned with the identification and application of selection criteria that are the basis for determining the suitability of an alloy for a particular application. Iron and wrought steel products are used primarily as structural members which must carry an applied load. Therefore the mechanical properties of these materials are of special interest. For this reason, tensile properties and related mechanical properties, elastic and plastic behavior, brittle fracture, and fatigue are discussed in detail.

In addition to these mechanical properties, certain pertinent physical properties, corrosion, stress corrosion, propellant compatibility, thermal conductivity and expansion, and density are discussed.

In the final section of the chapter the problem of materials selection as related to design requirements, material availability, costs, materials properties, and manufacturing considerations, is discussed.

MECHANICAL PROPERTIES

58. Elasticity. Consider a rod being acted upon by external forces, Figure 45. The intensity of load is called the stress in the rod. Stress is defined as the magnitude of the load divided by the area over which it acts.

$$f = \frac{P}{A_0} \quad (1)$$

where:

f = stress

P = applied load

A_0 = the original cross-sectional area

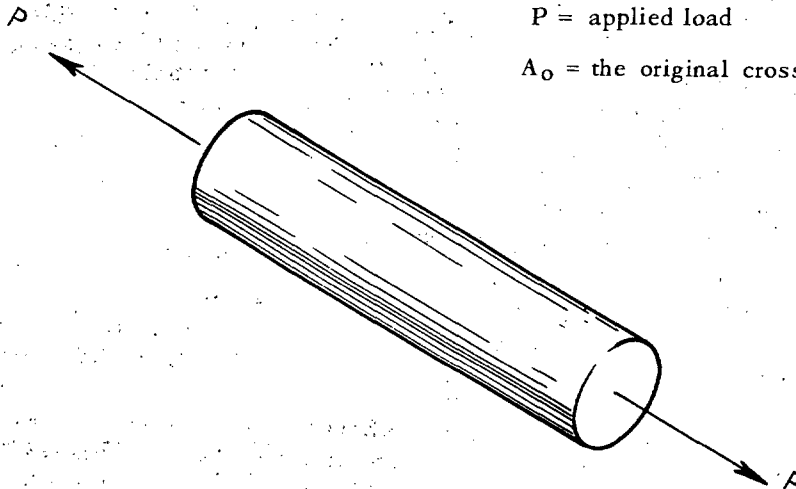


FIGURE 45. A Rod Subjected to Tensile Loading

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Stresses may be either tensile or compressive and are usually expressed in units of pounds per square inch (psi) or a similar load per unit of area term. A tensile stress is one which would tend to make the bar shown in Figure 45 longer, a compressive stress would make it shorter.

If a force acts normal to a given cross section, the resultant stress is a normal stress. If the force acts parallel to a cross section the resultant stress is a shear stress, and the magnitude of this shear stress is obtained by dividing the force by the area of the face.

$$f_s = \frac{P}{A} \quad (2)$$

where f_s = shear stress

P = applied force acting parallel to the cross section

A = cross-sectional area

An example of shear stress is given by a pin joining two plates, as shown in Figure 46. The shear stress in the pin is:

$$f_s = \frac{P}{A}$$

where A = cross sectional area of the pin parallel to the applied load.

Every stress is accompanied by a corresponding deflection, or change in dimension, in the stressed member. For the tensile loading shown in Figure 47 the rod will increase in length an amount δ . If the loading direction was reversed and the bar was put in compression, it would increase in length an amount δ , providing that the magnitude of load remained the same. When the deflection δ , is divided by the original length, L_o , a value defined as normal conventional strain is obtained. $e = \frac{\delta}{L_o}$, e = strain in units of inches per inch (in/in).

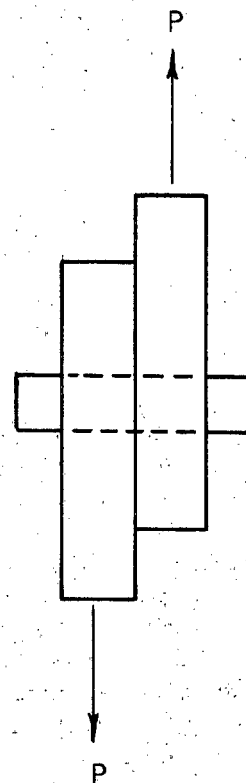


FIGURE 46. Shear Loading

Stress and strain are related by a constant, Young's Modulus, which is commonly called the Modulus of Elasticity, E , usually expressed in pounds per square inch.

$$E = \frac{f}{e} \quad (3)$$

where f = stress

e = strain

E = modulus of elasticity (about 30,000,000 psi for steel)

Knowing this relationship, based on Hooke's Law, if either f or e is known the other can be calculated.

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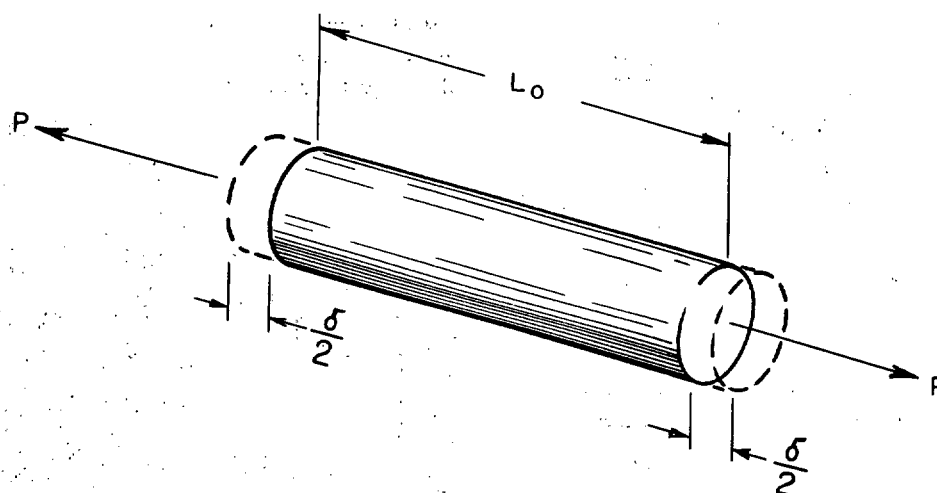


FIGURE 47. Deflection in a Rod Subjected to a Tensile Load

Shear strain, which is more complex in definition, can be described by considering Figure 48. If the rectangle is displaced by a force so that it assumes the configuration described by the dotted lines, the shear strain (e_s) is defined as:

$$e_s = \frac{\delta}{d_o}$$

Shear stress and shear strain are related in the same manner as are normal stress and strain.

$$f_s = G e_s \quad (4)$$

where G = shear modulus, $G = \frac{E}{2(1 + \mu)}$

E = modulus of elasticity

μ = Poisson's ratio (about 0.3 for steel)

The tensile properties of a material are determined by subjecting a specimen to an increasing tensile load until failure of the specimen occurs. Depending upon the instrumentation of the test, a load-deflection or a load-strain curve is usually obtained.

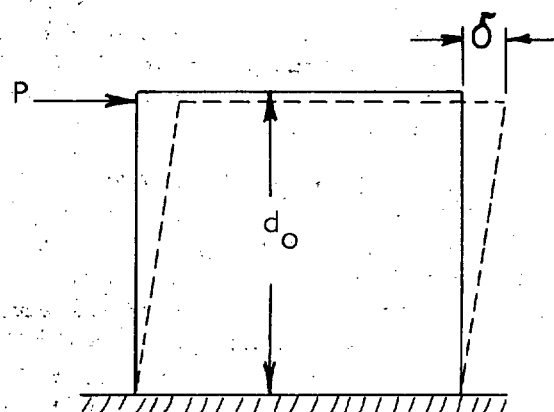


FIGURE 48. Shear Deflection

The curve in Figure 49 represents either of these curves. For engineering applications this curve is converted to a stress-strain curve, Figure 50. This curve has the same shape as the load-strain curve and is obtained by converting the load to stress by dividing the load by the cross sectional area of the specimen.

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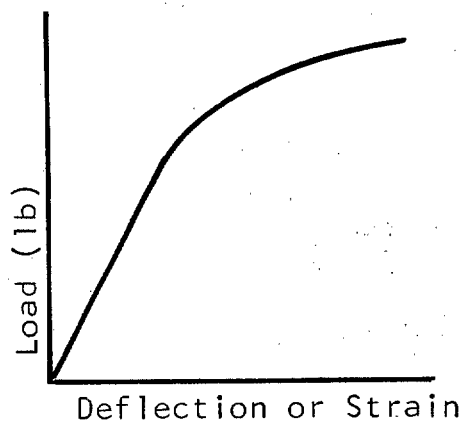


FIGURE 49. A Load-Deflection Curve

The stress-strain curve can be divided into two regions; the elastic region and the plastic region, as indicated in Figure 50. The initial straight line portion of the stress-strain (or load-deflection) curve is the elastic region. Here stress and strain are related by $f = Ee$, where E is the elastic modulus and is the slope of the stress-strain curve.

If a material is loaded to a stress, f_1 , in the elastic region a corresponding strain e_1 will occur, Figure 51. When the load is removed the total elastic strain will be recovered. If the total load is not removed but is instead reduced to f_2 , then the total existing strain will be e_2 , and the amount of strain recovered will be $e = e_1 - e_2$. This strain can be calculated by using the formula $f = Ee$.

$$f_1 = e_1 E \text{ or } e_1 = \frac{f_1}{E}$$

$$f_2 = e_2 E \text{ or } e_2 = \frac{f_2}{E}$$

so,

$$e_1 - e_2 = \frac{f_1}{E} - \frac{f_2}{E}$$

$$\Delta e = \frac{f_1 - f_2}{E}$$

No permanent deflection or strain will result if a material is stressed in the elastic region and the load is later released.

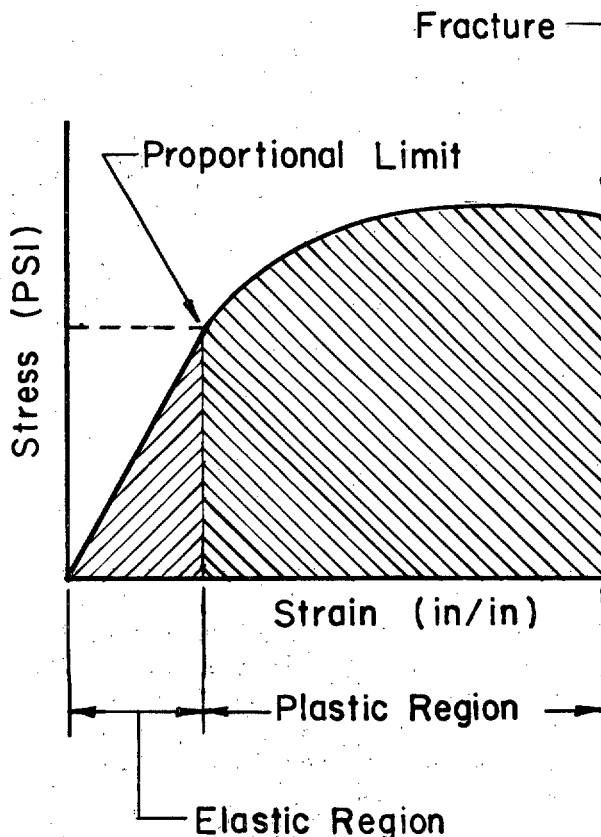


FIGURE 50. A Stress-Strain Curve

A tensile force acting along the x-axis in Figure 52 will produce a strain e_x . This force will also produce transverse strains e_y and e_z in the y and z directions respectively. As discussed previously $e_x = \frac{f}{E}$. e_y and e_z will not be as large as e_x and will be negative as the bar will contract in these two directions. The ratio of e_y and e_z to e_x is Poisson's ratio, μ , a non-dimensional term.

$$\mu = \frac{e_y}{e_x} = \frac{e_z}{e_x} \text{ or } e_y = e_z = \mu e_x \quad (6)$$

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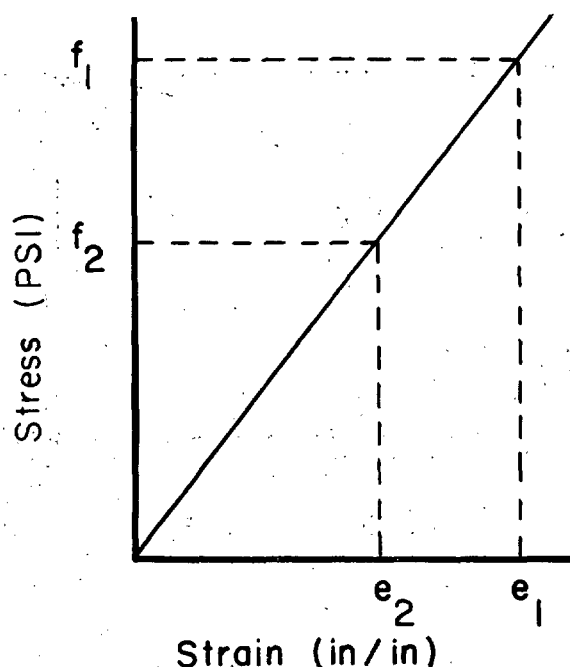


FIGURE 51. The Elastic Portion of a Stress Strain Curve

When a body is acted on by a stress or a system of stresses the total strain in a direction is determined by algebraically adding the direct $\frac{f}{E}$ strains and the Poisson's ratio strains, μe .

A material will behave elastically only until a characteristic stress is reached. At this stress the straight line portion of the stress-strain curve ends, Figure 53. This stress is the proportional or elastic limit stress. Beyond this limit the standard value of E cannot be accurately applied. The proportional limit, as defined in MIL-HDBK-5, is the stress at which the stress-strain diagram departs from a straight line by a strain of 0.0001 inch per inch.

After the proportional limit has been exceeded, stress and strain are no longer related by Hooke's Law. In this plastic region the total strain is composed of elastic strain + plastic strain. Plastic strain is permanent strain that is not recovered after the load has been removed. It is important to note that although plastic strain is occurring, elastic strain is also occurring, Figure 54. The magnitude of this elastic strain is still given by Hooke's Law as $e = \frac{f}{E}$. If a material is loaded to f_1 it will follow

the stress strain curve OAB and the total strain will be e_2 . When unloaded it will unload along BC which is parallel to the original elastic line OA. The remaining plastic strain at $f = 0$ will be e_1 . The recovered elastic strain will be $e_2 - e_1$.

59. Strain Hardening. When a metal is deformed past its proportional limit, the magnitude of the stress required for further deformation increases. This increase is caused by strain

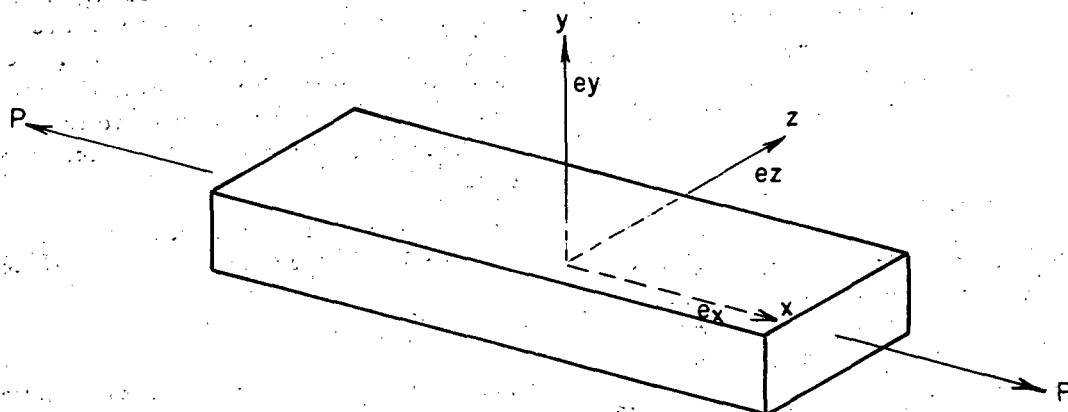


FIGURE 52. Three Dimensional Strain

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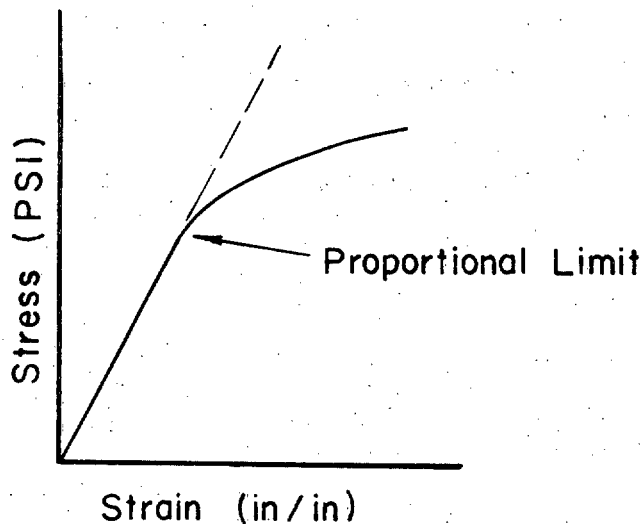


FIGURE 53. The Proportional Limit

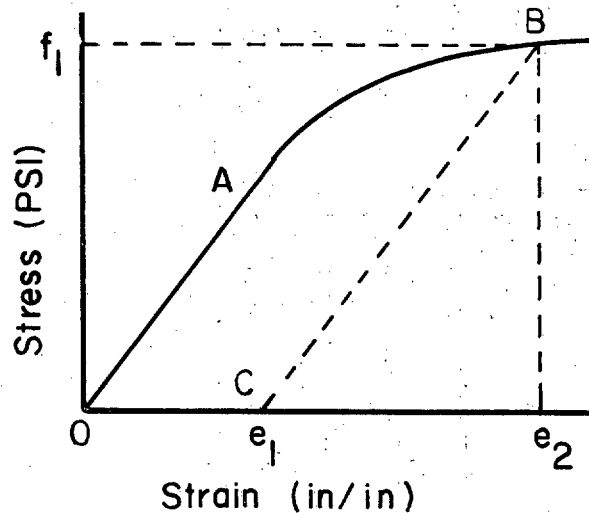


FIGURE 54. Plastic Behavior

hardening and the rate of increase is determined by the strain hardening exponent, m . For analysis the plastic portion of the stress-strain curve is often closely approximated by an equation of the form $S_0^1 = B \epsilon_0^m$, where B is a constant, and S_0^1 = true stress and is obtained by dividing the load by the actual instantaneous cross-sectional area of the bar. As previously defined the engineering stress f , is obtained by dividing the load by the original cross-sectional area ($f = P/A$). Since the area decreases, under tensile loading, with increasing plastic strain, the actual true stress is always greater than the engineering stress. ϵ_0 is the logarithmic plastic strain and is related to conventional plastic strain e by:

$$\epsilon_0 = \ln(1 + e). \quad (7)$$

In addition to describing the stress-strain behavior in the plastic region, the strain hardening exponent, m , is a measure of the uniform elongation an alloy may undergo before necking.

During a tensile test, as a tensile specimen elongates the load will increase due to strain hardening. At the same time the cross-sectional area of the specimen decreases. During the first

part of the test, strain hardening predominates and the load increases. During the later stages of the test strain hardening becomes less pronounced and the load reaches a maximum and then progressively decreases until fracture occurs. Strain will be uniform along the entire test section until the maximum load is reached. At this load some cross-section of the bar that is infinitesimally weaker than the rest of the specimen will stretch under the constant load, while other portions of the specimen will not. Because of this, localized strain will occur and the specimen will get thinner or "neck" at this particular location. Then the load will begin to decrease, the neck will continue to stretch and get thinner, and fracture will eventually occur at the neck.

The strain at which necking begins is directly related to the strain hardening exponent.

$$\epsilon_{\text{necking}} = m = \ln(1 + e). \quad (8)$$

where $\epsilon_{\text{necking}}$ = logarithmic plastic strain

e = conventional plastic strain

m = strain hardening exponent

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60. **The Tension Test.** There are two standard tensile specimens used for tensile testing. As shown in Figure 55 the specimens have either a rectangular or circular cross-section. The grips can be of any configuration that allows tensile loads to be applied axially through the specimens. The common grip configurations are shown. The general requirements for both specimens are as follows:

a. The gage section should be of uniform cross section along its length, it may taper slightly so that at the center of the gage length the width of flat specimens may be reduced to a width that is 0.010" less than the width of the specimen at the ends of the gage length. For round specimens the permissible reduction is limited to 1 percent of the diameter of the specimen at the center of the gage length.

b. The gage section should be free from burrs, scratches, pits or other surface defects.

c. The ratio of gage section length to specimen width or diameter should be at least 4:1.

d. The radius of the shoulder fillets should be large enough to preclude failures in this area.

e. The grip length should be long enough to prevent slipping or fracture in the grips.

The properties most frequently obtained from a tension test are yield strength, ultimate strength, percent elongation and reduction of area. Other properties, less frequently measured, are the elastic modulus, Poisson's ratio, and the strain hardening exponent. A typical sequence of events in tension testing is as follows:

a. The cross-sectional area of the gage section is measured.

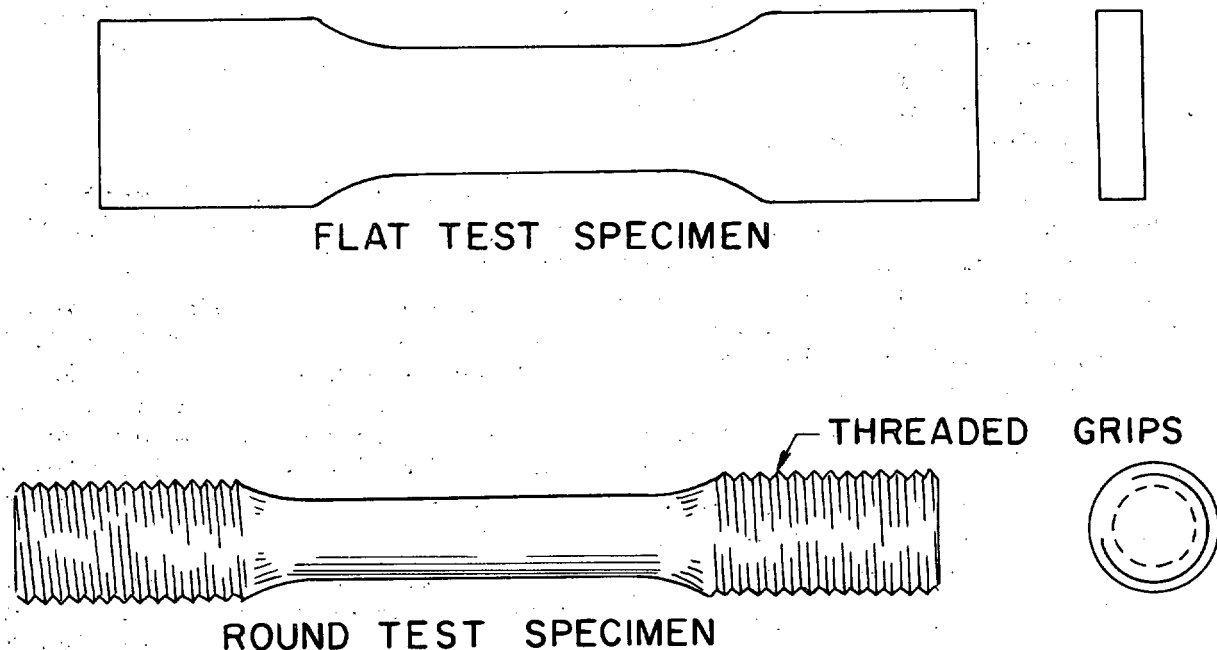


FIGURE 55. Flat and Round Tensile Specimens

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b. The specimen is marked with standard gage lengths for subsequent elongation measurements.

c. The specimen is placed into a tensile machine and a suitable strain measuring device is attached.

d. The specimen is loaded to fracture.

Depending on the type of data readout used, a load-strain, stress-strain, or load-deflection curve is obtained.

For those alloys having a distinct yield point, the stress at which the yield point occurs is the yield strength, Figure 56. For those alloys that don't have a distinct yield point, the yield strength is commonly designated as the stress at which 0.20 percent plastic strain has occurred. This stress is determined by the method illustrated in Figure 57.

A distance corresponding to 0.002 in./in. strain is measured along the x-axis. From this point, line BC is drawn parallel to OA. The intersection of this line with the curve gives the yield load, read from the y-axis. This yield load is converted to yield stress by dividing by the original cross-sectional area of the specimen.

The ultimate strength is obtained by dividing the maximum load that the specimen carried by the original cross-sectional area. This load can be obtained from the load-strain curve, Figure 57, but it is usually read directly from a dial on the tensile machine.

Percent elongation is the ratio of the increase in length of the gage section of the specimen to its original length expressed as a percent. It is measured by indexing a gage length (1" or 2" long usually) on the specimen gage section and then measuring this length after fracture. In Figure 58 the percent elongation (%el) would be:

$$\%el = \frac{\Delta L}{2"} \times 100 \quad (9)$$

Elongation measurements made in this manner are only an approximation of the true uniform

strain that an alloy can undergo before necking. The measurement is made across the fracture, introducing an error, and localized strain occurring in the necked portion introduces additional error. The true uniform elongation that can be expected can be determined by measuring the strain hardening exponent (m = slope of $\text{Log } S^1 - \log \epsilon$ curve). Then:

$$m = \epsilon = \ln(1 + e),$$

where

e = conventional plastic strain at necking.

Reduction of area is the ratio of the decrease in area at the fracture cross-section (the neck) to the original area, then:

$$\% R.A. = \frac{A_o - A_f}{A_o} \times 100 \quad (10)$$

where

A_o = original or initial cross section area

A_f = final cross section area

The tensile test is covered in good detail in Federal Test Method Standard 151, and ASTM Standard A370.

The application of tensile properties to design is straightforward. The yield and ultimate strengths designate how much load a structure can carry under ideal conditions. However, in many applications some other criteria such as fatigue characteristics, defect tolerance or shear stresses will determine the actual working stress of a structure.

Elongation and reduction of area are measurements of ductility and have primary application in fabrication and forming work. Elongation values are the main consideration in stretching or drawing operations, while the reduction of area is important in roll forming.

Elongation is also used as a qualitative indication of brittleness of an alloy or temper. This is reasonable because in every structure

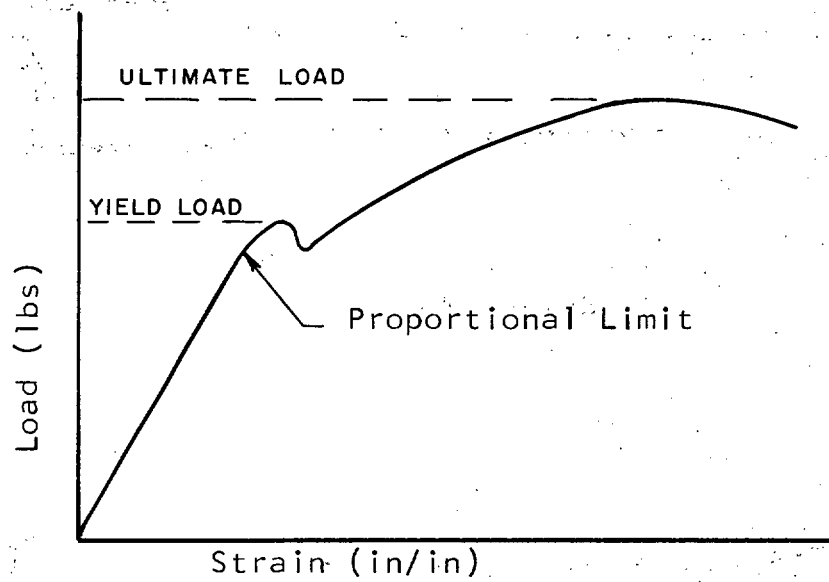
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FIGURE 56. A Load-Strain Diagram for a Material With a Definite Yield Point

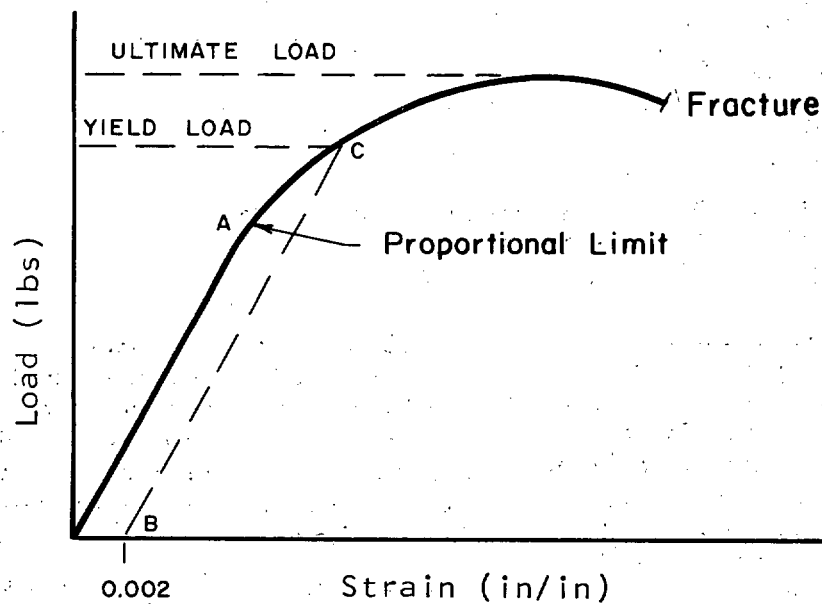


FIGURE 57. A Load-Strain Diagram for a Material Without a Definite Yield Point

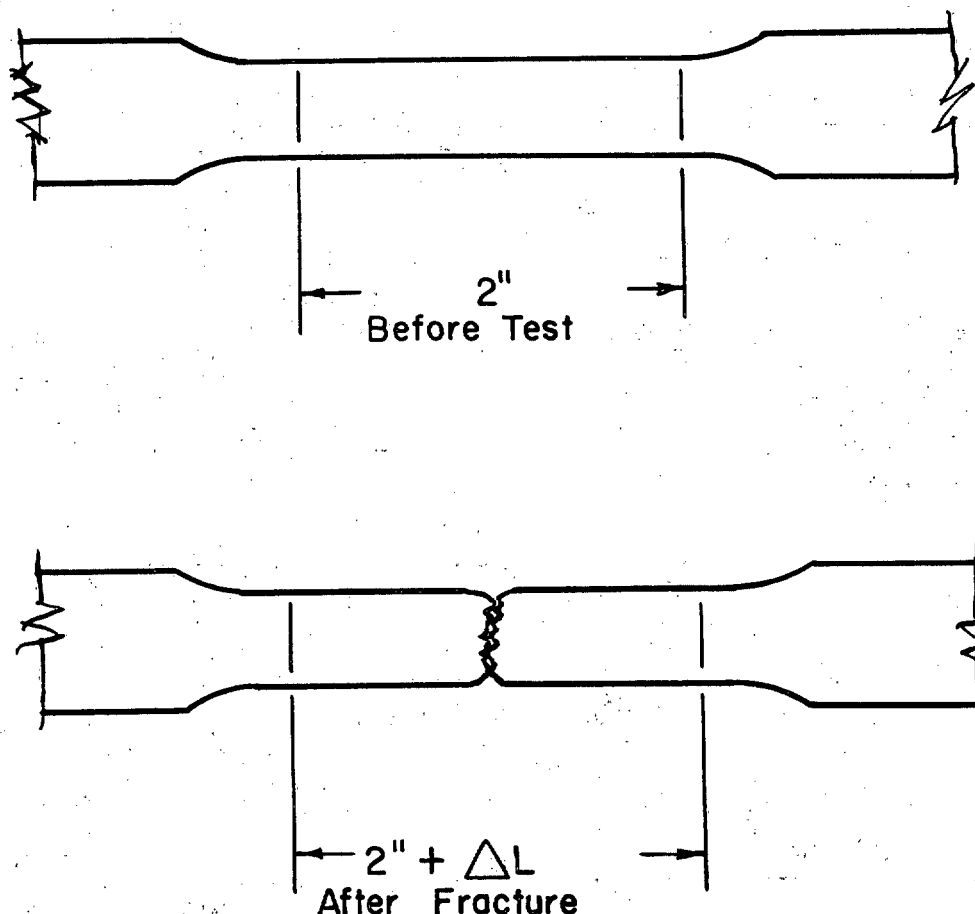
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FIGURE 58. Measurement of the Elongation of a Tensile Specimen

there is likely to be some localized plastic flow, even though it was designed to behave elastically. Of course if the particular temper or alloy cannot be subjected to some plastic strain without failure, the entire structure may be endangered. For a quantitative measure of brittleness the methods described in the section on Brittle Fracture should be used.

61. Compression Properties. Compression properties are determined by subjecting a specimen to an increasing compressive load until general yielding has occurred. Only the compressive yield strength and compressive elastic modulus are measured. This is done in

a manner similar to the methods of the tensile test. Theoretically these values should be the same as the tensile yield and modulus values. In reality there is usually some small difference. Generally no significant data are obtained from a compression test that are not obtained from a tension test.

A material fails by crack formation and propagation. Since a crack cannot form under compressive loading conditions a true compression failure will never occur. Failures under compressive loading can be attributed to buckling instability and in some cases shear or bending stresses.

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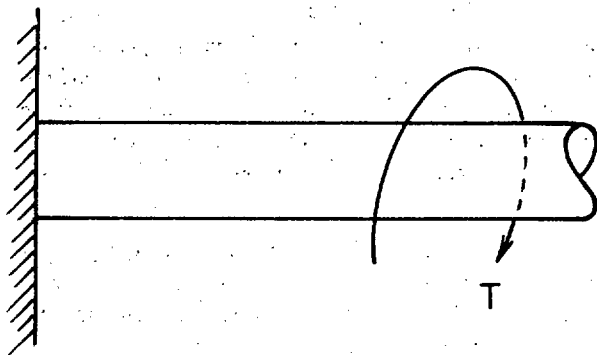


FIGURE 59. Torsion Loading

62. Shear Properties. Shear properties are usually determined in a torsion test. In the torsion test shear modulus, shear yield strength, shear ultimate strength (modulus of rupture) and the shear modulus are measured. The torsion tests are made by restraining a cylindrical specimen at one end and subjecting it to a twisting moment at the other, Figure 59. For accurate yield strength measurements a thin-walled cylindrical tube is used as the specimen. The shear stress is given by:

$$f_s = \frac{T}{2 r^2 t} \quad (11)$$

where

r = outer radius of tube

t = tube wall thickness

T = torque

A torque-angle of twist curve is obtained and the shear yield strength is determined at the proportional limit or at a specified permanent twist such as 0.001 radian per inch.

The shear ultimate, or modulus of rupture, is obtained by substituting the maximum moment into equation (11). The shear ultimate strength is usually in the range of 55% to 65% of the tensile strength of a material.

In actuality the shear stress at a point is one-half the algebraic difference between the maximum and minimum stresses at the point, equation

$$f_s = 1/2 (S_1 - S_3) \quad (12)$$

where

S_1 = maximum principal stress

S_3 = minimum principal stress

Furthermore, the shear stress law of yielding states that the uniaxial stress (S_o^I) in a tensile test is related to the stress under multiaxial loading by

$$S_o^I = S_1^I - S_3^I \quad (13)$$

Combining 12 and 13

$$S_o^I = 2f_s \quad (14)$$

$$f_s = \frac{S_o^I}{2}$$

If S_o^I is the ultimate stress (true) then the actual shear ultimate strength is 1/2 the tensile ultimate. For thin walled tubes in torsion, equation (11) is slightly in error. Experimentally determined values of the shear ultimate strength indicate the error to be about 10%. So the actual shear ultimate strength is about 10% higher than those predicted by equation (14).

63. Hardness Tests.

a. General. There are three basic types of hardness tests: (a) indentation hardness, (b) scratch hardness and (c) rebound hardness. Only indentation hardness, which is of primary importance to metals, will be discussed.

As the name implies, indentation hardness is measured by indenting the metal with a suitable load and indenter. The hardness obtained in this way is actually a measure of the resistance of the metal to plastic deformation, but through empirical correlations, hardness gives the designer an indication of the strength of the alloy or metal being tested.

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The advantages of indentation hardness testing are that it is fast, inexpensive, and essentially non-destructive. In the majority of cases the small indentation (usually less than 1/16" in diameter) will not cause any structural damage to the part being tested.

b. Brinell hardness. The Brinell hardness is measured by indenting the surface of the metal with a 10mm diameter ball under a static load of 3000 Kg. The Brinell hardness number (BHN) is then calculated by dividing the load, P , by the surface area of the indentation.

$$\text{BHN} = \frac{P}{(\pi D/2) (D - \sqrt{D^2 - d^2})} \quad (15)$$

where

P = applied load = (3000 Kg)

D = diameter of ball = (10mm)

d = diameter of indentation (mm)

It is usually unnecessary to calculate the BHN since tables are available for converting the impression diameter directly to hardness. The diameter of the impression is measured with a microscope having an ocular scale with 0.1 mm graduations. The diameter is measured to the nearest 0.05mm.

c. Vickers hardness. A square base diamond pyramid is used as the indenter for the Vickers hardness test. The static load used for testing varies from 1 to 120 Kg depending on the hardness of the material being tested. A diamond pyramid hardness (DPH) or Vickers hardness number (VHN) obtained in this way is defined as the load divided by the area of indentation. The hardness is calculated by using the following equation.

$$\text{DPH} = \frac{1.854 P}{L^2} \quad (16)$$

P = indenter load (Kg)

L = average length of the diagonals of the indentation (mm)

d. Rockwell hardness. The most widely used hardness test is the Rockwell hardness test. It is fast, easy, requires very little surface preparation, and is sensitive to small variation in hardness. The depth of penetration under load is the measure of hardness.

A minor load of 10 Kg is first applied to stabilize the indenter and specimen. The major load is then applied and the depth of penetration is read directly from a dial gage as arbitrary hardness numbers. The hardness number read from the gage varies directly with the actual material hardness, and inversely with depth of penetration. A hard material will not allow as deep a penetration of the indenter as will a softer material. The dial gage contains 100 divisions, each of which corresponds to a penetration of 0.00008".

A single combination of indenter and load is not satisfactory for determining hardness for materials having a wide range of hardness. Therefore, several combinations of indenters and loads are used. A 120° diamond cone (Brale indenter) and a 1/16" or a 1/8" diameter ball are generally used. Major loads of 60, 100 and 150 Kg are used. The hardness reading obtained depends on which combination of load and indenter is used; so the combination must be specified. This is done by adding a suffix to the letter R. The suffix corresponds to a particular scale which is determined by the load and indenter used. Thus if a reading of 40 is determined on the C scale, (Brale indenter and 150 Kg load) this hardness would be reported as Rockwell C 40 or $R_C 40$.

e. Microhardness tests. It is sometimes necessary to perform hardness tests on smaller samples and areas than is possible with the hardness tests previously discussed. For example the variation of hardness through the thickness of a carburized case may be desired. For this type of application a microhardness tester is used.

A microhardness test is analogous to the ordinary indentation hardness tests; the only difference being that a smaller indenter and

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much lighter loads are used. The Knoop indenter and Tukon tester are used for microhardness testing. The Knoop indenter is a pyramidal shaped diamond. The impression of the Knoop indenter, viewed normal to the specimen surface, is rhombic in shape with the long diagonal perpendicular to and seven times the length of the shorter diagonal. The loads applied by the Tukon tester are from 25g to 1000g. The length of the long diagonal of the impression is measured precisely with a microscope and a filar eyepiece calibrated in millimeters. The Knoop hardness number (KHN) is calculated as follows:

$$KHN = \frac{P}{L^2 C} \quad (17)$$

P = applied load (Kg)

L = length of longest diagonal (mm)

C = constant, characteristic of indenter

Knoop hardness numbers can be converted to more conventional scales with suitable conversion tables.

f. Hardness testing precautions. When a hardness test is made the following precautions should be observed:

(1) The indenter should be clean and in good condition.

(2) The test surface should be clean and free from scale or oxides. For the Vickers and the microhardness tests a metallurgically polished surface is required. A rough ground surface will usually suffice for Brinell and Rockwell tests.

(3) The specimen surface should be flat and perpendicular to the indenter. Tests may be made on cylindrical or spherical surfaces, but low readings are obtained and must be empirically corrected.

(4) The specimen should be thick enough so that the indenter does not produce a bulge on the surface opposite the test surface.

(5) Indentations should not be closer than 5 times the longest indentation dimension.

g. Hardness - tensile strength correlation.

The hardness of a steel can be closely correlated to the ultimate tensile strength of the steel:

$$f_{tu} = 500 \times BHN \quad (18)$$

f_{tu} = ultimate tensile strength

BHN = Brinell hardness number

For example, a hardness reading of 200 BHN would correspond to a tensile strength of 100,000 psi. Conversion tables are available for converting hardness values obtained from one type of test to equivalent hardness values for other tests. These tables also list the approximate tensile strength, for steel, corresponding to a given hardness value.

BRITTLE FRACTURE

64. General. The catastrophic failures of welded ships and tankers during World War II brought to the attention of engineers the fact that structural steels could fail at very low stress levels in some environments. These failures occurred at low ambient temperatures and there was generally a notch, crack or other defect present at the failure origin. This type of failure has been appropriately termed brittle fracture, because the failure is preceded by little or no plastic strain. However, it is not the brittleness of the fracture that is important. The important consideration is that the failure stress may be considerably less than the yield strength of the material. The engineering methods used to prevent such low strength failures are discussed in this section.

65. Quantitative Approaches. The basic methods used to design against the occurrence of brittle fracture may be divided into two broad categories, quantitative methods and qualitative methods. The quantitative methods are the more powerful since they give the designer some limiting parameter, such as: a minimum operating temperature; a maximum permissible defect size; or a maximum safe operating stress for a particular alloy in a given application. Quantitative methods include the Transition Temperature Method and the Fracture Mechanics Method.

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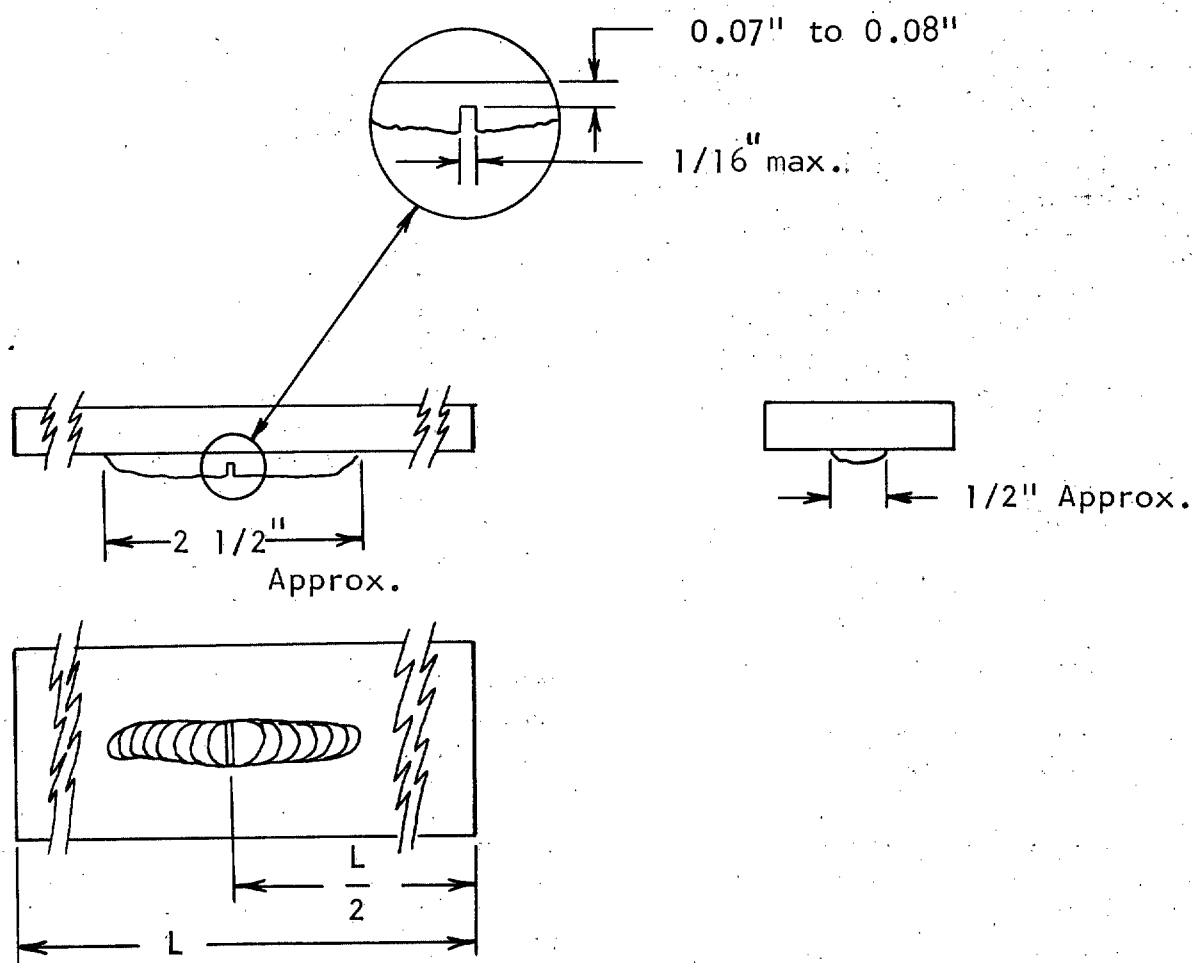


FIGURE 60. The Drop-Weight Test Specimen

a. **Transition temperature method.** The drop-weight test described in ASTM Standard E208-63T is a test method which was developed to determine the nil-ductility transition temperature of ferritic steels. This test is based on the concept that ferritic steels used in the notched condition are markedly affected by temperature so that there is a characteristic temperature below which a given steel will fail in a brittle manner and above which brittle fracture will not occur. The nil-ductility transition temperature determined by the drop-weight test is defined as the temperature at which, in a series of tests conducted under specific conditions, specimens

break; while at a temperature 10°F higher, under duplicate test conditions, no-break performance is obtained from similar specimens.

The drop-weight test is a simple and inexpensive test to conduct. ASTM E208 gives the particulars for several different sized specimens. The significant feature of all sizes of specimens is the weld bead deposited on the tension side of the specimen along its longitudinal centerline, as shown in Figure 60. The drop test is conducted by positioning a specimen in a fixture, as indicated in Figure 61; the specimen is then struck by a 60 or 100 lb.

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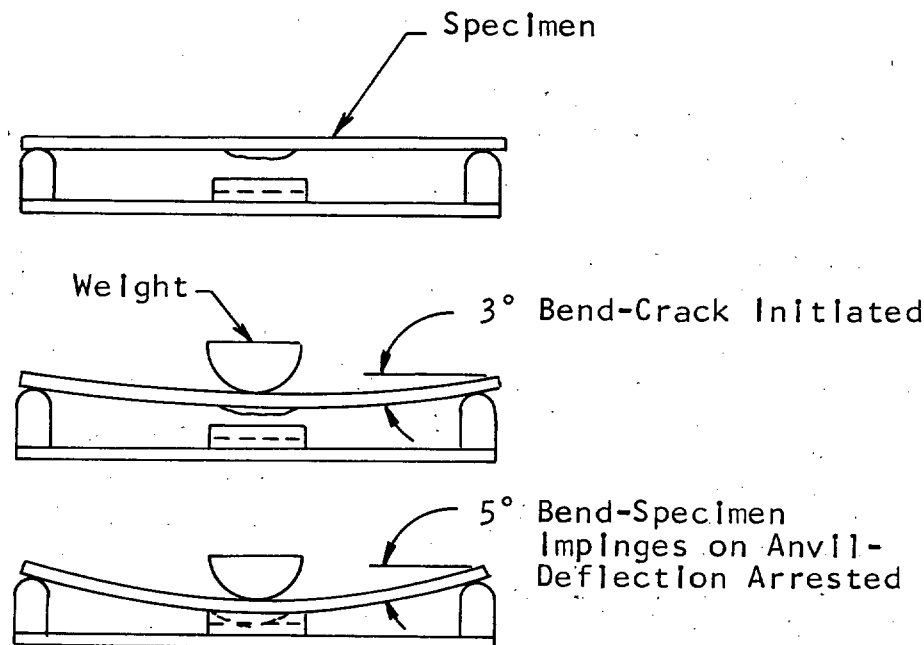


FIGURE 61. The Drop-Weight Test

weight which is dropped from a predetermined height, sufficient to develop the necessary impact energy to deflect the specimen until it impinges on the anvil, about 5° . A cleavage crack forms in the weld bead as soon as incipient yield occurs, at about 3° deflection. A series of specimens are tested over a range of temperatures. From these tests the nil-ductility transition temperature is determined. It is the temperature at which the steel, in the presence of a cleavage crack, will not deform plastically before fracturing, but will fracture at the moment of yielding. A specimen is considered broken if it fractures to one or both edges of the tensile surfaces. Complete separation at the compression side is not required. When a specimen develops a crack which does not extend to either edge of the tensile surface, it is considered a no-break performance.

After the nil-ductility transition temperature of an alloy has been determined, brittle fracture is prevented by using the alloy at temperatures above the transition temperature.

Or, if the operating temperature is fixed, an alloy is selected that has a transition temperature below the lowest operating temperature. A complete discussion of nil-ductility transition temperature determination and application is contained in ASTM Test Method E308-63T.

There are two major disadvantages of the transition temperature approach to designing against brittle fracture. It is often necessary to use an alloy at a temperature below its transition temperature, and it would be desirable to know what stress level is safe. Secondly, the higher strength steel alloys do not have definite transition temperatures. The fracture mechanics methods, does, however satisfy both of these requirements.

b. Fracture mechanics method.

(1) General. The fracture mechanics approach to brittle fracture analysis is to determine the fracture strength of an alloy in the presence of a defect of known geometry. The fracture mechanics method was developed

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originally from Griffith's elastic analysis of the fracture of brittle materials.

The Griffith theory of the fracture of elastic materials is based on the concept that small elliptical cracks in a material act as local stress risers that cause stresses to exceed the strength of the material, even though the nominal (P/A) stress across the section may be quite low. A crack will begin to propagate when the elastic energy released by propagation is equal to, or greater than, the energy of formation of the two new surfaces. Since the elastic energy increases with increasing stress, it is apparent that, at some value of stress, the strain energy released by the crack will be greater than the energy of formation of the surfaces, and the crack will become self-propagating under its own stress concentration.

Griffith's theory was developed for a completely brittle material and so it does not strictly apply to metals, which always undergo some localized plastic strain before a brittle fracture occurs.

To account for plastic flow, Irwin has modified the Griffith theory, with the result that the fracture stress of an alloy containing a crack of known size can be accurately predicted. The fracture stress is characterized by the strain energy release rate, G , an experimentally determined parameter. G increases with crack length, and at the stress at which a crack of known dimensions becomes self-propagating it is called the critical strain energy rate and is denoted by the subscript "c", e.g., G_c, G_{Ic} . G_c denotes the critical G determined under plane stress conditions, and G_{Ic} denotes the critical G determined under plane strain conditions. G can also be expressed in terms of the stress intensity factor K ,

$$K_c = \sqrt{G_c E} \quad (19)$$

and

$$K_{Ic} = \sqrt{\frac{G_{Ic} E}{(1 - \mu^2)}}$$

where E = modulus of elasticity

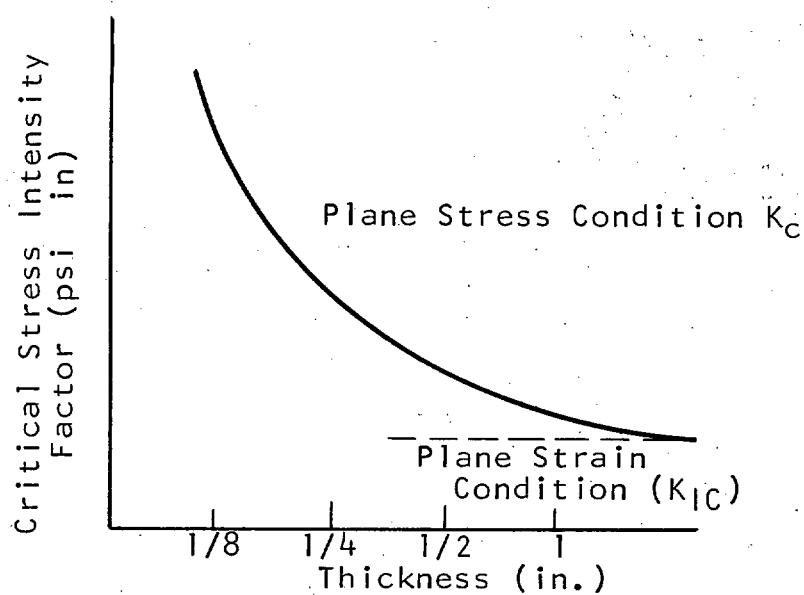
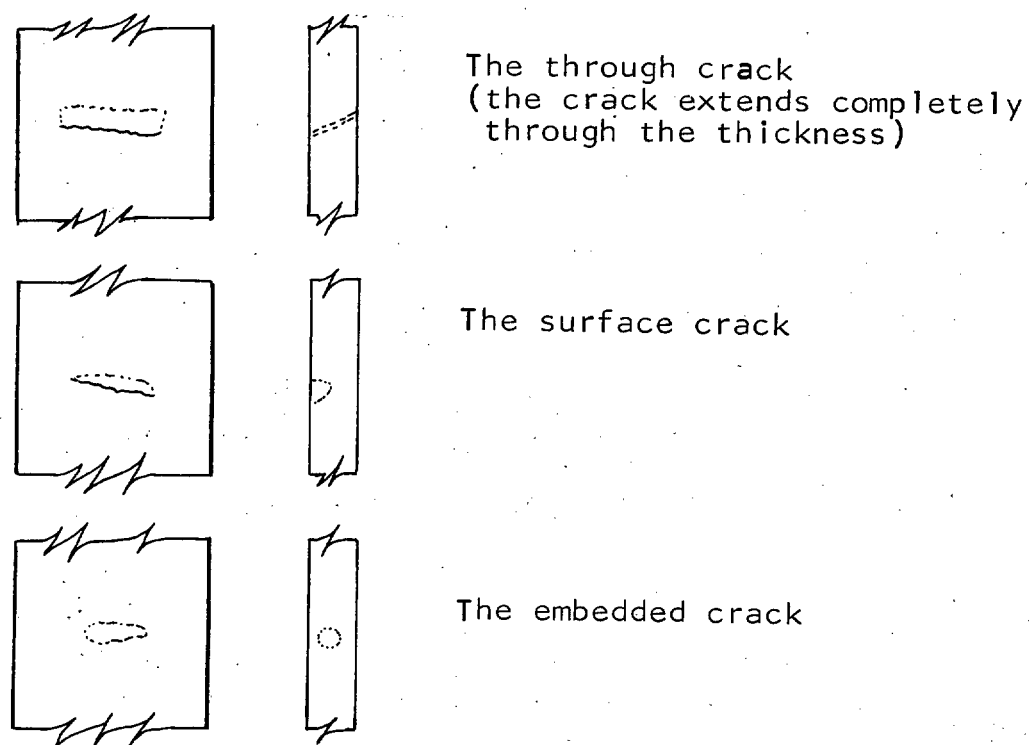
μ = Poisson's Ratio

G and K are both referred to as fracture toughness values. Since these values vary considerably from each other it is important to specify which is being discussed.

(2) Plane Stress and Plane Strain. By definition a plane stress condition is one in which the stress in at least one direction is zero. This is illustrated by a thin-walled pressure vessel or a thin sheet loaded in tension. In each instance the stress through the thickness is zero. As applied to fracture mechanics, plane stress actually describes the stress state or restraint at the leading crack edge. In view of this a through crack in thin material is in plane stress conditions because the stress in the thickness direction at the crack tip is zero or very small. For thicker material the restraint at the crack front increases until full restraint exists and the stress in the thickness direction is quite high. This fully restrained condition is the plane strain condition. The thickness at which full restraint is reached differs for different materials, but it is in the neighborhood of $1/4$ " to $1/2$ ".

The significance of the plane stress to plane strain transition is that a much lower fracture stress is required for a given defect size when plane strain conditions exist. This is apparent from the difference in magnitude between K_c and K_{Ic} , Figure 62. It can be seen from Figure 62 that as the thickness increases, the fracture toughness in the plane stress region (K_c) decreases to a constant value of K_{Ic} , corresponding to plane strain or full restraint.

Three types of cracks are likely to be encountered, Figure 63. A fracture initiated by a through crack may occur under either plane stress or plane strain conditions, depending on the material thickness. The initial propagation of the surface and the embedded crack is always under plane strain conditions. However, when the crack pops through the thickness it will be identical to a through crack and may be in either the plane stress or plane strain stress state. Again this depends on the thickness.

MIL-HDBK-723A**30 NOVEMBER 1970****FIGURE 62. Effect of Thickness on Fracture Toughness****FIGURE 63. Types of Cracks**

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The stress at which a tension member fails in the presence of a crack is dependent on the fracture toughness of the material, and the defect size. The relationship, sometimes called the inverse square root law, is the basis of fracture mechanics and is expressed by:

$$S_f = \frac{A}{\sqrt{2c}} \quad (20)$$

where

S_f = fracture stress

A = a constant which expresses the fracture toughness

$2c$ = crack length

For example, using this expression, if a stress of 100,000 psi will cause failure in a material in which a .25" long crack is present, then 50,000 psi would cause failure if the crack were 1" long.

$$S_{f1} = \frac{A}{\sqrt{2c_1}} = 100,000 = \frac{A}{\sqrt{0.25}}$$

$$A = 100,000 \sqrt{0.25}$$

So,

$$S_{f2} = \frac{100,000 \sqrt{0.25}}{\sqrt{1}} = 100,000 \times 0.5$$

$$S_{f2} = 50,000 \text{ psi}$$

For the case of a crack in an infinitely wide solid, such as a small crack in a pressure vessel, this equation takes the form:

$$S_f = \frac{K_c}{\sqrt{\pi c}} \quad (21)$$

for plane stress, where

K = fracture toughness, and

c = 1/2 the crack length, or

$$S_f = \frac{K_{Ic}}{\sqrt{\pi c (1 - u^2)}} \quad (22)$$

for plane strain.

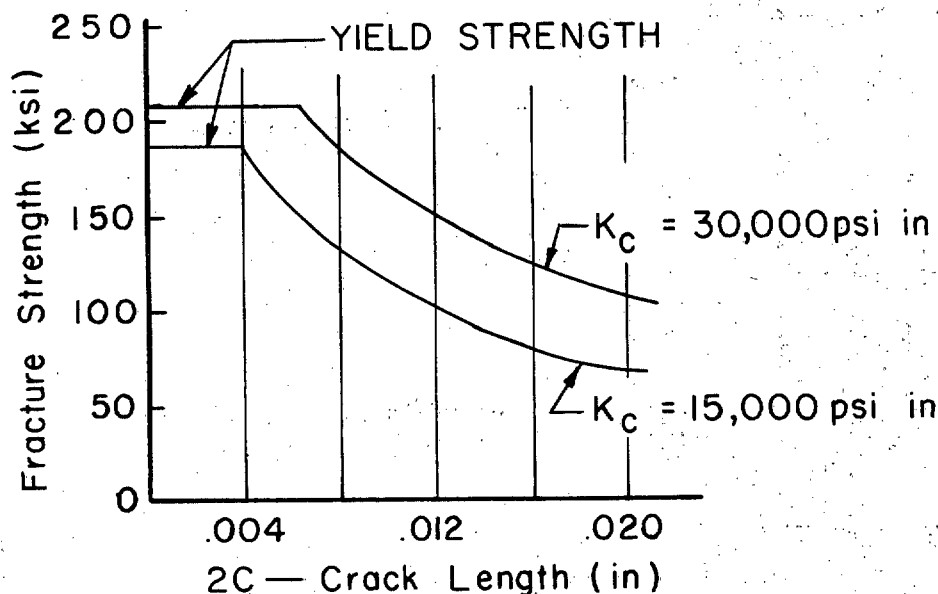


FIGURE 64. Effect of Crack Length on Fracture Strength

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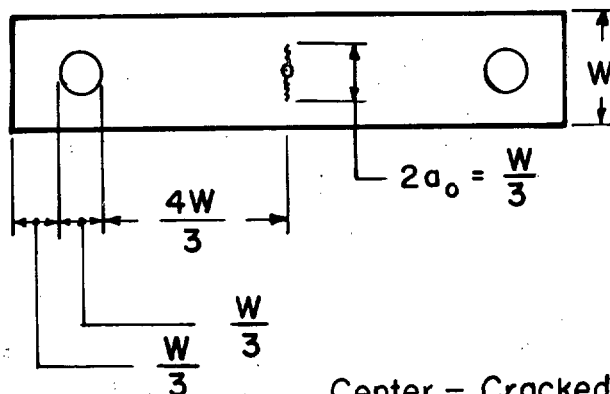
Equation 22, as plotted in Figure 64, is one of the standard ways of presenting fracture strength as a function of defect size. As discussed previously, the K_C values for thin material are considerably higher than K_{Ic} values. Plotting the lower K_{Ic} values in place of the K_C values would have the effect of shifting the curves in Figure 64 to the left, indicating that it takes a considerably longer crack to cause failure under plane stress conditions, than it does under plane strain conditions at a given stress level.

(3) Fracture Toughness Testing. The fracture toughness of a material is determined by loading a fatigue cracked specimen in tension and recording the load at which the crack begins to propagate, and also the failure load. The test methods employed to determine fracture toughness and the restrictions on them are numerous and sometimes complex. For a complete description of testing methods, the many publications covering the subject, especially

the ASTM publication "Fracture Toughness Testing and Its Applications", should be consulted.

The specimens most often used are shown in Figure 65. The specimens widths are usually in the range of 1" to 4". The thickness is usually the same as that of the part that is to be made from the given material. The major restriction on testing is that fracture toughness data may only be obtained in the elastic region of the tensile curve. If yielding of the specimen occurs, then the equations that are used to determine K are no longer valid, since they are based on the elastic theory of stress analysis.

The equations attendant the specimens shown in Figure 65 are those used to calculate K or G . K_{Ic} or G_{Ic} values are obtained by using the load at which the crack first begins to propagate ("pop-in values"). K_C and G_C are determined by using the load at fast fracture.



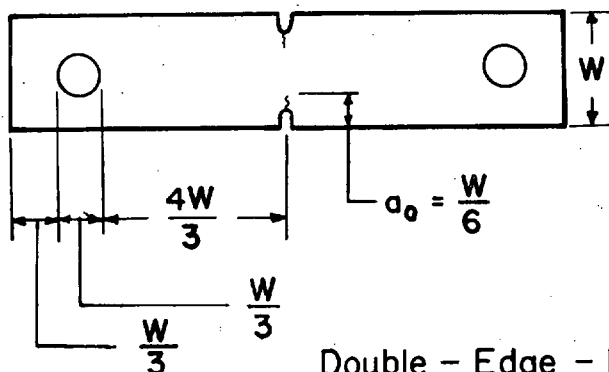
Center - Cracked Specimen

$$G = \frac{P^2}{EWt^2} \tan \frac{\pi a}{W}$$

$$EG_c = (1 - \mu^2) K_{Ic}^2 = EG_{Ic}$$

$$a = \frac{1}{2} \text{ Crack Length at Fracture}$$

t = Thickness



Double - Edge - Notched Specimen

$$G = \frac{P^2}{EWt^2} \left[\tan \frac{\pi a}{W} + 0.1 \sin \frac{2\pi a}{W} \right]$$

$$EG_c = (1 - \mu^2) K_{Ic}^2 = EG_{Ic}$$

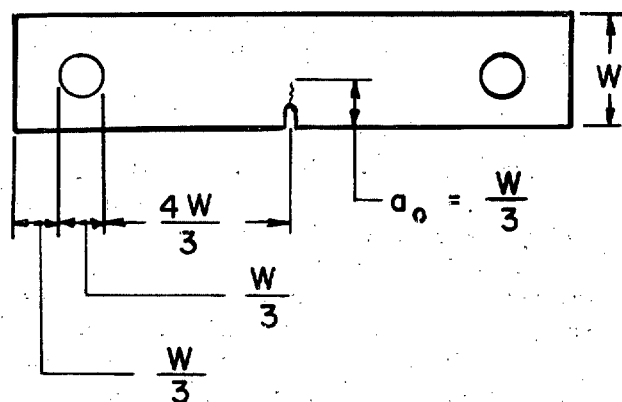
$$a = \frac{1}{2} \text{ Crack Length at Fracture}$$

t = Thickness

FIGURE 65. Common Fracture Toughness Test Specimens

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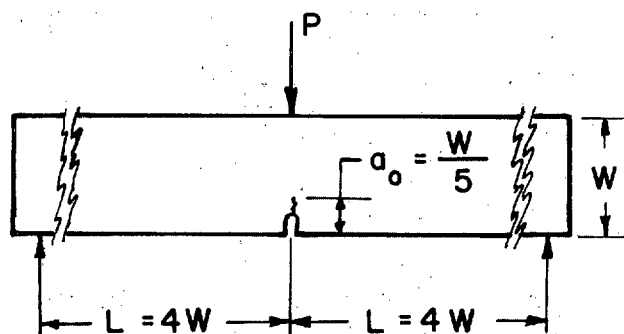
$$G_{Ic} = \frac{P^2}{EWt^2} \left[7.59 \frac{a}{W} - 32 \left(\frac{a}{W} \right)^2 + 117 \left(\frac{a}{W} \right)^3 \right]$$

$$EG_c = (1 - \mu^2) K_{Ic}^2 = EG_{Ic}$$

$$a = \frac{1}{2} \text{ Crack Length at Fracture}$$

t = Thickness

Single - Edge - Notched Specimen



$$G_{Ic} = \frac{P^2 L^2}{Et^2 W^3} \left[31.7 \frac{a}{W} - 64.8 \left(\frac{a}{W} \right)^2 + 211 \left(\frac{a}{W} \right)^3 \right]$$

$$EG_c = (1 - \mu^2) K_{Ic}^2 = EG_{Ic}$$

$$a = \frac{1}{2} \text{ Crack Length at Fracture}$$

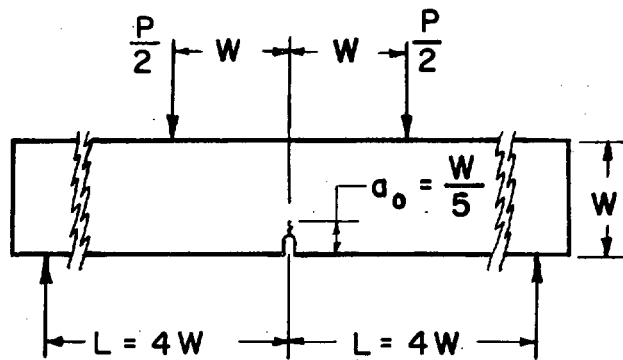
t = Thickness

Three Point Bend Specimen

FIGURE 65. Common Fracture Toughness Test Specimens (continued)

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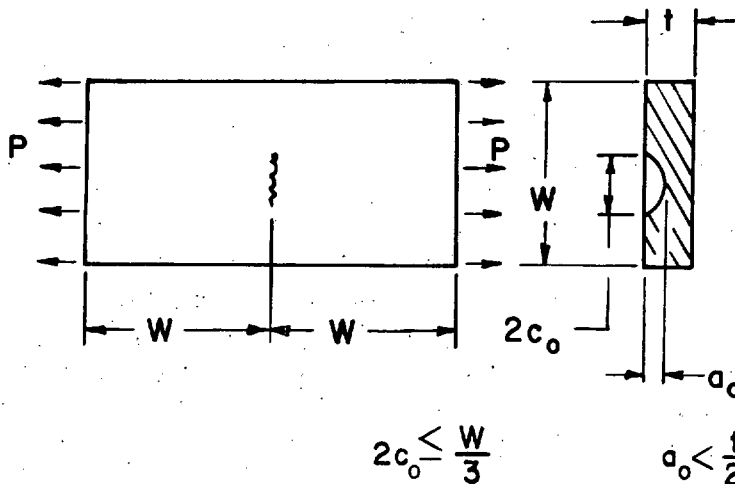
$$G_{Ic} = \frac{P^2 L^2}{E t^2 W^3} \left[34.7 \frac{a}{W} - 55.2 \left(\frac{a}{W} \right)^2 + 196 \left(\frac{a}{W} \right)^3 \right]$$

$$E G_c = (1 - \mu^2) K_{Ic}^2 = E G_{Ic}$$

$$a = \frac{1}{2} \text{ Crack Length at Fracture}$$

Four Point Bend Specimen

t = Thickness



$$2c_0 \leq \frac{W}{3}$$

$$a_0 < \frac{t}{2}$$

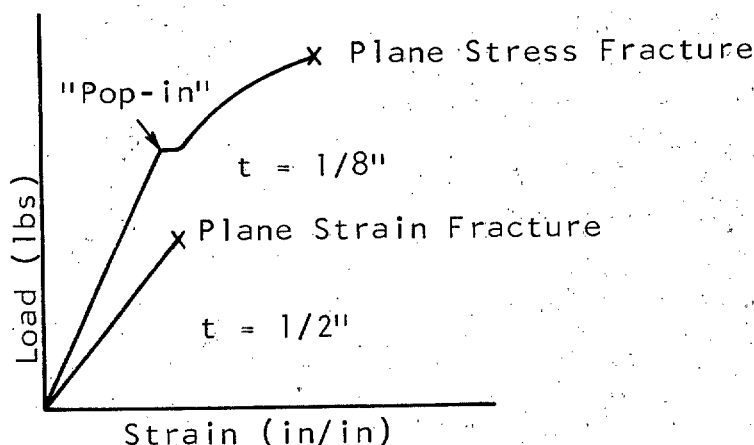
$$\Phi = \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{c_0^2 - a_0^2}{c_0^2} \sin^2 \theta} d\theta$$

$$G_{Ic} = \frac{1.2 \pi P^2 a_0 (1 - \mu^2)}{W^2 t^2 E}$$

$$\left[\frac{1}{\Phi^2 - 0.2 \left(\frac{P^2}{W^2 t^2 \sigma_{ys}^2} \right)} \right]$$

Surface Cracked Specimen

FIGURE 65. Common Fracture Toughness Test Specimens (continued)

MIL-HDBK-723A**30 NOVEMBER 1970****FIGURE 66. Fracture Toughness Load Curves**

The load at pop-in is measured by recording the strain occurring across the crack, in much the same way as in the tensile test. A load-strain curve, Figure 66 is attained. The deviation from linearity is the pop-in load. Two types of behavior are shown. In the first, pop-in occurs and then the load increases to failure under plane stress condition. In the second case, failure occurs immediately as pop-in initiates, indicating that at the 1/2" thickness full restraint exists and the plane strain conditions prevail.

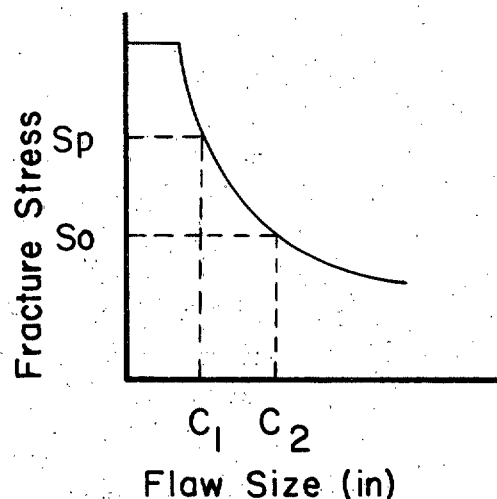
(4) Designing Against Low Strength Failures. There are three basic fracture mechanics philosophies to designing against low strength failures. These are: proof testing; leak before failure criteria; and stress analysis method.

(a) Proof Testing. If a structure contains a crack and it is loaded to a particular stress and the crack does not propagate, then it may be safely used at a slightly lower static operating stress. This is the basis of implementing fracture toughness through proof testing.

If a material has a characteristic fracture stress-flaw size curve like that in Figure 67, and it is proof tested at S_p , then the largest flaw that can possibly be present is slightly smaller than c_1 . The static operating stress in

this case is S_o . For a failure to occur at S_o , a crack of size c_2 must be present. However, it has already been shown that the largest possible flaw that can exist is c_1 . Since c_2 is larger than c_1 , the structure can safely operate at S_o .

(b) Leak Before Failure. This method has primary application in pressure vessel design. The success of this method is dependent on the plane strain-plane stress transition. A surface or embedded flaw in a pressure vessel

**FIGURE 67. Fracture Stress Flaw Size Curve**

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may propagate at the proof or operating pressure of the vessel. As previously discussed these flaws will initially propagate under plane strain conditions. The material used is selected on the basis that it will be able to tolerate a crack having a length of at least twice the wall thickness of the vessel, at the required stress level, under plane strain conditions. Then, if a surface or embedded crack exists, it may propagate at the operating stress. If it does, it will pop through the thickness when its length is approximately twice the wall thickness. At this time, providing the wall is thin enough, the crack is under plane stress conditions and additional load or stress is required for further crack propagation. Therefore, the vessel will leak and the defect can be easily detected before brittle failure can occur.

(c) Stress Analysis. In the stress analysis method the fracture toughness of the material and the defect size that can be detected by non-destructive inspection limit the working stress

of a part. The defect shape and size are both considered, and are expressed in terms of the defect size parameter a/Q . This parameter is the ratio of a , the crack depth, to Q , the flaw shape parameter. Q is in turn a function of the ratio of crack depth to crack length, that is,

$Q = f \frac{a}{2c}$ where $2c$ = crack length. This function

is plotted in Figure 68. To determine the fracture strength of a part having a known defect size, the value of Q is found from Figure 68. The fracture stress is then determined from equation 23.

$$S = \frac{K_{Ic}}{\sqrt{1.21 \left(\frac{a}{Q} \right) C_r}} \quad (23)$$

where

S = applied stress

K_{Ic} = plane strain fracture toughness

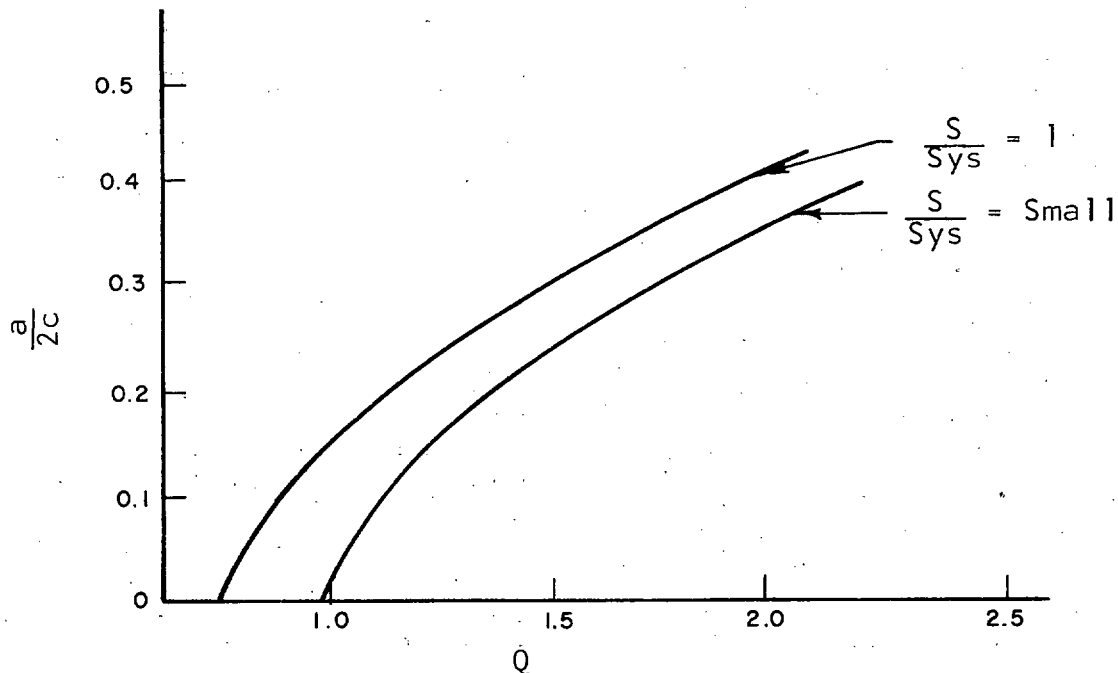
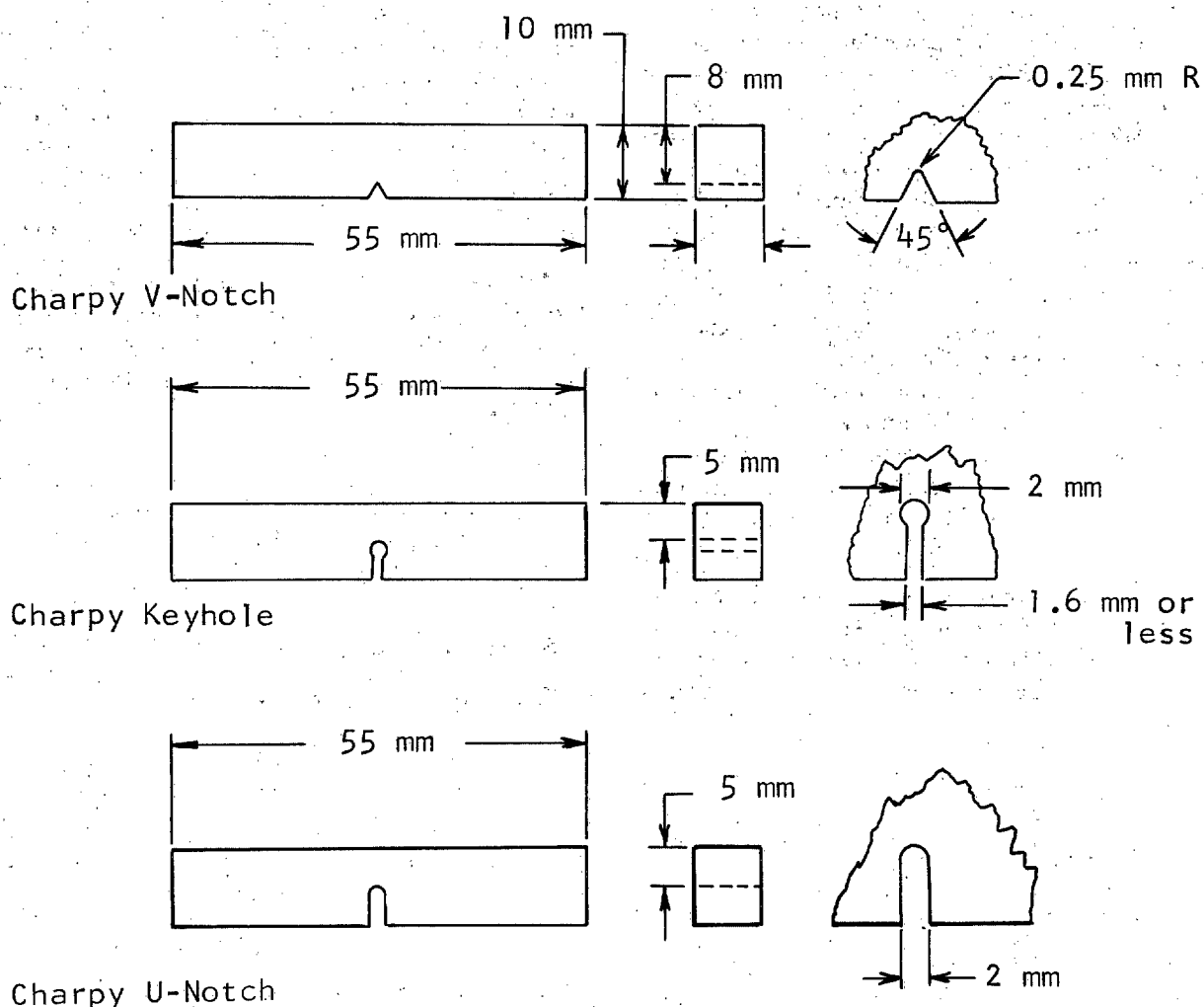


FIGURE 68. Flaw Shape Parameter Curve

MIL-HDBK-723A**30 NOVEMBER 1970****FIGURE 69. Charpy Impact Test Specimens****66. Qualitative Approaches.**

a. General. The Charpy impact test, and notched tensile tests, are classified as qualitative brittle fracture tests*, because the test data are not readily converted to design data.

b. The Charpy impact test. Numerous tests have been devised to evaluate the transition from brittle to ductile fracture in steels. One such test, the Charpy impact test, has gained wide recognition and acceptance because it is a simple and rapid test to conduct. The reliability of the Charpy impact test, and the reproducibility

of results obtained from Charpy tests, were confirmed through an experiment conducted at the Army Materials and Mechanics Research Center, Watertown, Massachusetts.⁽¹⁾

*Notched tensile test may be quantitative and provide fracture toughness values if the proper testing requirements are satisfied.

(1) D.E. Driscoll, "Reproducibility of Charpy Impact Tests", Symposium on Impact Testing ASTM STP No. 176, American Society for Testing and Materials, p. 170 (1955).

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The Charpy test is a swinging pendulum type of impact test. A pendulum is released from a known height to strike a specially prepared notched specimen (Figure 69) positioned in the anvil of the impact machine. The pendulum's knife edged striker contacts the specimen at the bottom of the swing, at which point the kinetic energy of the pendulum reaches a maximum value, Figure 70. After breaking the specimen, the pendulum continues in its swing to a height which is measured. Since the pendulum is released from a known height the kinetic energy of the pendulum at the time of impact is also a known quantity. The energy expended in breaking the specimen may be expressed as a function of the difference in the release height of the pendulum and the height it attains after the specimen is broken, so that:

$$E_a = W (h_o - h_f) \quad (24)$$

where:

W = weight of the pendulum in pounds

h_o = release height in feet

h_f = final height in feet

E_a = energy absorbed by the specimen in foot-pounds

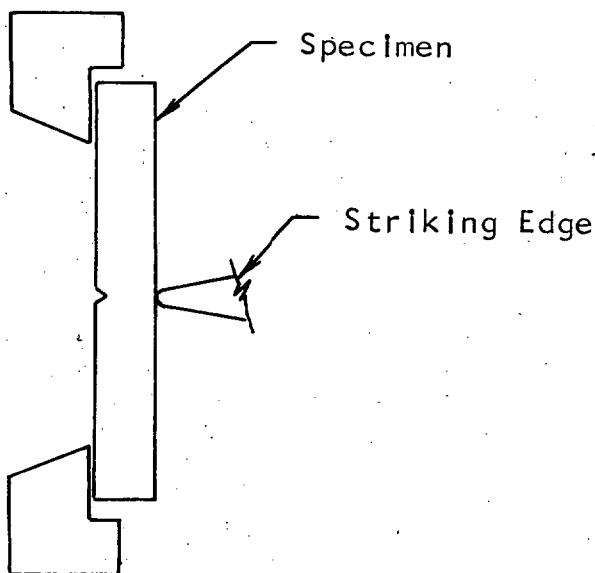


FIGURE 70. Charpy Impact Test

Normally, swinging pendulum impact machines are equipped with scales from which the energy absorbed by the specimen is read directly in foot-pounds.

The Charpy test is a convenient test method for determining the change in the fracture mode of a steel as a function of temperature. A series of specimens can be tested over a range of temperatures and the data thus obtained can be plotted to develop a brittle to ductile transition curve, such as that shown in Figure 71. As indicated in Figure 71, the transition from a brittle to a ductile fracture usually occurs over a range of temperatures. Likewise the fracture of the specimen changes from 100% cleavage (a bright, faceted appearance) to 100% shear (a silky, fibrous appearance). The temperature at which specimens show a fracture of 50% shear and 50% cleavage is frequently defined as the transition temperature. Fracture appearance data can be plotted as a function of temperature as shown in Figure 72.

The Charpy test is often used as an acceptance test for incoming material. In such cases the material is usually required to meet or exceed a specified impact energy level at a given testing temperature, for example, 15 foot-pounds at -40°F .

The Charpy test is also a convenient method for comparing the notch toughness characteristics of various materials.

The methods and procedures of conducting the Charpy Impact Test are specified in ASTM Standard E23, "Notched Bar Impact Testing of Metallic Materials". The test is also discussed in ASTM Standard A370, "Mechanical Testing of Steel Products". Detailed discussions of the Charpy test are contained in References 2, 8, 18 and 19 of the bibliography.

The Charpy test has been accepted as the standard impact test for steel for guns by the NATO Nations, as described in the following:

(1) NATO Standardization Agreement, STANAG 4020, Edition No. 2, 10 May 1966, "Impact Tests at Low Temperature for Steel for Guns".

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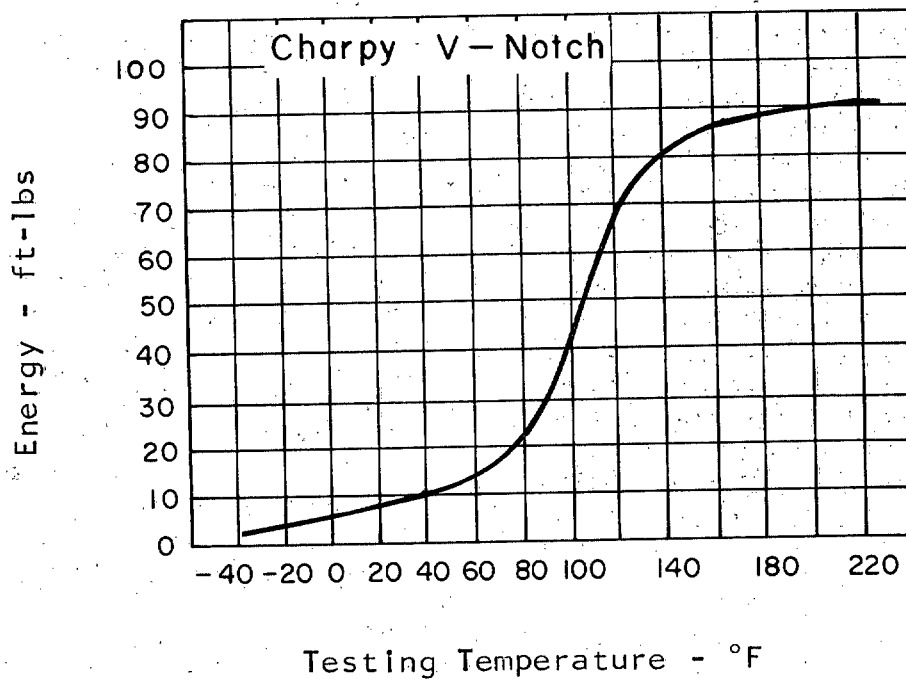


FIGURE 71. Brittle to Ductile Transition Curve

(2) Department of the Army Technical Bulletin, TB-34-9-90, 15 August 1966, "Impact Tests at Low Temperatures for Steel for Guns".

c. Notched tensile tests. Notch tensile tests are performed on cylindrical specimens having an annular notch, or on flat specimens having double edge notches, Figure 73. These notches act as stress concentrators and affect the load carrying capabilities of the specimens. The stress concentration due to a notch or an abrupt change of section is described in terms of K_t , the theoretical stress concentration factor. K_t is defined as the ratio of the maximum stress, due to the notch, to the nominal stress across the area under the notch. K_t should not be confused with K_c or K_{Ic} which are fracture toughness values. Values of K_t have been determined for various geometries and the values for the geometries of major importance in notch testing are shown in Figure 73. K_t depends on both the specimen size and the notch

radius, and is often approximated by the formula $K_t \approx \sqrt{a/R}$.

In the most commonly used notch tests a round specimen with a 50% notch depth is used. The restraint caused by the notch sets up a state of triaxial tension near the notch root. This stress state increases the flow resistance of the metal and thus decreases the ductility at failure, but it may increase the fracture strength. The notch strength ratio, NSR, (ratio of notched strength to unnotched strength), has been shown to increase with increasing notch sharpness, at a constant notch depth, to a maximum value at which the triaxiality becomes constant. Increasing the sharpness beyond this point causes a reduction in the NSR for notch sensitive materials. Increasing the notch depth will increase the triaxiality, and will increase the notch strength of the specimen. Notched tensile tests are used primarily as material screening tests.

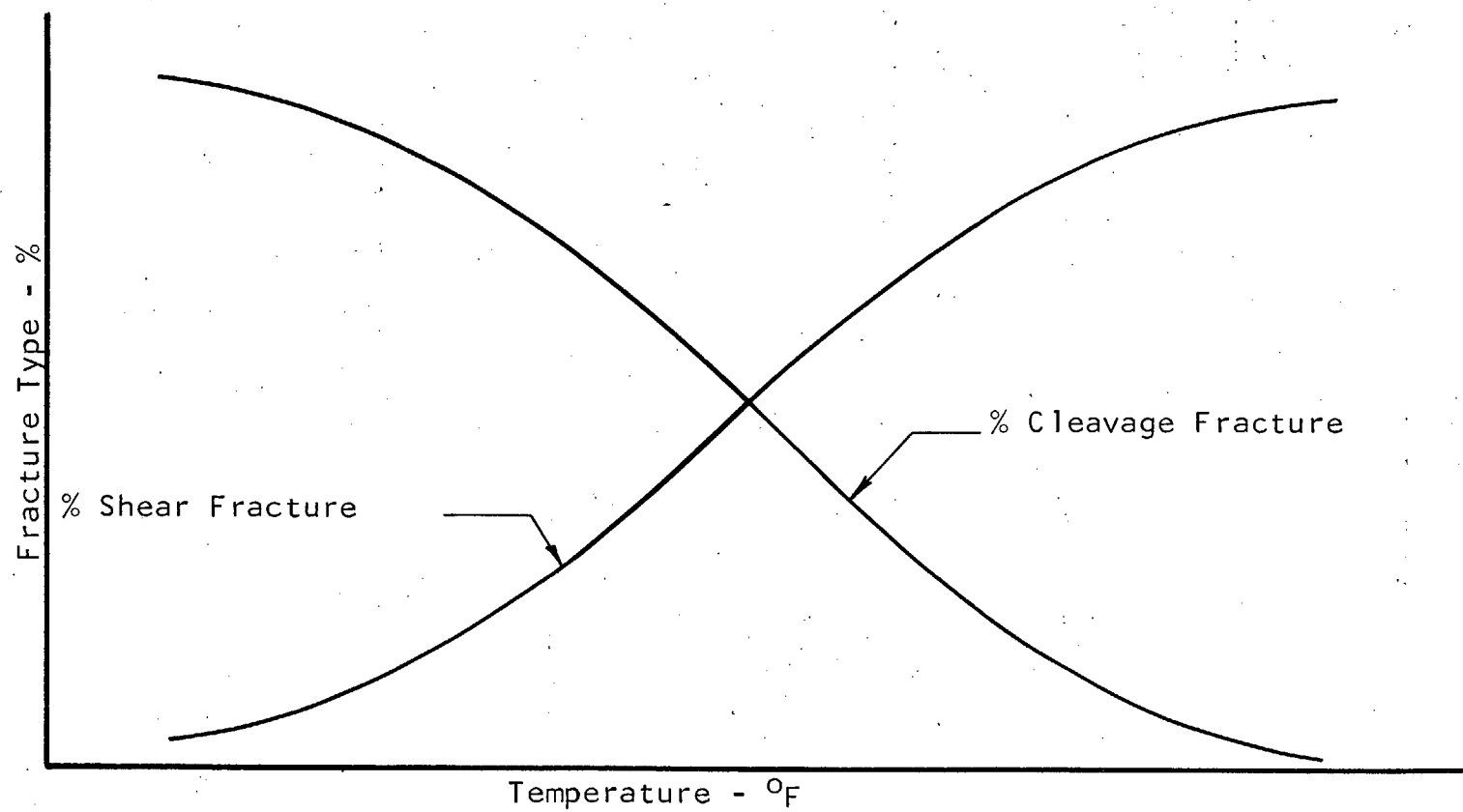


FIGURE 72. Transition of Fracture Appearance with Temperature

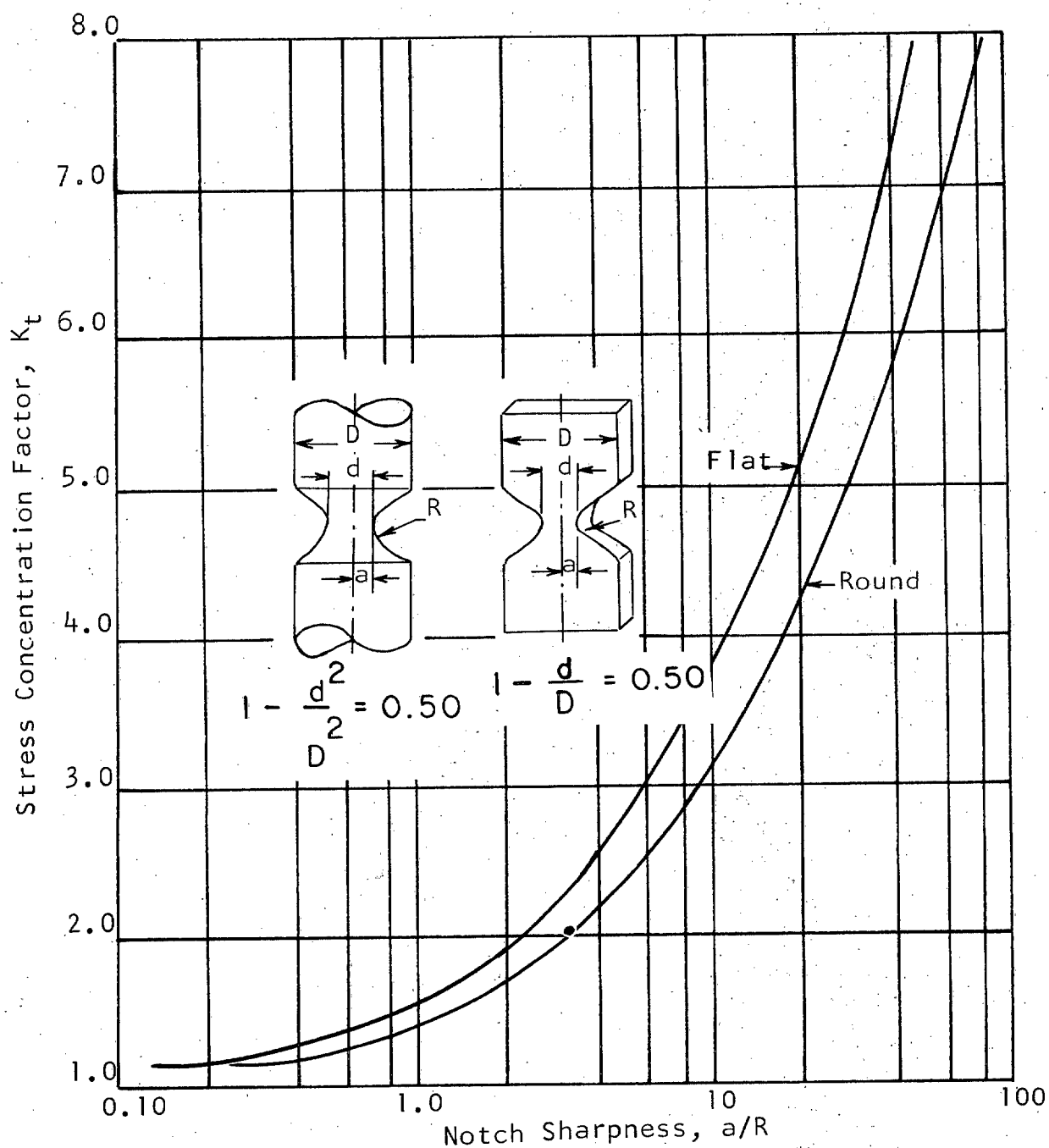
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FIGURE 73. Effect of Notch Sharpness on the Stress Concentration Factor

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FATIGUE

67. General. A material subjected to repeated tensile loading may fail even though the stresses are below yield strength. Failure may occur after a few load applications or after a few million applications. This phenomenon is known as fatigue. The fatigue life is dependent upon many variables, the most important of which are; maximum stress, average stress, alternating stress, the ratio of alternating to average stress, yield strength, surface condition, and environment. To determine the fatigue life of a material for a given application these factors must be considered.

68. Fatigue Tests. Fatigue tests are made by subjecting a specimen to repeated cyclic loading until failure occurs, or until the test is discontinued. The typical types of load-cycling are shown in Figure 74. The loading cycles are either tension-compression, tension-tension, or zero stress-tension.

The maximum stress, S_{max} , is the highest tension stress in the cycle. The minimum stress, S_{min} , is the largest compressive stress for compression-tension cycling, or the minimum tensile stress for tension-tension cycling. S_m is the average or mean stress of the cycle and is given by equation 25.

$$S_m = \frac{S_{max} + S_{min}}{2} \quad (25)$$

S_a is the alternating stress and is equal to the difference between S_{max} and S_m .

$$S_a = S_{max} - S_m \quad (26)$$

Another quantity useful in fatigue analysis is the stress ratio R .

$$R = \frac{S_{min}}{S_{max}} \quad (27)$$

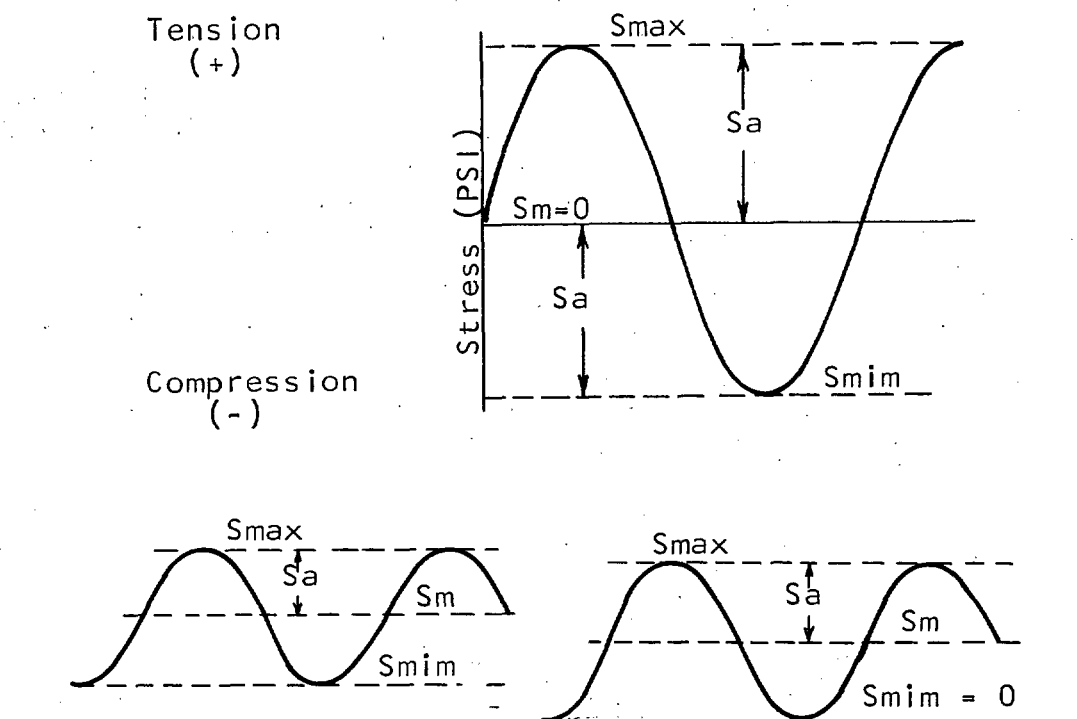


FIGURE 74. Fatigue Loading Cycles

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For reversed bending where $S_{\min} = -S_{\max}$

$$R = \frac{S_{\min}}{S_{\max}} = \frac{-S_{\max}}{S_{\max}}$$

$$R = -1$$

Another very similar quantity is the A ratio.

$$A = \frac{S_a}{S_m} \quad (28)$$

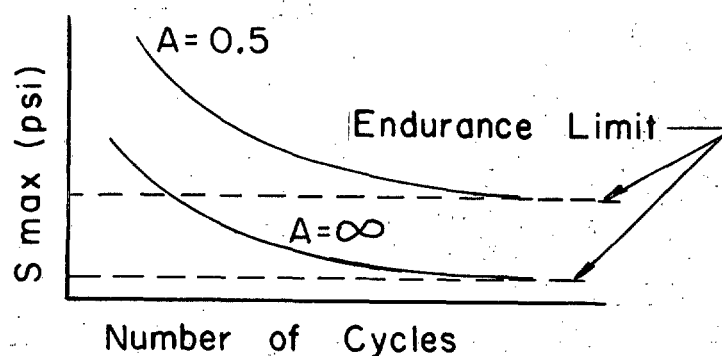
For reversed bending, $S_m = 0$ and $A = \frac{S_a}{0} = \infty$

69. Presentation of Fatigue Data.

a. The S-N curve. The basic method of presenting fatigue data is the S-N curve. The maximum stress is plotted as a function of the number of cycles to failure, Figure 75. When data are presented on an S-N curve it is necessary to identify the A ratio or the stress ratio, R, because the fatigue life of a material is dependent upon the maximum stress and mean stress of the applied cyclic load. At a specified maximum stress, the fatigue life of a material is the lowest under reversed bending, when $S_m = 0$, and $A = \infty$. For a given maximum stress, the fatigue life increases as S_m increases and A decreases. The horizontal lines labeled "Endurance Limit" in Figure 75 are the stresses below which a steel will not fail by fatigue, under the indicated conditions.

b. The Soderberg diagram. A more useful method of presenting fatigue data is the Soderberg diagram or modified Goodman diagram. In the Soderberg diagram the alternating stress is plotted against the mean stress, Figure 76. The diagram shows the dependence of fatigue life on the alternating and mean stress, as well as on the A ratio. If the fatigue life is to be determined under the conditions of $S_a = S_m$ ($A = 1$), at a given maximum stress, and if $S_a = S_{\max} - S_m = S_{a1}$, then the stress S_{a1} is read off the proper axis, and the fatigue life at the proper A ratio is read from the diagram, in this case 10^4 cycles. Notice that at an A ratio of 5, the alternating stress that could be endured would be S_{a2} , and the mean stress would be S_{m2} for 10^4 cycles.

Ideally the Soderberg diagram should be constructed by determining the S-N curve for several A ratios and then plotting these data. The diagram can, however, be determined by testing with only one A ratio. To do this the S-N curve is established and the points are plotted on the appropriate A ratio line. As an example, data might be obtained for an A ratio of 1. These data are plotted on the 45° ($A = 1$) line, Figure 77. A straight line is then drawn connecting these points and the material ultimate strength value that has been plotted on the S_m axis. This gives a Soderberg diagram that is conservative, and accurate enough for many engineering applications. This method is of considerable utility because most of the fatigue data found in the literature is in the form of

**FIGURE 75. S-N Curve**

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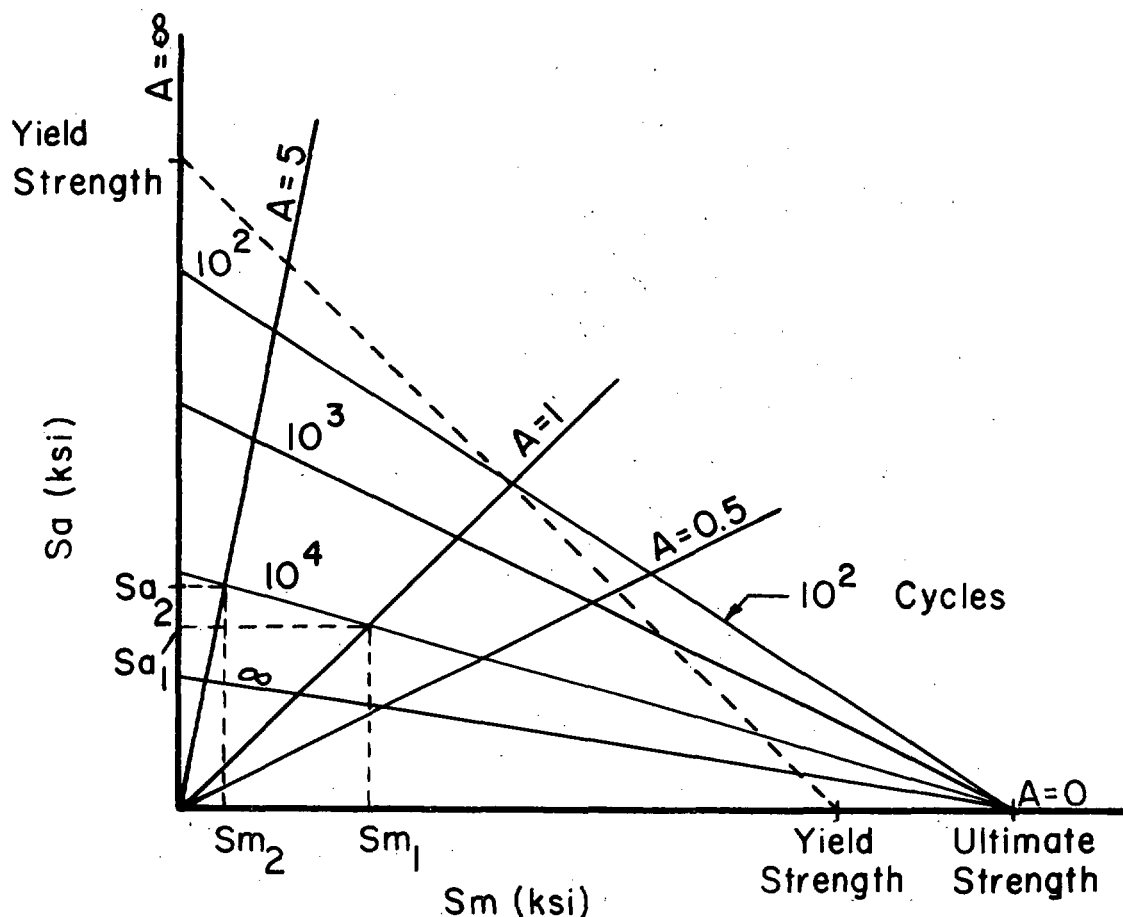


FIGURE 76. Soderberg Diagram

S-N curves for reversed bending (A ratio $= \infty$). This method of determining the Soderberg diagram makes it possible to use such data for applications in which the A ratio is other than ∞ .

The dashed line connecting the yield strengths plotted on each axis in Figures 76 and 77, limits the range over which the Soderberg diagram is used. If values beyond this line are picked the yield strength of the material is exceeded. General yielding is usually a criteria for failure, so fatigue tests in which the maximum stress is greater than yield are seldom needed.

70. Factors Affecting Fatigue Life. The presence of a notch or any other defect that causes a stress concentration seriously reduces

the fatigue strength of a metal. The reduction in fatigue strength is dependent on the stress concentration factor K_t . For a K_t of 2, the expected fatigue strength would be 1/2 of the unnotched fatigue strength for a given number of cycles. The actual amount that the fatigue strength is reduced is expressed by fatigue notch factor K_f .

K_f is simply the ratio of the unnotched strength to the notched strength for a given number of cycles.

$$K_f = \frac{S_u}{S_n} \quad (29)$$

S_u = unnotched fatigue strength

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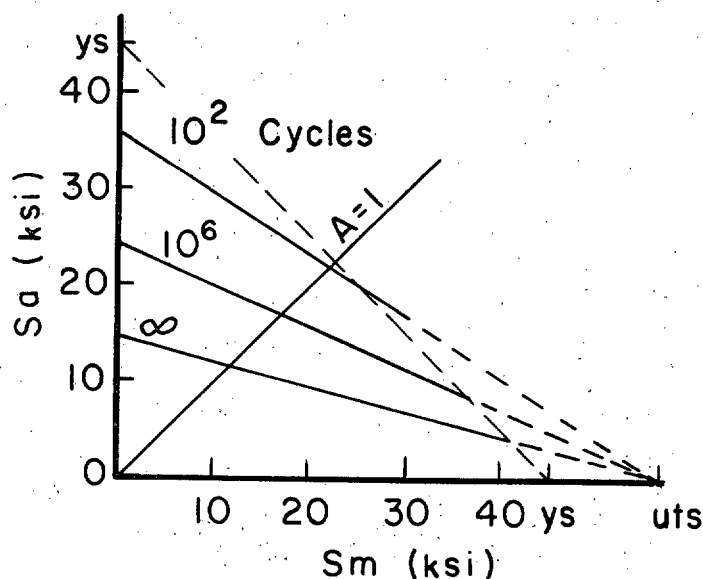


FIGURE 77. Method of Constructing the Soderberg Diagram

S_n = notched fatigue strength

K_f is equal to K_t for small values of K_t , but as

K_t increases the ratio $\left(\frac{K_f}{K_t}\right)$ decreases. K_f is

determined by obtaining S-N curves for unnotched specimens, and for notched specimens of the same material, Figure 78. Then for a given number

of cycles the ratio of $\frac{S_u}{S_n}$ is determined

from these curves. K_f is dependent on the notch radius and sharpness, and may have different values for the same K_t , when K_t is developed from two different geometries.

For applications where the cyclic loading does not vary, i.e., S_a and S_m remain constant, the fatigue life can be read directly from the S-N curve or the Soderberg diagram. When the loading cycle varies (S_a and S_m vary) a method such as the linear damage principal is used. This principal can be stated as follows: The total fatigue life is the sum of the number of cycles experienced at a given stress, divided by the fatigue life at that stress. In equation form this would be:

$$\frac{M_1}{N_1} + \frac{M_2}{N_2} + \frac{M_3}{N_3} + \frac{M_i}{N_i} = 1 \quad (30)$$

where:

M = cycles at a given stress

N = fatigue life at that stress

As an example; if a material having the fatigue characteristics shown in Table VIII had been subjected to 20,000,000 cycles at 20,000 psi, how many additional cycles could it withstand at 50,000 psi before it would fail?

TABLE VIII. FATIGUE CHARACTERISTICS

<u>S Max</u>	<u>Cycles to Failure</u>
10,000 psi	∞
20,000	70,000,000
30,000	20,000,000
50,000	6,000,000

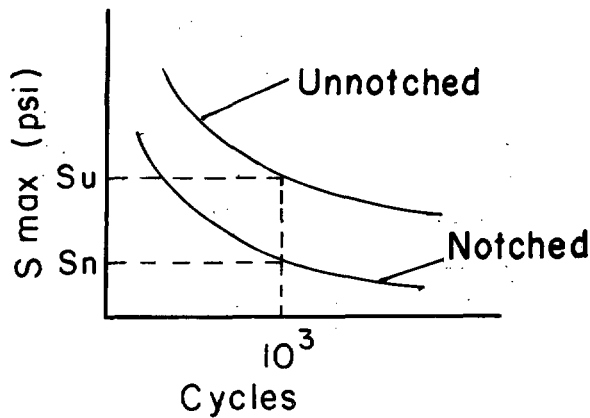
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FIGURE 78. S-N Curves of Notched and Unnotched Specimens

In this case, $M_1 = 20,000,000$ for $S = 20,000$ psi
and $N_1 = 70,000,000$ from Table I

$M_2 = \text{unknown for } S = 50,000 \text{ psi}$

$N_2 = 6,000,000$

$$\frac{M_1}{N_1} + \frac{M_2}{N_2} = 1$$

$$\frac{20,000,000}{70,000,000} + \frac{M_2}{6,000,000} = 1$$

$$\text{and } M_2 = 6,000,000 \times 1 - \frac{20,000,000}{70,000,000}$$

$$M_2 = 6,000,000 \times \frac{5}{7} = 4,280,000$$

Therefore the part could be expected to withstand an additional 4,280,000 cycles at 50,000 psi.

It is good design practice to eliminate stress concentrations. This applies not only to stress concentrations designed into a part, but also to those resulting from surface roughness and defects in the material. The effect of surface finish on fatigue life is indicated in Table IX.

TABLE IX. *FATIGUE LIFE OF 3130 STEEL SPECIMENS TESTED UNDER COMPLETELY REVERSED STRESS AT 95,000 PSI

	Surface Roughness, Min.	Average Fatigue Life (Cycles)
Lathe-formed	105	24,000
Partly hand-polished	6	91,000
Hand-polished	5	137,000
Ground	7	217,000
Ground & polished	2	234,000
Superfinished	7	212,000

* G. Dieter, Jr., Mechanical Metallurgy, McGraw-Hill, Inc., 1961

Other surface properties can be adjusted to improve fatigue life. Carburizing, nitriding and cold working, which increase the surface hardness, will increase the fatigue life. On the other hand, decarburization of the surface is particularly damaging to fatigue properties. Shot-peening introduces compressive residual stresses into the surface, as well as increasing the strength through cold work. Both of these factors increase the fatigue life. However, shot-peening also increases the surface roughness and this of course decreases fatigue life.

CORROSION

71. General. Corrosion is the deterioration of a metal due to chemical or electrochemical action. Because corrosion is so prevalent; corrosion losses are one of the most expensive problems that are faced in the application of metals.

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72. GALVANIC CORROSION.

a. *General.* In its simplest form, the galvanic cell consists of two electrodes immersed in a conducting solution (the electrolyte). The electrodes may be two dissimilar metals, a metal and a conducting nonmetal (e.g., carbon), or a metal and an oxide. In each case, an electrical potential is induced between the electrodes. This potential may produce current when the electrodes are joined by a suitable conductor. When current is flowing, reactions take place at each electrode, the reactions for one combination of electrodes and solutions are shown in Figure 79.

In a cell, dissolution of the metal occurs at the negative electrode (the anode), while hydrogen is evolved at the positive electrode (cathode). The anodic metal is corroded and the cathode is protected. The rate of corrosion of the anodic metal depends on the degree of separation of the two metals concerned in the practical galvanic series, Table X. The corrosion rate is also dependent on the conductivity and composition of the electrolyte and the relative areas of the two metals. Galvanic corrosion in service applications occurs through the formation of composition cells or concentration cells.

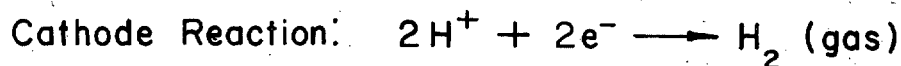
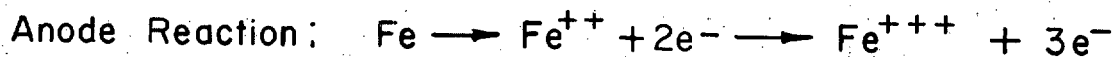
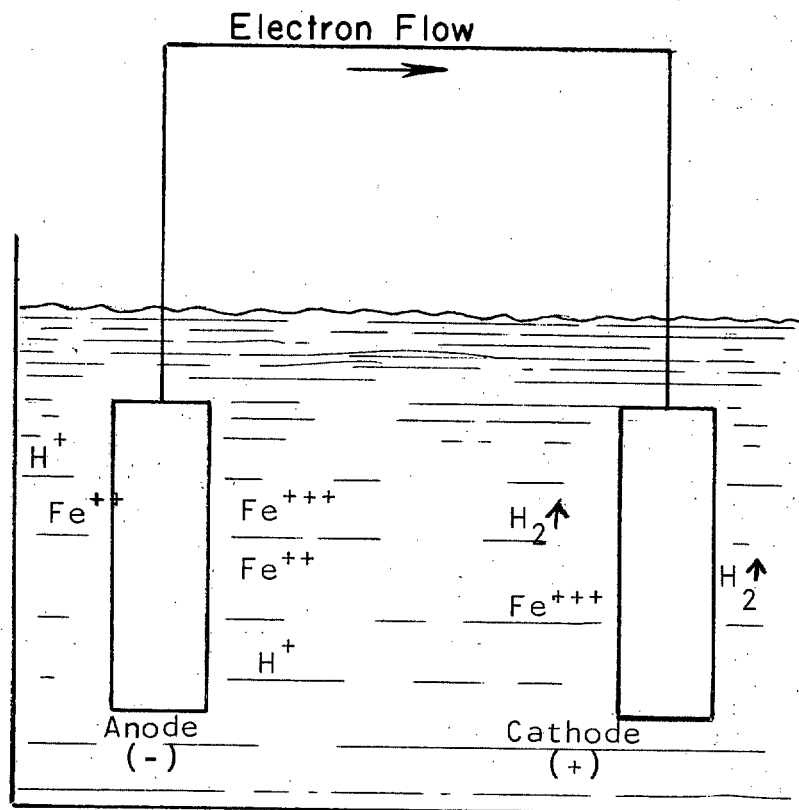


FIGURE 79. Galvanic Cell

MIL-HDBK-723A**30 NOVEMBER 1970****TABLE X - GALVANIC SERIES OF METALS AND ALLOYS**

Anodic End	Magnesium
	Magnesium Alloys
	Zinc
	Alclad
	Aluminum 6053
	Cadmium
	Aluminum 2024
	Cast Iron
	Wrought Iron
	Mild Steel
	13% Chromium Steel Type 410 (Active)
	18-8-3 Chromium Nickel Stainless Steel Type 316 (Active)
	18-8 Chromium Nickel Stainless Steel Type 304 (Active)
	Tin
	Lead
	Lead Tin Solders
	Naval Brass
	Manganese Bronze
	Muntz Metal
	76 Ni-16 Cr-7 Fe Alloy (Active)
	Nickel (Active)
	Silicon Bronze
	Copper
	Red Brass
	Aluminum Brass
	Admiralty Brass
	Yellow Brass
	76 Ni-16 Cr-7 Fe Alloy (Passive)
	Nickel (Passive)
	Silver Solder
	70-30 Cupro-Nickel
	Monel
	Titanium
	13% Chromium Steel Type 410 (Passive)
	18-8-3 Chromium Nickel Stainless Steel Type 316 (Passive)

18-8 Chromium Nickel Stainless Steel Type 304 (Passive)

Silver

Graphite

Gold

Cathodic End

Platinum

b. Composition cells. A composition cell may occur between dissimilar metals or in a single metal that has areas of differing electrode potential. An illustration of the dissimilar metal cell is galvanized (Zn coated) steel. The Zn coating is anodic to the steel base metal. Therefore when an electrolyte, such as water is present between the Fe and Zn a galvanic cell is produced. Since Zn is anodic to steel, it is preferentially attacked, protecting the steel.

A composition cell may be set up in a single metal because of differences in electrode potential between various phases, or between the grain boundaries and the matrix. An example of this is intergranular corrosion. This type of attack occurs when the grain boundaries are anodic to the matrix. The occurrence of intergranular corrosion is strongly dependent on the thermal and mechanical treatment given the metal. Generally speaking, the stronger the alloy is made through heat treat or coldwork, the less corrosion resistant it becomes.

c. Concentration cells. Concentration cells are formed when there is a difference in the concentration of the electrolyte between the areas in contact. The area that has the weakest concentration of electrolyte is attacked. The same type of cell, but of considerably more importance is the oxygen concentration cell. This cell is characterized by areas that have different oxygen concentrations. The area having the lowest oxygen concentration is anodic and attacked. Corrosion caused by an oxygen concentration cell can be expected to be found under surface dirt, mill scale or other areas that may be oxygen deficient.

MIL-HDBK-723A**30 NOVEMBER 1970****73. Stress Corrosion.**

a. General. Stress corrosion may occur in a susceptible material when it is subjected to residual or applied surface tensile stresses while exposed to a corrosive environment. Stress corrosion cracks initiate and propagate transverse to the loading direction, and a low strength failure results. The time required for stress corrosion to occur is dependent on several variables.

b. Strength level. As is the case with general corrosion, the higher the strength level obtained through the heat treatment or cold working of a given alloy, the lower will be its resistance to stress corrosion.

c. Grain orientation. The direction of the applied stress with reference to the grain orientation is of prime importance. The stress corrosion resistance is lowest in the short transverse grain direction and highest in the longitudinal direction, with the long transverse being intermediate. The stress corrosion resistance of a material in the short transverse may be only 10% as good as that in the longitudinal. The resistance in the long transverse direction is dependent on the grain geometry. A material with narrow elongated grains would have a long transverse susceptibility to stress corrosion nearly as poor as that in the short transverse direction. For equiaxed grains, such as found in cross-rolled material, there is no difference between the longitudinal and the long transverse direction.

Concentration of Corrosive Environment: The effect of varying the concentration of the corrosive environment on stress corrosion cannot always be predicted. In dilute solutions the stress corrosion rate is generally increased as the concentration of corrodents increases. However, it is often found that a concentrated solution is not as severe an environment as is a dilute one.

d. Stress level. At a high stress level a susceptible alloy, when exposed to a corrosive medium, may fail in a matter of minutes. As the stress is decreased, the time to failure increases. This is the basis for the threshold

stress concept, which postulates, that for stress corrosion susceptible materials there is a stress value, the threshold stress, below which stress corrosion cracking will not occur, while at higher stress levels, stress corrosion cracking should be expected to occur.

74. Corrosion Protection. There are two basic methods of corrosion protection, surface protection and galvanic protection. Surface protection simply involves keeping the corrosive environment away from the part. This is commonly achieved through plating, cladding or painting. Galvanic protection is achieved by electrically connecting the metal with a sacrificial anode. This is illustrated by Zn coating of steels and by magnesium bars buried in contact with underground pipelines.

Stress corrosion is not usually a problem with carbon steel and wrought iron, but the higher strength low alloy steels may be susceptible to stress corrosion. Stress corrosion is prevented primarily by surface protection, proper grain direction exposure and by control of the magnitude of applied stresses.

75. Rocket and Missile Propellant Compatibility. Although the low alloy and carbon steel are compatible (not attacked) by many of the common rocket and missile propellants, if no water is present, their use is usually not recommended in applications where propellant contact is likely. The combination of propellants with atmospheric humidity presents a corrosive environment that is too severe for this class of steel. When they are used, protection methods such as plating or painting are recommended, but even this may not be sufficient, and failures will only be delayed.

PHYSICAL PROPERTIES.

76. Thermal Conductivity. Thermal conductivity is the measure of the ability of a material to carry or conduct heat. It is analogous to electrical conductivity. The thermal conductivity is designated by the symbol K and has the units of $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})/\text{ft}$. Thermal conductivity is used in the analysis of heat transfer problems.

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77. Thermal Expansion. The change in dimension a solid experiences, when it is subjected to a change in temperature, is described by the coefficient of linear expansion, α . The coefficient of linear expansion can be expressed as:

$$\alpha = \frac{\Delta L}{L_0} \times \frac{1}{^\circ\text{F}} \quad (31)$$

where:

L_0 = original dimension

ΔL = change in dimension with temperature

$^\circ\text{F}$ = degrees Fahrenheit

The units of α are in/in/ $^\circ\text{F}$. It is apparent from these units that is actually the strain in the solid due to a temperature change of 1°F . The coefficient of expansion depends on the temperature at which it is measured, so the range of temperatures over which α is valid is always specified. α is used to calculate volume changes and to determine stresses in restrained members that are subjected to temperature changes. As an example of stresses induced by temperature changes consider Figure 80. If

the rigidly restrained steel rod is heated until a temperature rise of 200°F is obtained, the amount it would increase in length is

$$\Delta L = L_0 \alpha \Delta T$$

or,

$$\frac{\Delta L}{L_0} = \alpha \Delta T = e \quad (32)$$

where

T = temperature change

e = strain

L_0 = original length

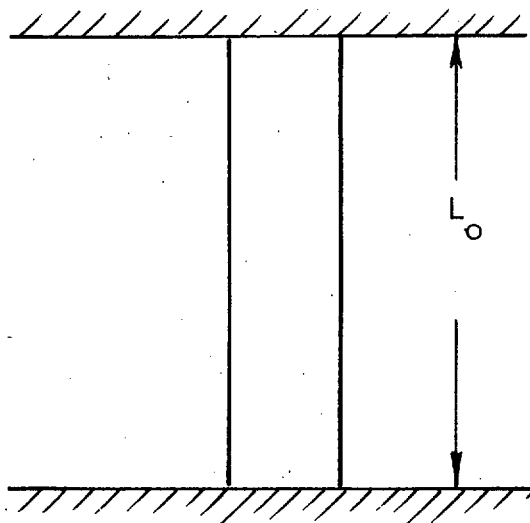
Since the rod is restrained it cannot increase in length and a compressive stress is induced in the rod.

By definition,

$$S = Ee \quad (33)$$

Combining equations 32 and 33,

$$S = Ee = E\alpha \Delta T \quad (34)$$



$$\alpha = 7.3 \times 10^{-6} \text{ in/in/}^\circ\text{F} \quad (100^\circ\text{F})$$

$$E = 30 \times 10^6 \text{ psi}$$

$$\Delta T = 200^\circ\text{F}$$

FIGURE 80. Restrained Rod

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Substituting the proper values into equation 34

$$S = (30 \times 10^6 \text{ psi})(7.3 \times 10^{-6} \text{ in/in}^\circ\text{F}) \\ \times (200^\circ\text{F})$$

$$S = 43,800 \text{ psi}$$

A compressive stress of 43,800 psi would be induced in the rod by a temperature change of $+200^\circ\text{F}$.

78. Density. Density is defined as the mass per unit volume of a solid, but it is common engineering practice to express density as weight per unit volume, either in lb/in^3 or lb/ft^3 .

Density is a design consideration when the weight of a structure must be controlled. The selection of an alloy is then often made on the basis of a high yield strength to density ratio, or as sometimes expressed, the "strength to weight ratio".

MATERIALS SELECTION

Choosing the correct material for use in a particular application can be a simple task or a complex one, depending upon the requirements which the material must satisfy. Generally a material is selected for use in a particular application because:

(1) The part or structure made from it will satisfy, as completely as possible, all of the essential requirements of the application.

(2) The part or structure can be produced and maintained for a lower total cost than is possible with any other material.

This doesn't, and isn't intended to imply that material should be selected on the basis of initial or raw material cost alone. Raw material cost is an important factor; however, the choice of material, encompassing alloy, form, temper and surface condition, can significantly affect manufacturing costs, maintenance costs, inspection costs, repair costs, handling costs, etc. The effect on these costs should be carefully analyzed before a material is actually selected for a particular application. Consideration of raw material costs alone very often does not reveal the true total cost situation.

Carbon and low-alloy steels are available in many different combinations of composition, form, temper and surface condition. As discussed in earlier chapters, different alloys possess different combinations of properties and characteristics. Many of the plain carbon steels and the high strength low alloy steels, for example, are most often used in the as-rolled condition, in applications where the moderate strength they develop in this condition is adequate for the purpose. When higher strengths are required, an alloy steel that can be heat treated to the required strength level is ordinarily used. Naturally, alloy steels are more expensive than plain carbon steels and in addition, the heat treatment increases the fabrication costs. An alloy can be selected on the basis of mechanical properties, machining characteristics, welding characteristics, forming characteristics, heat treat response, the capability of being case hardened, or any combination of properties and characteristics. Considering only carbon and alloy steels, a user may choose from a wide variety of alloys, each offering a particular combination of properties and characteristics. To further complicate the situation, other materials are competitive with steels in some applications; as for example, the high strength aluminum alloys and titanium alloys.

The functional requirements of some applications can be satisfied by any one of a number of different materials. Choosing the best material under such conditions can be a difficult decision and the choice of material can significantly affect the total cost of the project. Many variables can be involved and each should be accorded due consideration. In other cases requirements are so stringent or so unique that it is necessary to conduct a test program to evaluate various materials for the particular application. Often it is impossible to find any material that completely satisfies all of the essential requirements of a given application and some compromise must be effected. In any event, careful analysis of all pertinent factors is essential to arrive at a satisfactory solution.

As with other engineering problems, a logical, orderly approach is beneficial in solving materials selection problems. The Value

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Engineering technique first identifies essential functional requirements such as the type and magnitude of the loads which the part or structure must sustain, the operating environment, service life, surface finish requirements, surface hardness requirements, size, shape, and weight limits, and so forth. When all of the requirements are identified, candidate materials can be selected on the basis of the appropriate selection criteria, for example, tensile strength, endurance limit, hardenability, corrosion resistance, fracture toughness, etc. Then by comparative analysis, on the basis of satisfying the essential functional requirements and considering total cost, the most suitable material can be selected.

Again it must be emphasized that the materials should be compared on the basis of total

cost, not initial raw material cost alone. Also, it is essential that the end product must be capable of satisfying, as completely as possible, all of the essential functional requirements of the application. Further, before a particular material, that is, alloy, form, temper, and surface condition is specified on a drawing, its current availability and cost should be confirmed.

Careful attention to materials selection can help to keep the total cost of producing and maintaining an item at a minimum, whether it is a simple part or a complex structure. Some material selections are easily made, others require extensive analysis. In either case consultation with a qualified Materials Engineering organization is recommended.

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Chapter 5

Quality Assurance

GENERAL

When the term "quality assurance" is applied to the purchase of raw materials, such as iron or steel wrought products, it may be considered as a general definition of the various responsibilities which are incumbent upon the purchaser (purchasing agency) to assure that the material ordered and accepted for use in a particular application is of suitable quality. It is the responsibility of the purchaser to:

- a. Determine the exact requirements the materials must meet;
- b. Communicate these requirements, completely, concisely, and explicitly, to the material producer(s);
- c. Obtain confirmation from the producer that the requirements are realistic and that the producer is willing to supply material to these requirements;
- d. Verify that the incoming material satisfies the established requirements.

MATERIALS DESIGNATIONS

The American Iron and Steel Institute and the Society of Automotive Engineers, Inc., have developed similar numerical designation systems by which steels are identified by chemical composition. The basics of these systems are presented in Table XI, which was taken from Federal Standard No. 66 (Steel: Chemical Composition and Hardenability). The standard also contains a listing of the chemical composition limits for carbon and alloy steels, including the hardenability

steels (H-steels). The AISI designations are given for the various compositions, and, when there is no difference, the SAE designation is also listed. The data in Federal Standard No. 66 are directly applicable to the procurement of carbon and alloy steel wrought products and the Standard is referenced in, and forms a part of, many Federal and Military materials specifications.

SPECIFICATIONS

79. General. Material specifications are also used extensively in the procurement of steel and iron wrought products. Among the various specifications series available for use are the Military Specifications and Standards, the Federal Specifications and Standards, the AMS Specifications (Aerospace Material Specifications issued by the Society of Automotive Engineers, Inc.), and the ASTM Standards (issued by the American Society for Testing and Materials). The cross index at the end of this chapter lists the Federal, Military, AMS, and ASTM specifications which apply to the same composition and form of carbon or low alloy steel. When applicable the AISI-SAE standard composition designation number is also listed.

The different specifications that are shown to apply to steel of the same composition and form are not necessarily equivalent specifications. There are often slight differences between specifications issued by the various organizations; any two specifications should be carefully reviewed before they are used as equivalents.

Also, the cross index is not a complete listing

MIL-HDBK-723A**30 NOVEMBER 1970****TABLE XI. NUMERICAL DESIGNATION OF STEELS BY COMPOSITION**

Classification	Groupings	Series Designation		Explanation
		AISI	SAE	
Carbon Steels	Plain (nonresul.)	Up to 1013	Up to 1013	Each of the standard carbon and alloy steels is identified by a four-digit AISI or SAE number. The majority of AISI and SAE steels are identical. The first two digits of the number indicate the type of steel; i.e., for carbon steels 10xx indicates the non-resulphurized carbon steels, 11xx indicates the rephosphorized and re-sulphurized carbon steels. Similarly, for alloy steels, the first two digits indicate the grouping based on the significant alloying element or elements; i.e., 13xx for manganese steels. The last two digits of the number generally indicate the approximate middle of the carbon percentage range for the particular steel. For example in the composition identified as 1035, the 35 in the designation indicates that the steel has a carbon content range with a midpoint at 0.35 percent. In addition, prefix letters are used (primarily in AISI designations) to indicate the steelmaking process employed or the special end-use of the steel; i.e., B indicates acid bessemer steel. For alloy steels suffix letters indicate modifications or special types.
	Low carbon	1031 to 1022 incl	1013 to 1022 incl	
	Med. low carbon	Over 1022 to 1041 incl	Over 1022 to 1041 incl	
	Med. high carbon	Over 1041	Over 1041	
	High carbon			
Alloy Steels	Free-cutting (Free-machining)			
	Resulphurized	11xx	11xx	
	Rephosphorized and resulphurized	12xx	11xx	
	Acid bessemer	B11xx	11xx	
	Manganese	13xx	13xx	
	Boron	14xx	14xx	
	Nickel-chromium	31xx	31xx	
		33xx	33xx	
	Molybdenum	40xx	40xx	
		44xx	44xx	
		45xx	45xx	
	Chromium-molybdenum	41xx	41xx	
	Nickel-chromium-molybdenum	43xx	43xx	
		47xx	47xx	
		81xx	81xx	
		86xx	86xx	
		87xx	87xx	
		88xx	88xx	
		93xx	93xx	
		98xx	98xx	
	Nickel-molybdenum	46xx	46xx	
		48xx	48xx	
	Chromium			
	Low	50xx	40xx	
		51xx	51xx	
	Low (bearing)	50xxx	501xx	
	Medium (bearing)	51xxx	511xx	
	High (bearing)	52xxx	521xx	
	Chromium-vanadium	61xx	61xx	
	Silicon-manganese	92xx	92xx	
	Boron-intensified	xxBxx	xxBxx	
	Leaded	xxLxx	xxLxx	

of all of the specifications covering steel wrought products. Only the more common compositions and forms, to which more than one specification

applies, are listed. For a complete listing of specifications and standards the following should be consulted.

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a. The Department of Defense Index of Specifications and Standards. This is a two part index, numeric and alphabetical, listing all of the Military and Federal Specifications and Standards.

b. The Index of Aerospace Materials Specifications.

c. The Index to ASTM Standards.

80. Use of Specifications. The use of Military, Federal, AMS, and ASTM specifications greatly simplifies the communication of requirements from the purchaser to the supplier or producer. The specifications in these four series are generally recognized and accepted by the steel producers and are widely used throughout the industry. By using specifications from these series the purchaser communicates his requirements to the producer or supplier in a familiar standard form and minimizes the possibility of a misunderstanding.

The specifications are generally designed to fit the composition and form of steel to which they apply. Consequently, the requirements established by different specifications vary considerably. For example, many of the specifications for carbon steels establish requirements for chemical composition, temper, surface condition, form, and dimensional tolerances, but mechanical properties are often omitted. When these specifications are used it is necessary for the procuring agency to specify the mechanical properties requirements in the purchase order or contract, whenever the control of these properties is considered to be necessary.

The requirements which a material must satisfy are established by the purchaser on the basis of meeting the functional and processing requirements demanded by a particular application. A material specification should be selected which establishes requirements for a material that are consistent with the requirements of the application. Because of the wide difference in specifications it is advisable to select specifications on the basis of careful comparison with application requirements.

The material specifications establish pertinent requirements for a specific composition and form of steel. Examples are, chemical composition, mechanical properties, hardness, dimensional tolerances, austenite grain size, decarburization limits, and the like. As noted, the requirements established by the different specifications vary greatly. The tests and examinations which must be conducted to verify that a material satisfies established requirements necessarily vary with the requirements. It is the responsibility of the purchaser to determine what tests must be conducted to verify the quality of a lot of material. Many specifications require the performance of certain tests by the producer and require the producer to submit certified reports of the test results along with the material. In addition the purchaser is permitted to duplicate these tests and to perform any other appropriate tests that are deemed necessary. A wide variety of tests can be conducted on steel and iron wrought products and the purchaser must select those that are necessary and appropriate depending upon the composition, form, and requirements imposed upon the material.

STANDARDS

Federal and Military Specifications reference various Military and Federal Standards which are considered to form a part of the specifications. One such standard has already been noted, FED STD No. 66, "Steels - Chemical Composition and Hardenability", which provides the composition and hardenability requirements for various carbon and alloy steels. Federal Test Method Standard No. 151, "Metals, Test Methods" is another often referenced standard. Others are: MIL-STD 430, "Macrograph Standards for Steel Bars, Billets, and Blooms"; FED STD No. 48, "Tolerances for Steel and Iron Wrought Products"; FED STD No. 123, "Marking for Domestic Shipment (Civilian Agencies)"; FED STD No. 102, "Preservation, Packaging and Packing Levels"; MIL STD No. 163, "Steel Mill Products, Preparation for Shipment and Storage"; MIL-STD 271, "Nondestructive Testing Requirements for Metals"; MIL-STD 410, "Qualification of Inspection Personnel (Magnetic Particle and Penetrant)"; MIL-STD 453, "Inspection Radiographic"; FED STD No. 183, "Continuous Identification Marking of Iron and Steel Products."

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The ASM and ASTM specification systems have the equivalent of the Federal and Military Standards. These documents provide supplementary data which are applicable to many specifications.

Federal Test Method Standard No. 151, for example, establishes the procedures and methods for testing metals when Military and Federal specifications are used. There are various tests which may be used depending upon the properties and characteristics to be checked. Many are specifically called for in the various specifications, for example, tensile tests, analysis of chemical composition, austenite grain size determination, inclusion content, magnetic particle inspection, ultrasonic inspection, radiographic tests, etc. The purchaser should verify by appropriate tests that the incoming material satisfies the requirements established by the specification and by the contract with the producer. It is the responsibility of the purchasing agency to decide what

tests will be conducted and by whom.

Special skills are required for many of the tests specified in Federal Standard Test Method 151. Care should be exercised to assure that competent operators and equipment are used in performing the specified tests.

Many of the tests applicable to the inspection of raw materials are also useful as process control inspection tests. Careful selection and inspection of the raw materials used to produce a part or structure does not insure the quality of the final article. Steel wrought products can be severely damaged during fabrication unless the processes are effectively controlled. The hardness test, tensile test, X-ray examination, ultrasonic inspection, and many of the other tests described in Federal Test Method Standard 151 are applicable not only to the inspection of raw materials but are equally useful as in-process inspection tests.

TABLE XII. SPECIFICATION CROSS INDEX

AISI-SAE Designation	Specification Numbers			
	Federal	Military	AMS	ASTM
BAR - WROUGHT CARBON STEEL				
	QQ-S-630			A31
	QQ-S-631			A283, A306
	QQ-S-631			A306
	QQ-S-631			A113
	QQ-S-631			A108
	QQ-S-631			A108
	QQ-S-634			A615
	QQ-S-637			A616
	QQ-S-632			A617
	QQ-S-632			A615, A616, A617
	QQ-S-632			A615
	QQ-S-632			A615
	QQ-S-632			A615
	QQ-S-632			A615
1015	QQ-S-631		5060	
1018	QQ-S-631		5069	
1022	QQ-S-631		5070	
1035	QQ-S-631	Mil-S-16974	5080	
1095	QQ-S-631	Mil-S-8559	5132	
1117	QQ-S-637	Mil-S-3917	5022	A108
1137	QQ-S-637	Mil-S-3917	5024	A108
B1112	QQ-S-637	Mil-S-3917	5010	A108
	QQ-S-741			A283, A306
	QQ-S-741			A36
	QQ-S-741			A36

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AISI-SAE Designation	Specification Numbers			
	Federal	Military	AMS	ASTM
SHEET AND STRIP - WROUGHT CARBON STEEL				
1010	QQ-S-636(Cond. 2) QQ-S-698 (HRCQ) QQ-S-698 (HR Strip) QQ-S-698 (CRCQ) QQ-S-698 (Drawing Quality) QQ-S-699 (Classes 1, 2 & 3) QQ-S-699 (Classes 1, 2 & 3)		5044	A415 A425 A109 A365, A316, A320 A245 (Grade A, B & C) A303
1050	QQ-S-700 (1050)		5085	
1074	QQ-S-700 (1074)		5120	
1095	QQ-S-700 (1095)	Mil-S-7947	5121, 5122	
1095	QQ-S-777 (1095)	Mil-S-7947	5121, 5122	
PLATE - WROUGHT CARBON STEEL				
	QQ-S-741 QQ-S-741 QQ-S-741 QQ-S-691 (Class A & B) QQ-S-691 (Class C)			A36 A36 A201 (Grade A & B) A515, A516 A212 (Grade B) A515, A516
1009	QQ-S-635			A283
1020	QQ-S-635			A283
1035	QQ-S-635			A283
1040	QQ-S-635			A283
1045	QQ-S-635			A283
1050	QQ-S-635			A283
TUBING AND PIPE - WROUGHT CARBON STEEL				
		Mil-T-20157 (Pipe) Mil-T-20162		A53 (Type S Grades A & B)
1010	QQ-T-830			A513, A512, A519
1015	QQ-T-830			A513, A512, A519
1020	QQ-T-830			A513, A512, A519
1022	QQ-T-830			A513, A512, A519
1025	QQ-T-830	Mil-T-5066		A513, A512, A519
1026	QQ-T-830			A513, A512, A519
1030	QQ-T-830			A513, A512, A519
1035	QQ-T-830		5082	A513, A512, A519
1040	QQ-T-830			A513, A512, A519
1045	QQ-T-830			A513, A512, A519
1050	QQ-T-830			A513, A512, A519
1118	QQ-T-830			A519
1137	QQ-T-830			A519
		Mil-T-17188 Mil-T-16286 Mil-T-16343 (Pipe) Mil-T-16343 (Pipe) Mil-T-16343 (Pipe) Mil-T-16343 (Tube)		A178 A1292
			5075, 5077	A53 A135 A139 A344 (Grades 1 & 6)

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AISI-SAE Designation	Specification Numbers			
	Federal	Military	AMS	ASTM
STRUCTURAL SHAPES - WROUGHT CARBON STEEL				
	QQ-S-741 QQ-S-741 QQ-S-741			A36 A36
FORGINGS - WROUGHT CARBON STEEL				
		Mil-S-24093 (Class IV, V) Mil-S-23194 (Comp 2-Type C) Mil-S-890 Classes Ac, B-S Special, B and C) Mil-F-7190		A235 A235 A235 A235
WIRE - WROUGHT CARBON STEEL				
1020	QQ-W-461		5032	A228
1090	QQ-W-470		5112	
BAR - WROUGHT LOW ALLOY STEELS				
3135	QQ-S-624		6330	A304, A331, A322
3140	QQ-S-624			A304, A331, A322
3310	QQ-S-624	Mil-S-7393 (Comp. I)	6250	A304, A331, A322
3316	QQ-S-624	Mil-S-7393 (Comp. II)		A304, A331, A322
4037	QQ-S-624		6300	A304, A331, A322
4130	QQ-S-624	Mil-S-6758	6370	A304, A331, A322
4140	QQ-S-624	Mil-S-5626	6382	A304, A331, A322
4150	QQ-S-624			A304, A331, A322
4320	QQ-S-624		6299	A304, A331, A322
4340	QQ-S-624	Mil-S-5000	6415	A304, A331, A322
4615	QQ-S-624	Mil-S-866		
4615	QQ-S-624	Mil-S-7493	6290	A331, A322
4617	QQ-S-624	Mil-S-7493	6292	
4620	QQ-S-624	Mil-S-7493	6294	A304, A331, A322
4640	QQ-S-624		6312	A331, A322
6150	QQ-S-624	Mil-S-8503	6448	A304, A331, A322
8615	QQ-S-624	Mil-S-866	6270	A331, A322
8620	QQ-S-624	Mil-S-8690	6274	A304, A331, A322
8630	QQ-S-624	Mil-S-6050	6280	A304, A331, A322
8640	QQ-S-624			A304, A331, A322
8650	QQ-S-624			A304, A331, A322
8735	QQ-S-624	Mil-S-6098 (Cond. C)	6320	A304, A322
8740	QQ-S-624	Mil-S-6049 Cond. C)	6322	A304, A331, A322
9310	QQ-S-624	Mil-S-7393 (Comp. III)	6260, 6267	A304, A331, A322
945		Mil-S-7809		
950		Mil-S-7809		
9840	QQ-S-624		6342 6470	A304, A322
		Mil-S-6709 Mil-S-6709 (Cond. F) Mil-S-7420 Mil-S-18410 (CL. a) Mil-S-18410 (CL. b)	6472 6440, 6447	
52100				A182(GR. F-11) A336(CL. F-22)
SHEET AND STRIP - WROUGHT LOW ALLOY STEEL				
4130	QQ-S-627	Mil-S-18729	6350, 6351	A505
4135	QQ-S-627	Mil-S-18733	6352	A505
4140	QQ-S-627		6395	A505
4142	QQ-S-627			A505
4145	QQ-S-627			A505
4150	QQ-S-627			A505
4340	QQ-S-627		6359	A505
5140	QQ-S-627			A505

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AISI-SAE Designation	Specification Numbers				
	Federal	Military	AMS	ASTM	
SHEET AND STRIP - WROUGHT LOW ALLOY STEEL (Continued)					
5150	QQ-S-627	Mil-S-18731	6455	A505	
6150	QQ-S-627			A505	
8615	QQ-S-627			A505	
8617	QQ-S-627			A505	
8620	QQ-S-627	Mil-S-18728	6355	A505	
8630	QQ-S-627			A505	
8640	QQ-S-627			A505	
8645	QQ-S-627			A505	
8735	QQ-S-627	Mil-S-7809	6357	A505	
9262	QQ-S-627			A505	
945					
950					
PLATE - WROUGHT LOW ALLOY STEEL					
4130	QQ-S-626	Mil-S-18733	6395	6350, 6351	
4135					Mil-S-18729
4140	QQ-S-626				6359
4340	QQ-S-626				
4620	QQ-S-626	Mil-S-18728	6355	A514	
6150	QQ-S-626				
8620	QQ-S-626				
8630					
945		Mil-S-7809		A302(GR B)	
950		Mil-S-7809			
		Mil-S-16216			
		Mil-S-871			
		(CL. 2)			
TUBING - WROUGHT LOW ALLOY STEEL					
4130	QQ-T-00825	Mil-T-6736	6360, 6371	A513, A519	
4135	QQ-T-00825	Mil-T-6735	6365, 6372	A519	
4140	QQ-T-00825		6381, 6390	A519	
6150	QQ-T-00825	Mil-T-6734	6281	A513, A519	
8630	QQ-T-00825				Mil-T-6732
	QQ-T-00825				6530, 6550
	QQ-T-00825				
8640	QQ-T-00825	Mil-T-6733	6323	A519	
8720	QQ-T-00825				6282, 6535
8740	QQ-T-00825				6260
8735					
9310					
STRUCTURAL SHAPES - WROUGHT LOW ALLOY STEEL					
945		Mil-S-12505		A440	
950		Mil-S-7809			
		Mil-S-7809			
FORGINGS - WROUGHT LOW ALLOY STEELS					
4130		Mil-S-23194		A237	
4135		Mil-S-24093		A237	
4140		Mil-F-7190		A237	
4320		Mil-F-7190	6370		
4340		Mil-F-7190	6382	A237	
8630		Mil-S-23194			
8735		Mil-F-7190	6415	A237	
8740		Mil-F-7190	6280	A237	
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Appendix A

Glossary

alloy steel: (The American Iron and Steel Institute Definition). By common custom, steel is considered to be alloy steel when the maximum range given for the content of alloying elements exceeds one or more of the following limits: manganese, 1.65 percent; silicone, 0.60 percent; copper, 0.60 percent; or in which a definite range or a definite minimum quantity of any of the following elements is specified or required within the limits of the recognized field of constructional alloy steels; aluminum, boron, chromium up to 3.99 percent, cobalt, columbium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to obtain a desired alloying effect. Small quantities of certain elements are present in alloy steels which are not specified or required. These elements are considered as incidental and may be present to the following maximum amounts; copper, 0.35 percent; nickel, 0.25 percent; chromium, 0.20 percent; molybdenum, 0.06 percent.

alpha iron: The body-centered cubic form of pure iron, stable below 1670°F.

annealing: A heat treat process; heating a metal to and holding it at a particular temperature and then cooling it at a suitable rate to achieve a desired result, such as, reducing hardness, grain refinement, developing a particular microstructure, stress relieving, etc.

austempering: A heat treat process which consists of quenching a ferrous alloy from a temperature above its transformation range in a medium having a sufficiently high rate of heat abstraction to prevent the formation of high temperature transformation products. The alloy is held at a temperature below that of pearlite formation and above that of martensite formation until transformation is complete.

austenite: The solid solution of one or more elements in gamma-iron (face-centered cubic). The solute is assumed to be carbon, unless otherwise designated, e.g., nickel austenite.

austenitizing: The process of forming austenite in a ferrous alloy by heating it to a temperature within the transformation range (partial austenitizing), or to a temperature above the critical range (complete austenitizing).

bainite: A transformation product of austenite. Bainite is formed by isothermal transformation of austenite at temperatures lower than that for the fine pearlite and above the M_s temperature. Bainite is an aggregate of ferrite and cementite, when formed at temperatures in the upper portion of the transformation range it has a feathery appearance (upper bainite), while that formed at lower temperatures has an acicular or needlelike structure (lower bainite).

basic-oxygen process: A process of steelmaking in which molten pig iron and scrap are refined in a converter by blowing high purity oxygen onto the surface of the charge.

Bessemer process: A process of steelmaking in which air is blown through the charge of molten pig iron contained in a bessemer converter.

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billet: A semifinished hot rolled, forged, or extruded product, generally with a round or square cross-section. For ferrous materials the minimum diameter or thickness for a billet is 1 1/2 inches, and the cross-sectional area may range from 2 1/4 to 36 square inches.

blast furnace: A shaft furnace in which solid fuel is burned with an air blast to smelt ore in a continuous operation. The molten metal and molten slag are collected at the bottom of the furnace and are drawn off periodically.

bloom: A semifinished hot rolled product, usually with a square or rectangular cross section. If rectangular the width is no greater than twice the thickness. The cross-sectional area of a bloom usually exceeds 36 square inches.

carbon steel: (The American Iron and Steel Institute Definition). Carbon steel is classed as such when no minimum content is specified or guaranteed for aluminum, chromium, columbium, molybdenum, nickel, titanium, tungsten, vanadium, or zirconium; when the minimum for copper does not exceed 0.40 percent; or when the maximum content specified or guaranteed for any of the following elements does not exceed the percentages noted; manganese, 1.65; silicon, 0.60; copper, 0.60.

cementite: Iron carbide a hard brittle compound of iron and carbon, Fe_3C .

cold working: Plastic deformation of a metal at a temperature below its recrystallization temperature.

critical cooling rate: The slowest rate at which steel can be cooled from above the upper critical temperature to prevent the transformation of austenite at any temperature above the M_s .

critical point: In an equilibrium diagram, the specific combination of composition, temperature, and pressure at which the phases of a heterogeneous system are in equilibrium.

critical range: In ferrous alloys, the temperature ranges within which austenite forms on heating and transforms on cooling. The heating and cooling ranges may overlap but they never coincide.

critical temperature: Synonymous with critical point when pressure is constant.

crystal: A solid in which the atoms, ions, or molecules are arranged in a definite pattern which is repetitive in three directions.

decarburization: The loss of carbon from the surface of a ferrous alloy as the result of heating in a medium that reacts with the carbon at the surface of the material.

delta iron: The body-centered cubic crystalline form of pure iron, stable in the temperature range of 2535°F to the melting temperature, 2795°F.

delta solid solution: The solid solution of carbon in delta iron.

deoxidizer: A substance that can be added to molten metal to react with free or combined oxygen to facilitate its removal.

elastic deformation: The change in dimensions accompanying stress in the elastic region, the original dimensions are restored upon release of stress.

elastic limit: The greatest stress that a material can withstand without any permanent strain remaining upon complete release of the stress.

elastic modulus: See modulus of elasticity.

element: A substance that cannot be decomposed by ordinary chemical reactions.

endothermic: A reaction attended by the absorption of heat.

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equilibrium: A dynamic condition of balance between atomic movements where the resultant change is zero and the condition appears to be static rather than dynamic.

equilibrium diagram: A graph of the composition, temperature, and pressure limits of the phase fields in an alloy system under equilibrium conditions. In metal systems pressure is usually considered to be constant.

eutectic: An intimate mechanical mixture of two or more phases having a definite composition and a definite melting point.

eutectic reaction: An isothermal reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the system.

eutectoid: A mechanical mixture of two or more phases having a definite composition and a definite temperature of transformation within the solid state.

eutectoid reaction: An isothermal reversible reaction in which a solid solution is converted into two or more intimately mixed solids on cooling. The number of solids formed is the same as the number of components in the solution.

exothermic: A reaction attended by the liberation of heat.

fatigue: The phenomenon which results in the fracture of materials under repeated cyclic stresses having a maximum value lower than the tensile yield strength of the material.

fatigue limit: The maximum or limit stress value below which a material can presumably endure an infinite number of stress cycles.

fatigue strength: The maximum stress that can be sustained by a material for a specified number of cycles without failure. Completely reversed loading is implied unless otherwise qualified.

ferrite: The solid solution of carbon in alpha iron, body-centered cubic structure.

ferroalloy: An alloy of iron that contains a sufficient amount of some other element(s) to be useful as an agent for introducing the other element(s) into molten metal.

gamma iron: The face-centered cubic form of pure iron, stable from 1670°F to 2535°F.

gangue: The worthless portion of ore.

grain: An individual crystal in a polycrystalline metal or alloy.

hardenability: The property of a ferrous alloy which determines the depth and distribution of hardness that may be induced by quenching.

heat treatment: The operation or series of operations of heating and cooling a metal or alloy in the solid state to develop specific desired properties or characteristics.

Hooke's Law: Stress is proportional to strain. This law is valid only up to the elastic limit.

hot shortness: Brittleness in metal when hot.

hypereutectoid steel: Steel containing more than the eutectoid amount of carbon.

hypoeutectoid steel: Steel containing less than the eutectoid amount of carbon.

ingot: A special kind of casting (in steelmaking) intended for rolling or forging to wrought form.

iron carbide: A binary compound of iron and carbon, Fe_3C , see also cementite.

iron-carbon diagram: The equilibrium diagram for the iron-carbon binary system.

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isothermal transformations: A phase change which is made to occur at a constant temperature within the transformation range.

killed steel: Steel that has been deoxidized with a strong deoxidizer such as aluminum so that little or no reaction occurs between carbon and oxygen during solidification.

low-alloy steel: Alloy steels with a total alloy content of five percent or less.

martempering: A heat treat process that consists of quenching a ferrous alloy from an austenitizing temperature to a temperature slightly above or within the martensite transformation range, holding the material in the quench medium until the temperature throughout the mass is essentially uniform, after which the material is removed from the quench medium and cooled slowly in air.

martensite: A transformation product of austenite that forms below the M_s temperature. Is a metastable phase; as formed, alpha-martensite is a supersaturated interstitial solid solution of iron carbide in ferrite having a body-centered tetragonal crystal structure, characterized by an acicular or needlelike microstructural appearance. Aging or tempering alpha-martensite converts the tetragonal crystal structure to the body-centered cubic structure, in which form it is called beta-martensite.

modulus of elasticity: Within the proportional limit, the ratio of stress to corresponding strain. A measure of the rigidity of a metal; in tension or compression, Young's modulus; in torsion or shear, the modulus of rigidity, or modulus of torsion, or the modulus of shear.

normalizing: A heat treat process for ferrous materials that consists of cooling the material in air from a temperature slightly above the transformation range to room temperature.

open-hearth process: A steelmaking process in which pig iron and scrap are refined in a reverberatory furnace having a shallow hearth and low roof. The charge is heated by a long sweeping flame that passes over it.

ore: A natural mineral that may be mined and treated to extract any of its components.

pearlite: The lamellar aggregate of ferrite and iron-carbide that results from the transformation of austenite at the lower critical point on cooling.

permanent set: Plastic deformation that remains after the release of the stress that produced the deformation.

plastic deformation: Deformation that will or does remain permanent after the load that caused it is removed.

Poisson's ratio: The ratio of the transverse strain to the corresponding axial strain in a body subjected to uniaxial stress; usually applied to elastic conditions.

proportional limit: The maximum stress at which strain remains directly proportional to stress.

quench hardening: Hardening a ferrous alloy by austenitizing and then cooling rapidly enough so that all or some of the austenite transforms to martensite. Austenitizing temperatures for the hypoeutectoid steels are usually above the A_3 , for the hypereutectoid steels austenitizing temperatures are usually between the A_1 and the A_{cm} .

red shortness: See hot shortness.

rimmed steel: A low carbon steel containing sufficient iron oxide to promote a continuous evolution of carbon monoxide during solidification of the ingot.

semikilled steel: Steel that is incompletely deoxidized so that sufficient oxygen remains to react with carbon to form carbon monoxide to offset solidification shrinkage.

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shear modulus: See modulus of elasticity.

slab: A semifinished hot rolled product of rectangular cross section with a width greater than twice the thickness.

stress relieving: A heat treatment which consists of heating a metal to a suitable temperature and holding it at the temperature long enough to reduce residual stresses and then cooling it slowly to minimize the possibility of developing new residual stresses.

tempering: Reheating a quench-hardened or normalized ferrous alloy to a temperature below the transformation range and then cooling at any suitable rate.

transformation temperature: The temperature at which a phase change occurs. Often used to denote the limiting temperature of a transformation range. Standard identification symbols for iron and steel are as follows:

A_{cm}	For hypereutectoid steel, the temperature at which the solution of cementite in austenite is completed on heating.
A_{c1}	The temperature at which austenite begins to form on heating.
A_{c3}	The temperature at which the transformation of ferrite to austenite is completed on heating.
A_{c4}	The temperature at which austenite transforms to delta ferrite on heating.
$A_{r_{cm}}$	For hypereutectoid steels, the temperature at which cementite begins to precipitate from austenite on cooling.
A_{r1}	The temperature at which the transformation of austenite to ferrite, or to ferrite plus cementite is completed on cooling.
A_{r3}	The temperature at which austenite begins to transform to ferrite on cooling.
A_{r4}	The temperature at which delta ferrite transforms to austenite on cooling.
$A_{e1}, A_{e3},$ A_{e4} or $A_{cm}, A_1,$	
A_3, A_4	Transformation temperatures under equilibrium conditions.
M_s	(Martensite Start) The temperature at which austenite starts to transform to martensite.
M_f	(Martensite Finish) The temperature at which the formation of martensite is completed.

welding: (American Welding Society Definition) "A localized coalescence of metal wherein coalescence is produced by heating to suitable temperatures, with or without the application of pressure, and with or without the use of filler metal. The filler metal either has a melting point approximately the same as the base metals or has a melting point below that of the base metals but above 800°F.

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wrought iron: (ASTM definition) A ferrous material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron, with which, without subsequent fusion, is incorporated a minutely and uniformly distributed amount of slag.

Young's modulus: See modulus of elasticity.

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Appendix C

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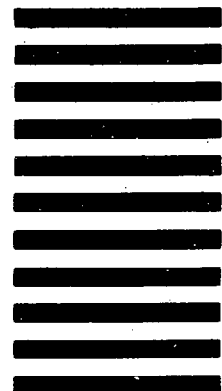
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