

Welding Handbook

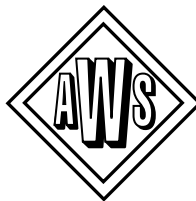
Ninth Edition

Volume 4

MATERIALS AND APPLICATIONS, PART 1

Prepared under the direction of the
Welding Handbook Committee

Annette O'Brien, Editor
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DEDICATION

Phillip I. Temple

This book is dedicated to Phil Temple in recognition of the guidance he has provided to the *Welding Handbook* as a contributor, reviewer, Chapter Chair, and as Chair of the Welding Handbook Committee from 1996 through 1999 and again from 2004 through 2007. He has been a Welding Handbook volunteer for the past 20 years, contributing to the publishing of several volumes of the 8th and 9th editions.

The leadership he brought to the *Welding Handbook* was gleaned from experience as he progressed from welder to welding instructor, welding superintendent to welding engineer, then to quality assurance management in the nuclear power industry. A graduate of LeTourneau University, he has been an active member of the American Welding Society for more than 35 years. In 2000, he received the National Meritorious Award for good counsel, loyalty, and dedication to the affairs of the Society.

CONTENTS

ACKNOWLEDGMENTS	x
PREFACE.....	xi
REVIEWERS.....	xii
CONTRIBUTORS	xiii

CHAPTER 1—CARBON AND LOW-ALLOY STEELS	1
Introduction	2
Welding Classifications.....	2
Fundamentals of Welding Carbon and Low-Alloy Steels	3
Common Forms of Weld-Related Cracking in Carbon and Low-Alloy Steels	12
Carbon Steels	23
High-Strength Low-Alloy Steels.....	41
Quenched and Tempered Steels	55
Heat-Treatable Low-Alloy Steels	67
Chromium-Molybdenum Steels	75
Applications	83
Safe Practices.....	90
Bibliography.....	90
Supplementary Reading List	92

CHAPTER 2—HIGH-ALLOY STEELS	95
Introduction	96
Classification of High-Alloy Steels.....	96
Precipitation-Hardening Steels.....	98
Maraging Steels	99
Nickel-Cobalt Steels	108
Austenitic Manganese Steels	119
Applications	130
Safe Practices.....	133
Conclusion	133
Bibliography.....	134
Supplementary Reading List	135

CHAPTER 3—COATED STEELS.....	137
Introduction	138
Terneplate.....	138
Tin-Plated Steel (Tinplate)	142
Joining Processes for Tinplate.....	143
Galvanized Steels.....	145
Aluminized Steels	186
Chromized Steels	193
Other Coated Steels.....	196
Painted Steels.....	207
Applications	209
Safe Practices.....	216
Bibliography.....	217
Supplementary Reading List	218

CHAPTER 4—TOOL AND DIE STEELS	221
Introduction	222
Metallurgical Properties	222
Tool Steel Classifications	223
Weldability	229

Heat Treatment	229
Arc Welding of Tool and Die Steels	233
Flash Welding and Friction Welding	244
Brazing.....	244
Tool Steel Welding Applications	246
Safe Practices.....	253
Conclusion	253
Bibliography.....	253
Supplementary Reading List.....	254
CHAPTER 5—STAINLESS AND HEAT-RESISTANT STEELS	255
Introduction	256
Martensitic Stainless Steels	272
Ferritic Stainless Steels.....	282
Austenitic Stainless Steels	289
Precipitation-Hardening Stainless Steels	334
Superferritic Stainless Steels.....	340
Superaustenitic Stainless Steels	343
Duplex Stainless Steels	351
Brazing and Soldering of Stainless Steels	369
Thermal Cutting.....	378
Applications	380
Safe Practices.....	385
Bibliography.....	386
Supplementary Reading List.....	390
CHAPTER 6—CLAD AND DISSIMILAR METALS.....	393
Introduction	394
Welding Variables.....	395
In-Service Properties of Dissimilar-Metal Welds	403
Filler Metals	405
Welding Process Selection.....	412
Specific Dissimilar Metal Combinations.....	413
Welding of Clad Steels.....	432
Applications	445
Safe Practices.....	448
Bibliography.....	450
Supplementary Reading List.....	450
CHAPTER 7—SURFACING MATERIALS	453
Introduction	454
Fundamentals.....	454
Surfacing Variables.....	461
Surfacing Processes.....	469
Base Metals for Hardfacing.....	491
Surfacing Metals	498
Applications	506
Safe Practices.....	511
Bibliography.....	511
Supplementary Reading List.....	512
CHAPTER 8—CAST IRONS	513
Introduction	514
Metallurgy of Cast Irons	515
Properties of Cast Irons.....	519

Welding Variables	527
Joining Processes and Filler Metals	535
Other Joining Processes	547
Surfacing	551
Applications	553
Safe Practices	561
Conclusion	561
Bibliography	562
Supplementary Reading List	562
CHAPTER 9—MAINTENANCE AND REPAIR WELDING	565
Introduction	566
Preventive Maintenance and Corrective Repair Welding	567
Systematic Planning of Repair Welding	567
Documenting the Cause of Failure	574
Codes, Standards, and Specifications	576
Establishing Repair Welding Procedures	583
Repair of Machine Components by Surfacing and Hardfacing	585
Applications	591
Safe Practices	603
Conclusion	604
Bibliography	607
Supplementary Reading List	607
CHAPTER 10—UNDERWATER WELDING AND CUTTING	609
Introduction	610
Preparation for Underwater Welding	612
Fundamentals of Underwater Welding	613
Dry Hyperbaric Welding	616
Underwater Wet Welding	621
Underwater Thermal Cutting	649
Qualification of Welding Personnel	655
Underwater Welding Codes and Specifications	656
Underwater Weld Inspection	657
Applications	660
Safe Practices	664
Conclusion	669
Bibliography	670
Supplementary Reading List	670
APPENDIX A—SAFETY CODES AND OTHER STANDARDS	675
Publishers of Safety Codes and Other Standards	677
APPENDIX B—WELDING HANDBOOK REFERENCE GUIDE	679
MAJOR SUBJECT INDEX	697
Volumes 3 and 4, Eighth Edition	697
Volumes 1, 2, 3, and 4, Ninth Edition	697
INDEX OF VOLUME 4, NINTH EDITION	719

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The Welding Handbook Committee and the editors gratefully recognize the contributions of the volunteers who have created, developed, and documented the technology of welding and shared it in past editions of the *Welding Handbook*, beginning with the first edition published in 1938. The enthusiasm and meticulous dedication of the authors and technologists reflected in the previous eight editions of the *Welding Handbook* are continued in this volume of the Ninth Edition.

This volume was compiled by the members the Welding Handbook Volume 4 Committee and the WH4 Chapter Committees, with oversight by the Welding Handbook Committee. Chapter committee chairs, chapter committee members, and oversight persons are recognized on the title page of the chapters.

The Welding Handbook Committee and the editors recognize and appreciate the AWS technical committees who developed the consensus standards that pertain to this volume, and acknowledge the work of W. R. Oates and A. M. Saitta, editors of Volume 4, Eighth Edition. The Welding Handbook Committee is grateful to members of the AWS Technical Activities Committee and the AWS Safety and Health Committee for their reviews of the chapters. The editors appreciate the AWS Technical Services staff for their assistance during the preparation of this volume.

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PREFACE

This is Volume 4 of the five-volume series in the Ninth Edition of the *Welding Handbook*. It is *Materials and Applications*, Part 1, presented in ten peer-reviewed chapters covering the metallurgical properties of various forms of ferrous metals and how these properties affect welding. The titles of the chapters in this book, which includes two applications chapters, indicate the variety of challenges presented to welders, designers, welding engineers, and others in the welding workplace.

The ability of scientists to examine the microstructures of the metals, identify constituent elements, and determine how the properties of the metals can be used and controlled during welding is reflected in the updated and expanded information in this book. Many of the best scientists in the welding industry from university, government or other research laboratories, metals producing companies, fabricators, consulting firms, and testing facilities have stepped forward as volunteers to update this volume. These highly regarded experts are recognized on the title pages of their respective chapters.

Three basic chapters of this volume, Chapter 1, Carbon and Low-Alloy Steels; Chapter 2, High-Alloy Steels; and Chapter 5, Stainless and Heat-Resistant Steels contain detailed sections on the metallurgy, composition and properties of steels, and methods of producing high-integrity welds in carbon steels, alloy steels, and stainless steels.

Different sets of welding conditions, challenges, and solutions are presented for the specialized steels represented in Chapter 3, Coated Steels; Chapter 4, Tool and Die Steels; Chapter 6, Clad and Dissimilar Metals; Chapter 7, Surfacing Materials; and Chapter 8, Cast Irons. The chapters provide information on the composition, metallurgy, weldability, and recommended welding procedures for these metals.

Two major applications are included in this volume. Chapter 9, Maintenance and Repair Welding, contains a model for a systematic approach to the sometimes difficult procedures involved in repair welding. Chapter 10, Underwater Welding and Cutting, contains critical information on producing strong, durable welds, sometimes under very difficult welding conditions, for use in the severest of service conditions.

A table of contents of each chapter is outlined on the cover page, along with names and affiliations of contributors of the updated information. A subject index with cross-references appears at the end of the volume. Appendix A contains a list of safety standards and publishers. Frequent references are made to the chapters of Ninth Edition Volumes 1, 2, and 3. To avoid repetition of information published in these volumes, a reference guide is presented in Appendix B.

This book follows three previously published volumes of the Ninth Edition of the *Welding Handbook*: Volume 1, *Welding Science and Technology*, which provides prerequisite information for welding and the welding processes; Volume 2, *Welding Processes, Part 1*, which contains the technical details of arc welding and cutting, the gas processes, brazing, and soldering; and Volume 3, *Welding Processes, Part 2*, which is devoted to the resistance, solid state, and other welding processes, such as laser beam, electron beam, and ultrasonic welding.

The Welding Handbook Committee welcomes your comments and suggestions. Please address them to the Editor, *Welding Handbook*, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126. www.aws.org.

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CHAPTER 1

CARBON AND
LOW-ALLOY
STEELS



Photograph courtesy of W. Virginia Dept. of Transportation—High-Performance Steel Bridge over the Ohio River

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Contents

Introduction	2
Welding Classifications	2
Fundamentals of Welding Carbon and Low-Alloy Steels	3
Common Forms of Cracking	12
Carbon Steels	23
High-Strength Low-Alloy Steels	41
Quenched and Tempered Steels	55
Heat-Treatable Low-Alloy Steels	67
Chromium- Molybdenum Steels	75
Applications	83
Safe Practices	90
Bibliography	90
Supplementary Reading List	92

CHAPTER 1

CARBON AND LOW-ALLOY STEELS

INTRODUCTION

Carbon and low-alloy steels represent over 95% of the construction and fabrication metals used worldwide. Good mechanical properties over a wide range of strengths combined with relatively low cost and ease of fabrication account for the widespread use of these steels. These attributes make carbon and low-alloy steels excellent choices for use in appliances, vehicles, bridges, buildings, machinery, pressure vessels, offshore structures, railroad equipment, ships, and a wide range of consumer products. The extensive use of these steels means that welding, brazing, and thermal cutting are essential processes of continuing importance.

This chapter contains information on steel compositions and properties, weldability considerations, recommended practices and procedures for welding, brazing, and thermal cutting of carbon and low-alloy steels; and also provides guidance on how to avoid problems when welding these steels.¹ A section on typical applications illustrates the scope and the importance of high-integrity welding of carbon steels and low-alloy steels.

temperature properties. Overlap exists among these groups due to the use of some steels in more than one heat-treated condition. The groups, each of which is discussed in a section of this chapter, are identified as follows:

1. Carbon steels,
2. High-strength low-alloy (HSLA) steels,
3. Quenched and tempered (Q&T) low-alloy steels,
4. Heat-treatable low-alloy (HTLA) steels, and
5. Chromium-molybdenum (Cr-Mo) steels.

Steels in these five groups are available in a variety of product forms, including sheet, strip, plate, pipe, tubing, forgings, castings and structural shapes. Regardless of the product form, in order to establish satisfactory welding procedures, the composition, mechanical properties, and condition of heat treatment must be known, as weldability is primarily a function of these three factors. Although most steels are used in rolled form, the same considerations for welding, brazing and thermal cutting apply also to forgings and castings. However, with large forgings and castings, consideration should be given to the effect of size or thickness with respect to heat input, cooling rate, and restraint. Other factors to be considered with castings are the effects of residual elements and localized variations in composition, which may not occur in wrought steels.

The compositions of carbon steels typically include weight percentages (wt %) of up to 1.00% carbon, up to 1.65% manganese, and up to 0.60% silicon. Steels identified as low-carbon steels contain less than about 0.15% carbon; mild steels contain 0.15% to 0.30% carbon; medium-carbon steels contain 0.30% to 0.50% carbon; and high-carbon steels contain 0.50% to 1.00% carbon. Although wrought carbon steels are most often used in the as rolled condition, they are sometimes used in the normalized or annealed condition.

WELDING CLASSIFICATIONS

From a weldability standpoint, carbon and low-alloy steels can be divided into five groups according to composition, strength, heat-treatment requirements, or high-

1. At the time of the preparation of this chapter, the referenced codes and other standards were valid. If a code or other standard is cited without a date of publication, it is understood that the latest edition of the document referred to applies. If a code or other standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

High-strength low-alloy steels are designed to provide better mechanical properties than conventional carbon steels. Generally, they are classified according to mechanical properties rather than chemical compositions. Their minimum yield strengths commonly fall within the range of 290 megapascals (MPa) to 550 MPa (40 000 pounds per square inch [40 kips per square inch {ksi} to 80 ksi]). These steels usually are welded in the as-rolled, normalized, or precipitation-hardened condition.

Quenched and tempered steels are a group of carbon and low-alloy steels that generally are heat treated by the producer to provide yield strengths in the range of 340 MPa to 1030 MPa (50 ksi to 150 ksi). In addition, they are designed to be welded in the heat-treated condition. Normally, the weldments receive no postweld heat treatment (PWHT), unless it is required to achieve dimensional stability or to conform to a construction code.

Many grades of heat-treatable low-alloy steels exhibit poor weldability. These steels generally have higher carbon content than high-strength low-alloy or quenched and tempered steels. Consequently, although they are capable of higher strengths, they may lack toughness in the as-welded condition and may be susceptible to cracking in the heat-affected zone (HAZ). Postweld heat treatment may reduce the risk of cracking and enhance the notch toughness of heat-treatable low-alloy steel weldments.

Chromium-molybdenum steels are used primarily for service at elevated temperatures up to about 700°C (1300°F) to resist creep and corrosion for applications in power plants, chemical plants, or petroleum refineries. Chromium-molybdenum steels may be welded in various heat-treated conditions (i.e., annealed, normalized and tempered, or quenched and tempered). Postweld heat treatment is often required by fabrication codes to improve ductility, toughness, and corrosion resistance, and to reduce stresses caused by welding.

FUNDAMENTALS OF WELDING CARBON AND LOW-ALLOY STEELS

Carbon steels and low-alloy steels can be welded by arc, oxyfuel gas, resistance, electron beam, laser beam, electroslog, and solid-state welding processes. These steels also can be joined by brazing, soldering, and adhesive bonding.² Subsequent sections of this chapter provide

information on the most commonly used joining processes for each of the five steel groups previously described.

METALLURGY AND WELDABILITY

The versatility of steel as an engineering material can be attributed to the wide variety of microstructures that can be created through changes in composition and processing. Understanding the basic properties of these structures and the effects of changes in chemistry are essential in designing and fabricating welds that are fit for their intended purpose.

PHASES AND MICROSTRUCTURES

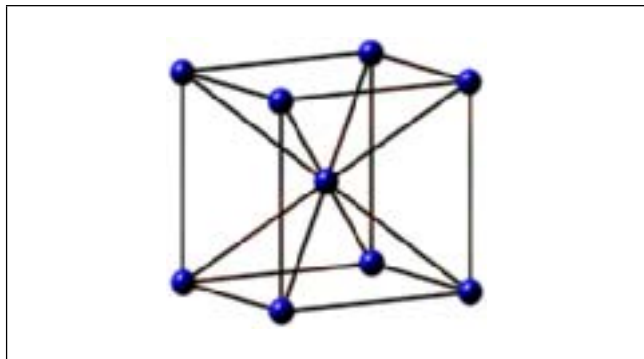
In metals and other material systems, a phase is considered to be a physically homogeneous and distinct portion of the system.³ It is bound by compositional limits, which vary with temperature. The term *microstructure* is used because virtually all of the geometric features of the phases and other structures that determine the properties of steels are observable only with the aid of microscopy. The microstructure of a type of steel is dependent on the amount of the various alloying elements that it contains, and also on both its present temperature and thermal history. The following section outlines the phases of the iron-iron carbide system, of which steel is composed, and the microstructures commonly observed in steel.

Ferrite

Pure iron (Fe) at room temperature has a body-centered cubic (BCC) crystal structure. Its *unit cell* (smallest repeating unit) is a cube with iron atoms at each corner and one iron atom in the center, as depicted in Figure 1.1. The atomic packing factor, or volume fraction occupied by atoms, of this structure is 0.68. The phase of iron exhibiting this structure is called either *alpha* (α)-iron or α -ferrite. The shape of its octahedral interstices gives it very low solubility for carbon, on the order of 10⁻⁵% at room temperature, gradually increasing to a maximum of 0.022% at 727°C (1341°F). At temperatures below 770°C (1418°F), ferrite is ferromagnetic and thus can be attracted by a magnet, while at temperatures between 770°C and 910°C (1418°F and 1675°F), it is paramagnetic. The temperature at which the change in magnetic properties takes place, changing

2. Standard welding terms and definitions used in this chapter are from American Welding Society (AWS) Committee on Definitions and Symbols, 2010, *Standard Welding Terms and Definitions*, AWS A3.0M/A3.0: 2010, Miami: American Welding Society.

3. Sinha, A. K., 1989, *Ferrous Physical Metallurgy*, Boston: Butterworth Publishers.



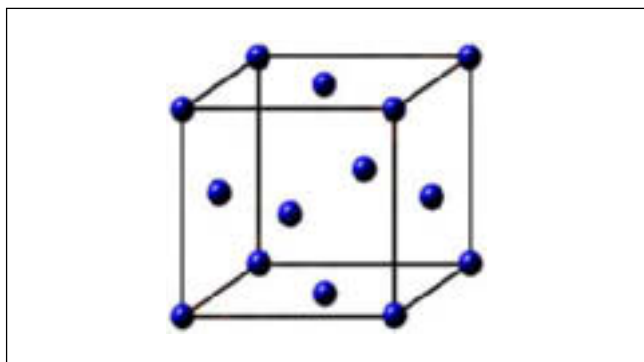
Source: American Welding Society (AWS), 2008, *Welding Inspection Technology*, 5th ed., Miami: American Welding Society.

Figure 1.1—Body-Centered Cubic Unit Cell

from ferromagnetic to paramagnetic (770°C [1418°F]), is called the *Curie temperature*.

Austenite

At temperatures between 912°C and 1394°C (1674°F and 2541°F), the stable crystal structure of pure iron is face-centered cubic (FCC). This structure is so named because its unit cell is a cube with iron atoms at each corner and in the center of each cube face. An FCC unit cell is shown in Figure 1.2. The atomic packing factor for this atom arrangement is 0.74, which represents the closest possible packing for spheres of uniform diame-



Source: American Welding Society (AWS), 2008, *Welding Inspection Technology*, 5th ed., Miami: American Welding Society.

Figure 1.2—Face-Centered Cubic Unit Cell

ter. The phase of iron exhibiting this structure is called *gamma* (γ)-iron or *austenite*, and its lattice parameter is 0.359 nm. The changing packing factor between ferrite and austenite is responsible for a volumetric contraction when ferrite changes to austenite on heating above 912°C (1674°F). Austenite is paramagnetic. In spite of closer packing of austenite, the more open shape of its octahedral interstices makes carbon much more soluble in austenite than in ferrite. The sudden change in carbon solubility as iron changes from FCC to BCC on cooling below 912°C (1674°F) is the primary reason the mechanical properties of steels can be so widely varied, and thus can be “tailored” for specific applications.

Delta Iron

In pure iron, the structure reverts to BCC from 1394°C (2541°F) to its melting temperature at 1538°C (2800°F). This form of iron is referred to as *delta* (δ)-iron or δ -ferrite. The result is another volume change when the transformation from austenite to δ -iron occurs, except that in this case it is a volumetric expansion.

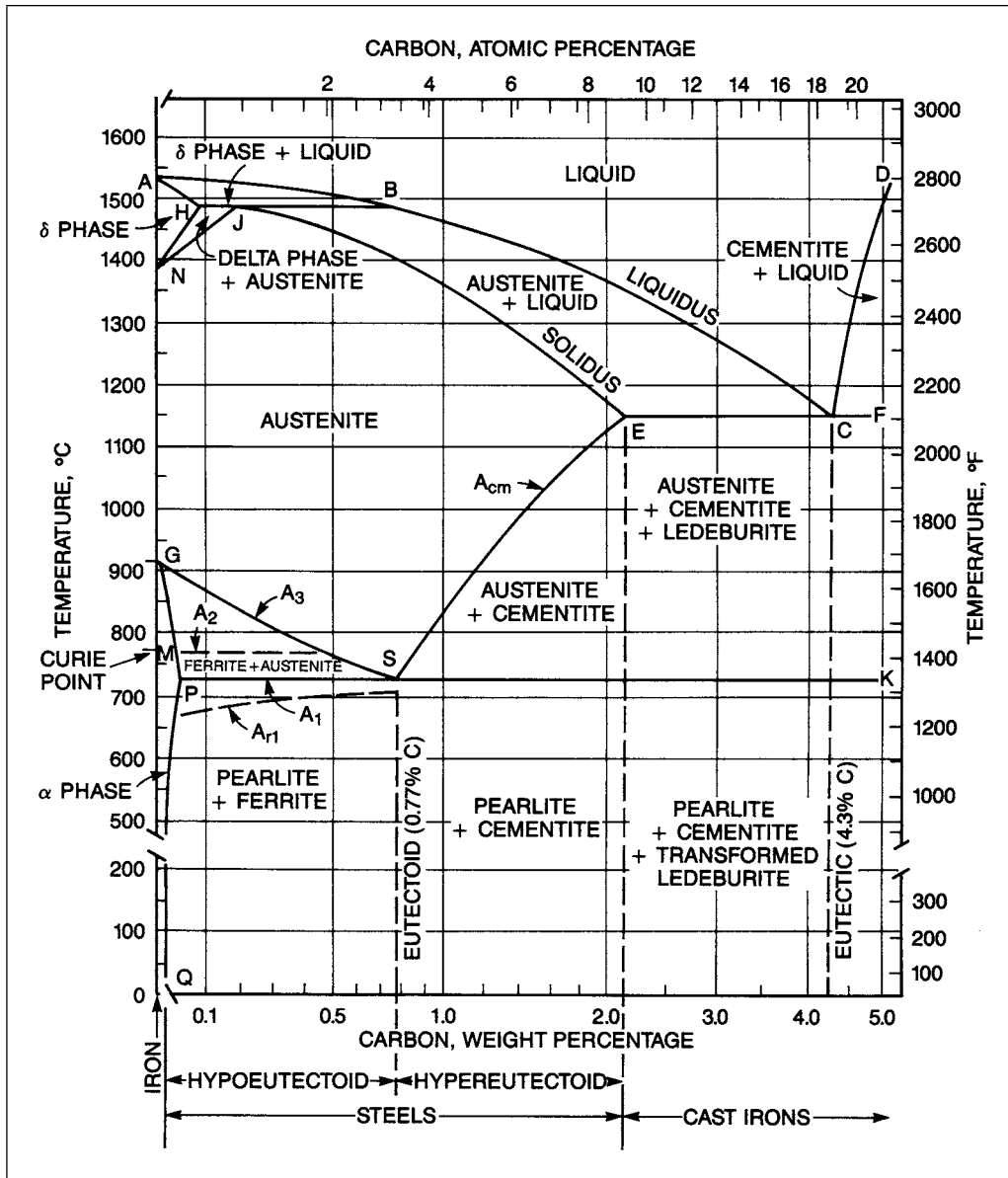
Cementite

Iron and carbon readily form a metastable intermetallic compound called *cementite*. It is represented by the chemical formula Fe_3C . Given enough time, cementite will decompose into iron and graphite. However, once formed, cementite is stable enough to be treated as an equilibrium phase. Unlike the ferrite and austenite phases of iron, cementite is noncubic and has an orthorhombic crystal structure. If tested by itself, it exhibits essentially zero tensile ductility and a Brinell hardness (HB) of more than 700 HB.⁴

Iron-Iron Carbide Phase Diagram

A phase diagram is a graphic representation of the temperature and composition limits for the various phases exhibited by a particular material system. The most common phase diagrams are binary equilibrium diagrams. For two-component systems, binary equilibrium diagrams represent the phases and also their respective compositions and mass fractions that are stable at any temperature under steady-state conditions. Figure 1.3 shows the iron-cementite (Fe- Fe_3C) equilibrium phase diagram for steels and cast irons. As noted in the axis labels, very small changes in the carbon concentration have a large effect on phase equilibrium. The effect of carbon on the stability of austenite also is

4. Davis, J. R., ed. 1992, *ASM Materials Engineering Handbook*, Materials Park, Ohio: ASM International.



Source: Linnert, G. E., 1994, *Welding Metallurgy*, Vol. 1, 4th ed., Miami: American Welding Society.

Figure 1.3—Fe-Fe₃C Phase Diagram for Steels and Cast Irons

shown in the diagram. Carbon is an austenite stabilizer, and in sufficient concentration, enables austenite to remain stable to temperatures well below the equilibrium temperature of austenite in pure iron. The diagram illustrates that over certain ranges of composition and temperature, it may be possible for two phases to coexist. For example, the triangular region bounded by points G, S, and P in the diagram contains a two-phase region known as the *intercritical region*, within which

both ferrite and austenite are stable. The line from Point G to the point labeled S on the A₃ line represents the locus of upper critical temperatures, that is, temperatures above which austenite becomes the only stable phase. The horizontal line at 727°C (1341°F) is commonly referred to as the A₁ line or *lower critical temperature*.

The microstructural behavior of steel heated into the intercritical region can be understood in a practical way

by considering a steel containing 0.20% carbon and being held at 780°C (1440°F). Both ferrite and austenite would be present, with all of the ferrite containing ~0.02% carbon and all of the austenite containing ~0.42% carbon. These values correspond to the equilibrium carbon concentrations for ferrite and austenite at 780°C (1440°F), as indicated by the phase boundary intersections of a horizontal “tie” line drawn across this region at 780°C (1440°F). It should be noted that while the composition of each individual phase varies with temperature, the overall or “bulk” composition remains constant at 0.20% carbon.

For a specified composition, the mass fractions of the two phases present at a given temperature may be calculated using what is referred to as the *lever law*. The bulk composition of the steel may be considered as the fulcrum of a lever, while the horizontal line between the compositions of the coexisting phases represents the lever. The amount of each phase present must balance the lever. In the preceding example, the equilibrium percentage of ferrite in a 0.20% carbon steel being held at 780°C (1440°F) can be expressed as follows:

$$\frac{0.42 - 0.2}{0.42 - 0.02} \times 100\% = 55\% \text{ ferrite} \quad (1.1)$$

Phase Morphologies

Phase diagrams such as those shown in Figure 1.3 are made under equilibrium conditions; samples are heated and cooled at very slow rates, allowing time for atoms to diffuse and energy barriers to be overcome, which is required for changing from one phase to another. While this is useful for determining the transformation temperatures of the equilibrium phases, welding normally involves dynamic thermal processes. These rapid thermal processes typically do not allow enough time for the nucleation and growth of equilibrium phases. When cooling is fast enough, a phase may continue to exist below its equilibrium transformation temperature in a phenomenon known as *supercooling* or *undercooling*. When transformations occur as a result of rapid cooling from elevated temperatures, the cooling rate has a significant effect on the resulting structure.

It should be noted, as pointed out by both Linnert⁵ and Samuels,⁶ that a variety of terms have been used to identify the same microstructures over the years. While there have been efforts to arrive at an internationally accepted terminology, final agreement has not been reached. The following sections cover some of the morphologies commonly found in steels, using the nomenclature according to Samuels.

Pearlite

Pearlite was named for its mother-of-pearl appearance when optically observed without sufficient magnification to resolve its microstructural features. It is a lamellar product of austenite decomposition, consisting of alternating lamellae of ferrite and cementite. Rather than grains, pearlite forms nodules.⁷ Each nodule is composed of colonies of parallel lamellae which have different orientations from those of adjacent colonies, as shown in Figure 1.4. When resolved under a microscope, pearlite often resembles the stripes on a zebra. Very fine pearlite is often difficult to resolve and may appear as very dark or even black grains. This difficulty led early metallurgists to identify fine pearlite as a separate phase. Pearlite may form under isothermal, continuous cooling, or directional growth conditions.

Bainite

There are two classic morphologies of bainite in ferrous microstructures: upper bainite and lower bainite. These two types form over different temperature ranges; upper bainite forms at higher temperatures than lower bainite. Upper bainite is often characterized by a

7. See Reference 3.

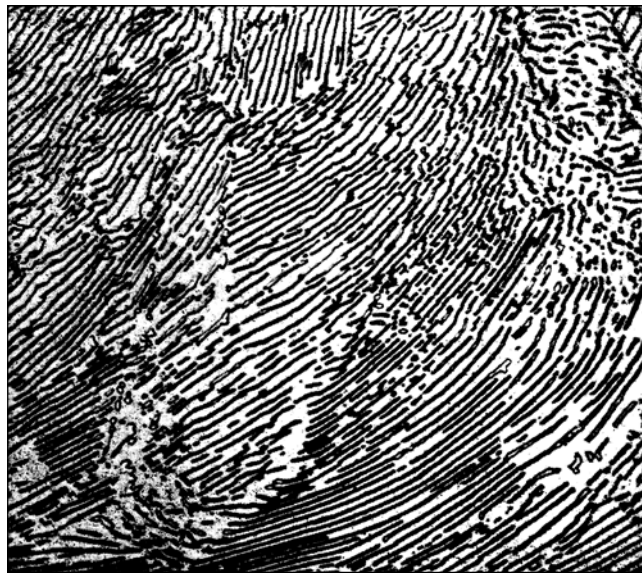


Figure 1.4—Typical Lamellar Appearance of Pearlite, 1500X Magnification (before Reduction), Etchant: Picral

5. Linnert, G. E., 1994, *Welding Metallurgy*, Vol. 1, 4th ed., Miami: American Welding Society.

6. Samuels, L. E., 1980, *Optical Microscopy of Carbon Steels*, Materials Park, Ohio: American Society for Metals.

feathery structure of low-carbon ferrite laths in cementite. It forms at temperatures between 350°C and 550°C (660°F and 1020°F).⁸ Lower bainite generally forms below 350°C (660°F), although carbon content may influence the temperature at which lower bainite begins to form. Lower bainite is characterized by a plate-like morphology. Plates of ferrite are separated by cementite, as in upper bainite. However, the ferrite plates that form in lower bainite have carbide precipitates within them.⁹

Martensite

Martensite has a body-centered tetragonal (BCT) crystal structure in iron. This structure is similar to the BCC crystal structure, except that four of the faces of the cube are rectangular rather than square. The *martensite* phase is formed by a martensitic transformation, which has been defined as the coherent formation of one phase from another, without change in composition, by a diffusionless, homogeneous lattice shear.¹⁰ In steels, transformation to martensite is achieved by rapid cooling from an austenitic state. When resolved with optical microscopy, low- to medium-carbon martensite appears as a lathy structure, as shown in Figure 1.5. Martensite can be differentiated from bainite by hard-

ness, with martensite being harder, and by etching, with martensite etching lighter.¹¹

For a given steel composition, the amount of martensite formed is determined by the degree of austenite supercooling, which is determined by the cooling or “quench” rate imposed upon it. Figure 1.6 illustrates this principle with a continuous cooling transformation (CCT) diagram for a steel containing 0.76% carbon and essentially no other alloy content.¹² This steel, having a eutectoid carbon content, has perhaps the simplest transformation behavior of any that might be considered. It should be noted that for this particular composition, 140°C (285°F) per second (as measured at 700°C (1290°F)) is the slowest cooling rate that will produce a fully martensitic microstructure. Similarly, 35°C (95°F) per second is the fastest cooling rate that will produce a fully pearlitic microstructure. Any cooling rate between these two rates will produce a mixture of martensite and pearlite. Also, the cooling rate through a range of temperatures from around 800°C to 500°C (1470°F to 930°F) is crucial to determining the amount of martensite in the resulting microstructure. This concept is applied more specifically to the behavior of the HAZ of steels in the section titled Carbon Equivalent in this chapter.

8. See Reference 3.

9. Bhadeshia, H. K. D. H., 2001, *Bainite in Steels*. 2nd ed., London: Institute of Materials.

10. See Reference 3.

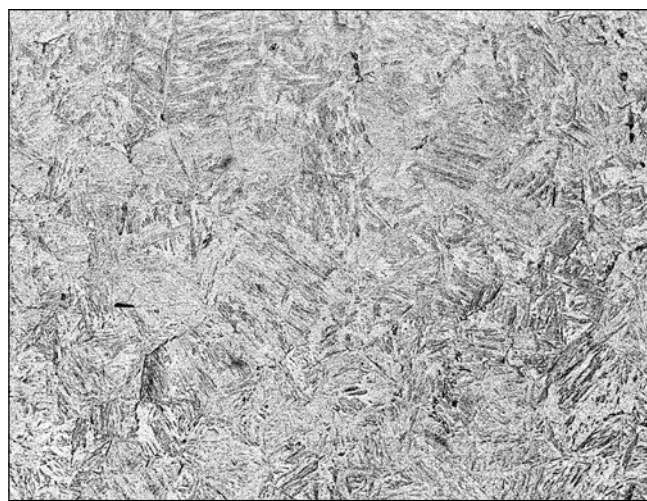


Figure 1.5—Lath-Type Martensite in a Medium-Carbon Steel, As-Quenched, 2% Nital Etched, 500X Magnification (before Reduction)

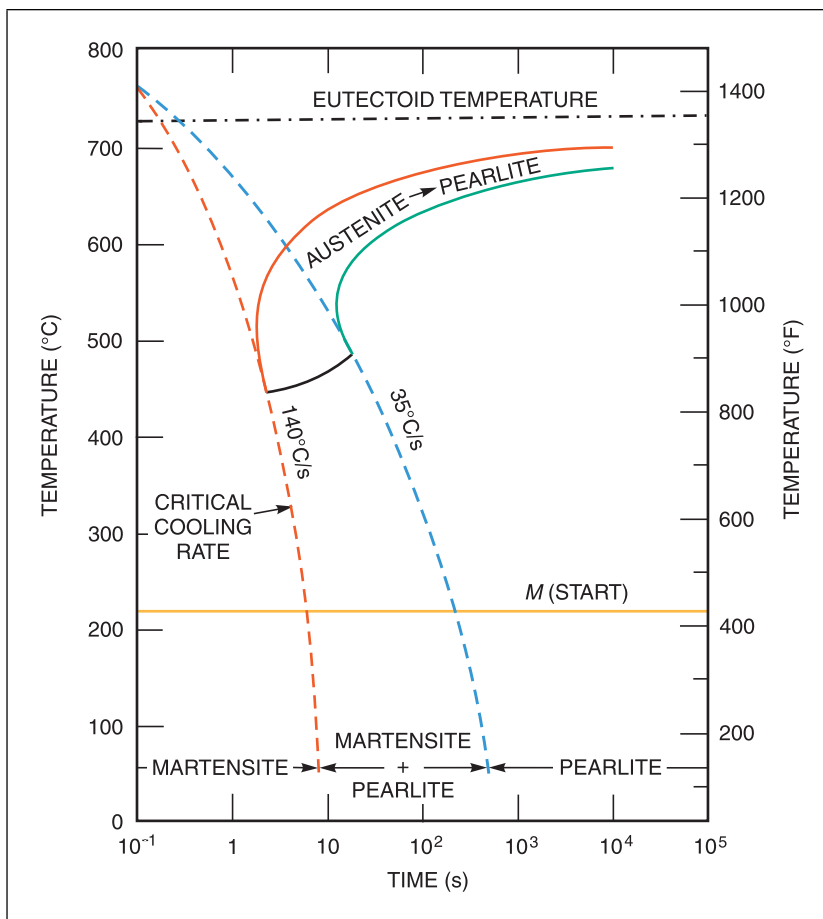
ALLOYS AND ALLOYING ELEMENTS

Alloys of iron containing up to approximately 1% carbon are classified as carbon and low-alloy steels. Carbon has a crucial influence on the mechanical properties of steel: very small changes in carbon contents can have a significant effect. However, steels are composed not only of iron and carbon, but also contain residual elements from processing. Steels may also contain other elements intentionally added to produce one or more desired characteristics.

The addition of even very small amounts of other elements to a pure metal or to a binary system like Fe-Fe₃C can significantly affect its phase equilibria. In general, alloying elements added to steels may be classified as either *austenite stabilizers* or *ferrite stabilizers*. Austenite stabilizers expand the γ -phase field, making austenite stable over a wider range of carbon contents and temperatures. Ferrite stabilizers shrink the γ -phase field, promoting the formation of ferrite over a wider range of compositions and temperatures. Additionally, some elements significantly impede the kinetics of transformation from one phase to another, particularly the decomposition of austenite upon cooling below A_1 . They do so primarily by inhibiting the diffusion of carbon, thereby increasing the hardenability of a steel. The

11. See Reference 3 and Reference 9.

12. Callister, W. D., 2007, *Materials Science and Engineering: An Introduction*, 7th ed., Hoboken, New Jersey: John Wiley & Sons, Inc.



Source: Callister, W. D., 2007, *Materials Science and Engineering, an Introduction*, 7th ed. Hoboken, New Jersey: John Wiley & Sons, Inc.

Figure 1.6—Continuous Cooling Transformation Diagram for Eutectoid (0.76% C) Plain Carbon Steel

common elements found in steels and the reasons for their presence are discussed in this section.^{13,14}

Carbon

Carbon has a greater effect on iron than any other alloying element. It is a potent austenite stabilizer and forms an interstitial solid solution in austenite. The solid solubility of carbon in ferrite at room-temperature is only about 0.008%, so most of the carbon is rejected

from solution in the form of cementite as the temperature falls below A_1 temperature (refer to Figure 1.3). The maximum attainable hardness for any particular microstructure in a steel is determined almost entirely by the amount of carbon it contains.

Manganese

Manganese (Mn) is added to virtually all steels because it has several helpful attributes and is inexpensive compared to most other alloying elements. Manganese combines with sulfur to form manganese sulfide (MnS) and combines with oxygen to form manganese oxide (MnO). In molten steel, manganese reduces the amount of both oxygen and sulfur in the steel. When ing these compounds, most of which are removed as

13. See Reference 5.

14. For additional information on the effects of deformation and heat treatment, refer to American Welding Society (AWS) Welding Handbook Committee, Jenney, C. L. and A. O'Brien, eds., 2001, *Welding Science and Technology*, Volume 1 of the *Welding Handbook*, 9th edition, Chapter 3, pp 121–132. Miami: American Welding Society.

slag. Manganese that is not consumed in the formation of MnS may form manganese carbide (Mn_3C), which is optically indistinguishable from cementite. It is a promoter of hardenability (the formation of martensite and other nonequilibrium structures when cooled from above the A_3 temperature). Manganese refines pearlite nodules and ferrite grain sizes, which increases the yield strength of carbon steel. The combination of these actions by manganese normally brings about an increase in fracture toughness.

Sulfur

Although sulfur (S) may be added to steels to promote chip formation when machining, it generally is considered a “tramp” element and held to very low levels (below 0.05%). When present in iron alloys, sulfur can form iron sulfide (FeS), which has a relatively low melting point (1200°C [2190°F]) compared to the iron solidus temperature. The effect of this low-melting-point constituent in the manufacture of steel is known as *hot shortness*, a loss of ductility at hot-working temperatures. Traditionally, FeS formation has been controlled by the addition of manganese to the melt. The affinity of manganese for sulfur is greater than that of iron, thus it reacts and binds with most of the sulfur in the form of relatively innocuous manganese sulfides (MnS). The MnS compound has a higher melting temperature and its internal surface-wetting characteristics are less detrimental than those of FeS .

However, the deleterious effects of sulfur are of even greater concern from a weldability standpoint, as FeS can produce solidification cracking and HAZ liquation cracking in fusion welds. Moreover, the MnS inclusions formed in the steelmaking process can lead to lamellar tearing, which is discussed in the section of this chapter titled Lamellar Tearing. Current techniques for sulfur control can reliably achieve residual sulfur contents below 0.005%.

Steels to which sulfur has been intentionally added to enhance machinability (i.e., with sulfur content of 0.08% up to about 0.35%) are called *free-machining steels* and generally should not be welded.

Phosphorus

Very small additions of phosphorus (P) can increase the strength, hardness, and corrosion resistance of steel. However, like sulfur, phosphorus is considered a tramp element. In the solid state, phosphorus forms Fe_3P , which is extremely brittle. The presence of this compound in steel causes cold shortness, the tendency to crack during cold working. Phosphorus causes a decrease in fracture toughness of steels designed to be strengthened by heat treatment. Another problem caused by phosphorus is segregation during solidifica-

tion. Phosphorus tends to become enriched in the metal that solidifies last, and as a weak ferrite former, promotes the formation of ferrite and its rejection of carbon into the surrounding metal. This results in bands in the microstructure that contain less cementite and more ferrite. These negative effects are incentives to keep the phosphorus content to 0.04% or less in most steels.

Silicon

Silicon (Si) is used in the steelmaking process to remove oxygen from the melt. When silicon is not used as a killing agent (removing oxygen from molten steel) it is only a residual element and may be found in trace amounts (approximately 0.008%). Silicon is a potent ferrite stabilizer that can prevent the transformation to austenite altogether if it is present in large enough quantities. Silicon also promotes the fluidity of molten steel, which makes it a useful addition in casting and welding applications.

Copper

Copper (Cu) is a very weak austenite stabilizer, but it is used in alloying for other purposes. Until the early 1900s, copper was regarded only as a tramp element responsible for surface checking and hot cracking. This problem was solved with the addition of nickel. In modern alloys, the motive for most copper additions is the significant increase in corrosion resistance imparted by copper in concentrations above 0.20%. Also, the addition of about 1.25% copper with an equal amount of nickel can form precipitates that significantly increase hardness.

Chromium

Chromium (Cr) is a very potent ferrite stabilizer. Like silicon, sufficient chromium can completely prevent the transformation from ferrite to austenite in steels. Chromium has a strong effect on the corrosion resistance of steel, and when present in sufficient quantities, it promotes the formation of a protective oxide surface film, which is the basis of the stainless steel alloys. Chromium is also added to maintain the strength of steel at elevated temperatures and it strongly increases the hardenability of steel.

Nickel

Nickel (Ni) is a strong austenite stabilizer and is added to stainless steels to counterbalance the ferrite-stabilizing effect of chromium. Nickel is completely soluble in FCC iron, and when alloyed with iron in concentrations greater than about 25%, it makes austenite stable at all temperatures. Nickel also contributes the ability to increase hardenability while also increasing

fracture toughness. Nickel has little affinity for oxygen and carbon and therefore forms no carbides or oxides when alloyed with iron. As previously mentioned, nickel is used in some steels with copper as a precipitation-hardening agent.

Molybdenum

Molybdenum (Mo) is a potent ferrite stabilizer. Additions to iron of just 3% will cause the retention of ferrite at all temperatures. Molybdenum readily forms carbides and increases hardenability. For this purpose, it is frequently added in concentrations ranging from 0.25% to 0.5%, along with chromium and nickel. In steels to be used at elevated service temperatures, molybdenum may be added in amounts from 0.5% to 4% to improve strength and creep resistance. In steels with low alloy composition, molybdenum is added in small amounts (0.05% to 0.25%) along with manganese and some nickel to suppress the formation of pearlite or to produce fine carbide lamellae that reduces the size of pearlite areas.

Niobium

Niobium (Nb) has a BCC crystal structure and is a ferrite stabilizer when added to iron. Prior to the standardization of element names, niobium was also known as *columbium*. Niobium is added to steels in very small amounts to form niobium carbide and carbonitride precipitates, which increase strength and inhibit grain coarsening at temperatures above A_3 . Niobium carbides begin to precipitate in steel at about 1200°C (2190°F); additions of niobium as small as 0.05% can produce a significant increase in strength. When properly controlled, niobium additions also promote fine ferrite grain size, which tends to improve toughness. Niobium is commonly added with vanadium and nitrogen to form complex niobium and vanadium carbonitrides. The optimum size and distribution of niobium-based precipitates and refinement of ferrite grains is achieved by carefully designed and controlled hot-rolling sequences. This technology, called *thermomechanically controlled processing* (TMCP), and the steels produced by it, are discussed in the High-Strength Low-Alloy Steel section of this chapter.

Vanadium

Vanadium (V), like niobium, is a ferrite stabilizer. It has traditionally been added to steels, especially tool steels, to promote hardenability. When a sufficient amount of manganese is present, small additions of vanadium (0.05% to 0.10%) provide effective strengthening. A benefit of vanadium is the reduced coarsening of austenite grains when heated above the A_3 tempera-

ture. Vanadium has a strong affinity for nitrogen and a tendency to form carbides. Strengthening of steels alloyed with vanadium is achieved by controlled rolling, heat treatment, or a combination of the two.

Aluminum

Aluminum (Al) is a potent ferrite stabilizer; as little as 1% added to iron will make ferrite stable at all temperatures. It is used primarily in the steelmaking process to remove oxygen from the melt by forming Al_2O_3 . Aluminum also has the ability to form aluminum nitride (AlN) particles, which act to restrict austenite grain coarsening at temperatures above the A_3 . A beneficial side effect of the AlN reaction is to counteract the adverse effects of excess nitrogen on the toughness of ferrite.

CARBON EQUIVALENT

The heat of welding, thermal cutting, and brazing causes changes in the microstructure and mechanical properties in a region of the heated steel that is referred to as the *heat-affected zone* (HAZ). The width of this region and the microstructure(s) it contains depend on the composition and prior microstructure of the steel, the peak temperature reached, and the rates of heating and cooling. This heating-cooling thermal cycle may result in the formation of martensite in the weld metal or HAZ, or both.¹⁵ The amount of martensite formed and the resulting hardness of these areas depend on the carbon and alloy content, the length of time at elevated temperatures, and the subsequent cooling rate through a critical temperature range. This range is usually considered to be 800°C to 500°C (1470°F to 930°F), and the cooling rate through the HAZ is often stated in terms of the length of time within the range, designated Δt_{8-5} .¹⁶

The overall alloy content of a type of steel determines its hardenability (the minimum cooling rate necessary to produce martensite). However, carbon content alone determines the maximum attainable hardness of any martensite that does form. Figure 1.7 shows this relationship for steels that are 50% and 100% martensite after quenching. High hardness levels increase susceptibility to hydrogen cracking in the weld or HAZ, thus the degree of hardening is an important consideration in assessing the weldability of a carbon or low-alloy steel. The weldability of steels, particularly resistance to hydrogen cracking, generally decreases with increasing carbon or martensite in the weld metal or HAZ, or both.

15. See Reference 3.

16. See Reference 3.

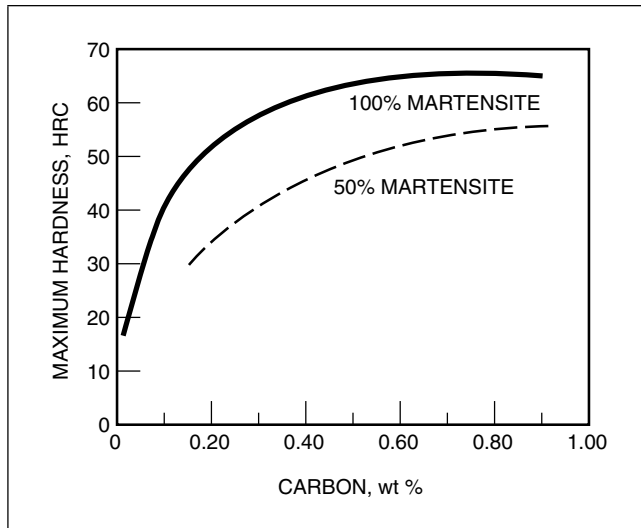


Figure 1.7—Relationship between Carbon Content and Maximum Hardness of Steels with Microstructure of 50% and 100% Martensite

Although carbon is the most significant alloying element affecting weldability of steels, the effects of other elements can be estimated by equating them to an equivalent amount of carbon. Thus, the effect of total alloy content can be expressed in terms of a carbon equivalent (CE). An empirical formula that may be used for judging the risk of underbead cracking in carbon steels is the following:¹⁷

(1.2)

$$CE = C + \frac{(Mn + Si)}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

Figure 1.8 shows the general relationships between carbon steel composition (the carbon equivalent) and hardness, underbead cracking sensitivity, or weldability

17. American Welding Society (AWS) Committee on Structural Welding, 2010, *Structural Welding Code, Steel*, AWS D.1.1/D1.1M:2010, Annex I, Miami: American Welding Society.

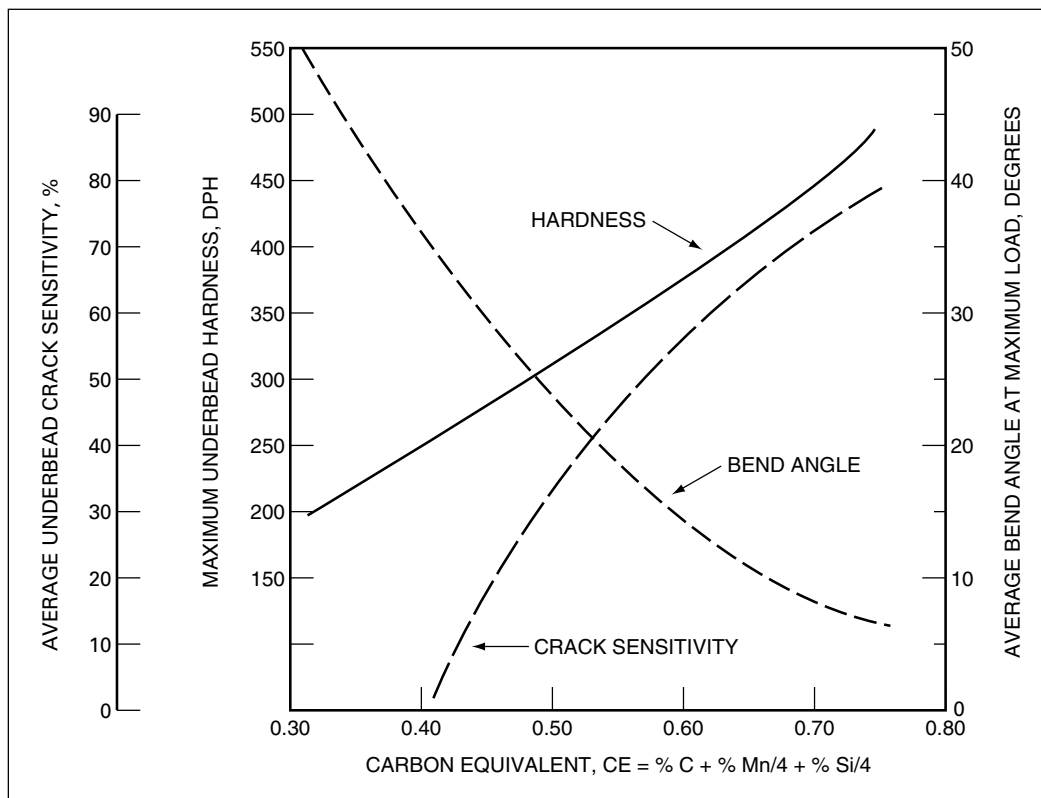


Figure 1.8—Relationship Between Composition and Underbead Hardness, Crack Sensitivity, and Notched-Weld-Bead Bend Angle for 25 mm (1 in.) Thick C-Mn Steel Plate Welded with E6010 Covered Electrodes

based on the slow-bend capacity of notched weld-bead test bars. Generally, steels with low CE values (e.g., 0.2 to 0.3) have excellent weldability; however, the susceptibility to underbead cracking from hydrogen increases when the CE exceeds 0.40. A steel with only 0.20% C and 1.60% Mn will have a CE of 0.60, indicating relatively high sensitivity to cracking.

COMMON FORMS OF WELD-RELATED CRACKING IN CARBON AND LOW-ALLOY STEELS

The various types of cracking, including hydrogen cracking, solidification cracking, liquation cracking, lamellar tearing, reheat cracking, and fatigue cracking are discussed in this section. Methods of preventing cracking also are described.

Surface preparation is standard practice in all welding applications, and is especially important in preventing most types of weld cracking. The presence of impurities has a very significant effect on the various cracking mechanisms and thus the quality of welds. Oil, grease, dirt, rust, metal filings, paint or other coatings must be cleaned from the surface of the steel in the region where the weld is to be made. For example, copper residue from tools such as cooling blocks and fixturing should be removed from the surface of the steel workpiece because copper can be a source of solidification cracking.

HYDROGEN CRACKING

Hydrogen cracking (also known as *underbead cracking*, *cold cracking*, or *delayed cracking*) can occur when welding carbon and low-alloy steels.^{18,19,20} The potential for hydrogen cracking in the weld metal or heat-affected zone, or both, depends on the composition, hydrogen content, and tensile stress level of these areas. Hydrogen cracking generally occurs at a temperature below 150°C (300°F), either immediately on cooling or after an incubation period of up to 48 hours. Increasing amounts of diffusible hydrogen, more susceptible (har-

der) microstructures or higher tensile stresses, or all three, increase the likelihood of cracking and shorten the incubation period. The following sequence describes the overall process:

1. Water (H₂O) or hydrocarbon (H_xC_x) molecules dissociate into atomic hydrogen in the welding arc;
2. Atomic hydrogen readily dissolves into the weld pool;
3. As the pool solidifies, hydrogen begins diffusing outward into the surrounding HAZ;
4. As the welded area cools, hydrogen diffusion slows, especially below about 200°C (390°F);
5. Over time, hydrogen accumulates at regions of triaxial tensile stress, such as at the weld toe or weld root at slag inclusions, or at small solidification or liquation cracks; and
6. When (or if) the hydrogen concentration at any location exceeds a threshold value, as determined by the present stress and microstructure, cracking begins.

Cracking sometimes occurs in the weld metal, particularly when its yield strength is over 620 MPa (90 ksi). In general, however, alloy steels are more likely to crack in the HAZ.

To summarize, hydrogen cracking in welded joints is associated with the combined presence of the following four conditions:

1. The presence of atomic (diffusible) hydrogen;
2. A susceptible microstructure, typically but not necessarily martensitic;
3. A sustained tensile stress at the sensitive location; and
4. A temperature below 150°C (300°F).

Hydrogen Sources

Molten steel has a high solubility for atomic (diffusible) hydrogen, which may be present due to the dissociation of water vapor or hydrocarbons in the welding arc. The diffusion rate of atomic hydrogen in steel is high at or near its melting temperature. Therefore, the molten weld metal can rapidly pick up atomic hydrogen from arc plasma. Once in the weld metal, hydrogen atoms can diffuse rapidly into the HAZ of the base metal.

There are several possible sources of moisture and other hydrogenous compounds that can dissociate in the welding arc and introduce diffusible hydrogen into the weld metal. Sources include the filler metal, moisture in the electrode covering, welding torch shields, gas, or surface contaminants, such as adsorbed mois-

18. For additional information, refer to Reference 14.

19. See Reference 5.

20. For a definitive work on hydrogen cracking, refer to Bailey, N., and F. R. Coe, 1993, *Welding Steels Without Hydrogen Cracking*, Edition: 2, illustrated; 1855730146, 9781855730144, Great Abington, Cambridge, UK: Woodhead Publishing.

ture, hydrated rust, oil, grease, or paint on the filler metal or base metal. The welding wire or rod may be contaminated with lubricants used during the wire-drawing operation. In shielded metal arc welding (SMAW), the primary sources of hydrogen are cellulose or moisture, or both, in the electrode covering. In submerged arc welding (SAW), the primary source is moisture in the flux. In flux-cored arc welding (FCAW) and gas-metal arc welding (GMAW) with metal-cored wire, moisture in the core ingredients is the primary source. Shielding gases contaminated with humid air or moisture are additional sources of hydrogen.

The American Welding Society standard AWS A4.3 describes methods for measuring the diffusible hydrogen content of welds deposited by shielded metal arc welding, gas metal arc welding, flux cored arc welding, and submerged arc welding processes.²¹ As a result of standardized testing provided by this specification, a diffusible hydrogen designator, H16, H8, H4, or H2, can be attached to the classification of carbon steel and low-alloy steel filler metals to identify the maximum diffusible hydrogen limit the filler metal will meet.

The tendency for hydrogen cracking is approximately proportional to the logarithm of the diffusible hydrogen content of the weld deposit. Accordingly, the diffusible hydrogen designators in AWS filler metal specifications are based on a geometric progression of hydrogen content limits, as shown in Table 1.1.

A low-hydrogen electrode classified with one of these designators is certified to meet the corresponding hydrogen limit under the standardized test conditions specified in AWS A4.3.²²

21. American Welding Society (AWS), 2006, *Standard Methods for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding*, AWS A4.3-93 (R2006), Miami: American Welding Society.
22. See Reference 17 and American Welding Society (AWS), 2008, *The Official Book of D1.1 Interpretations*, AWS D1.1-BI:2008, Miami: American Welding Society.

Electrodes that resist moisture pickup for extended time periods under conditions of high atmospheric humidity are designated with an “R” in the electrode classification. The AWS standard, *Structural Welding Code—Steel*, AWS D1.1/D1.1M:2010²³ permits longer exposure times for such electrodes, thus a moisture-resistant E7018 low-hydrogen electrode might be designated as E7018-H4R. Similar designations also are available in alloy combinations. This is an area of active development in shielded metal arc electrodes; therefore, recommendations from the manufacturers of electrodes, in addition to the most recent editions of AWS A5.1 and A5.5, should be consulted for the latest information.²⁴

Microstructure

Hydrogen is most likely to promote cracking when the steel has a martensitic microstructure. With this microstructure and a quantity of hydrogen present, a tensile stress much lower than the normal cohesive strength of the metal can initiate a crack. In general, the stress required to produce a crack in steel is progressively lower as the hydrogen content increases. The susceptibility of martensite to hydrogen cracking is believed to be due partly to high local transformation stresses.

Bainitic microstructures in steel display a distinctly lower susceptibility to hydrogen cracking compared to martensitic microstructures. The local stresses are significantly lower in bainite, even though it may have a degree of hardness approaching that of any martensite in the microstructure. A mixture of ferrite and high-carbon martensite or bainite also is quite susceptible to hydrogen cracking. This microstructure is produced during cooling from austenite at a rate that is slightly faster than the critical cooling rate for the steel. Therefore, in the presence of sufficient hydrogen, any localized area with this sort of mixed microstructure will be susceptible to cracking in the HAZ.

Susceptibility to cracking can be reduced by minimizing the formation of martensite in the weld metal and HAZ. This is accomplished by controlling the cooling rate of the weld with either higher preheat temperature or higher heat input. The cooling rate depends on the thickness of the workpiece, preheat temperature, and welding heat input. With some steels, however, a change in welding procedures that reduces the amount of martensite in the microstructure may result in a detrimental change in certain mechanical properties of the welded joint.

23. See Reference 17.
24. Refer to AWS Committee on Filler Metals and Allied Materials, 2004, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*, AWS A5.1/A5.1M:2004, and 2006, AWS A5.5/A5.5M:2006, *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*, Miami: American Welding Society.

Table 1.1 Diffusible Hydrogen Limits for Weld Metal	
Designator	Diffusible Hydrogen Content, mL/100g of Deposited Metal
H16	no more than 16
H8	no more than 8
H4	no more than 4
H2	no more than 2



High-heat-input welds, such as electroslog welds, also can exhibit hydrogen cracking in the extensive ferrite veining common to the weld metal. In these instances, high moisture content in the welding flux is usually the cause of the cracking.

Stresses

Possible sources of stress are phase transformation, thermal contraction, mechanical restraint, applied loads, or fabrication sequence. These stresses may be reduced by preheating, adjusting the welding procedure, or redesigning the weldment or fabrication sequence to reduce restraint on the joint. The *Welding Handbook*, Volume 1, Chapter 3, Heat Flow in Welding; Chapter 5, Design for Welding; and Chapter 7, Residual Stress and Distortion, can be consulted for background information on the development of stresses in weldments and information on weldment design. Appendix B of this volume provides a reference guide to the contents of various volumes of the *Welding Handbook*.²⁵

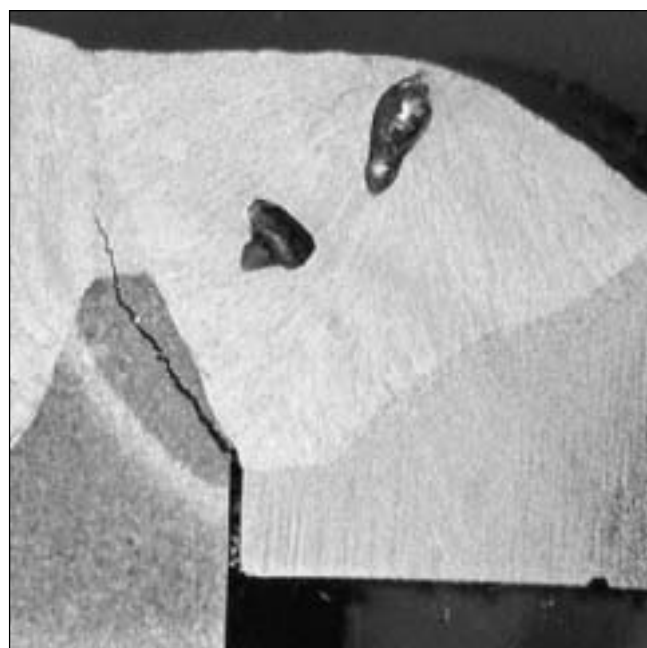
25. See Reference 14.

Underbead Cracking

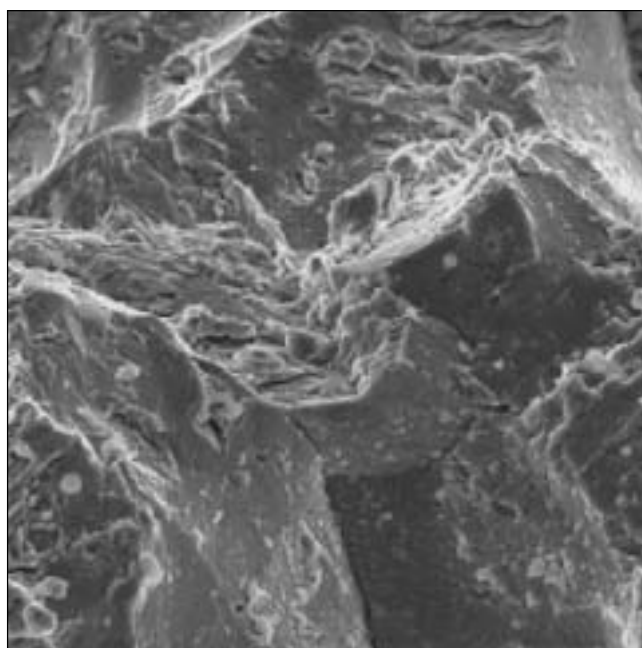
The most common occurrence of hydrogen-induced cracking is in the grain-coarsened HAZ of a steel with a susceptible microstructure that has not been adequately preheated. When cracking occurs in this particular location it is often called *underbead cracking* because of its proximity to the weld interface, as illustrated in Figure 1.9.

Weld Metal Cracking

Weld metal normally presents fewer problems than base metal with regard to hydrogen cracking. This is probably a result of the general use of filler metal with lower carbon content than the base metal. Nevertheless, in some cases hydrogen can still cause weld metal cracking to a significant extent. For example, consumables alloyed to produce weld metal with strength levels matching those of certain high-strength low-alloy (HSLA) steels, particularly those designed to meet United States Navy requirements for ships and submarines, have resulted in weldments that are more susceptible to



(A)



(B)

Figure 1.9—(A) Underbead Crack in a Transverse Metallographic Section of a Weld in SAE 9310 Steel and (B) SEM Fractograph of the Same Crack

hydrogen cracking in the weld metal than to hydrogen cracking in the HAZ. Thus, for these steels, preheating requirements are dictated by the weld metal rather than the base metal.

Hydrogen cracking in the weld metal may take several forms. It usually occurs transverse to the weld bead length and at right angles to the surface. Hydrogen cracks can occur longitudinally, or also as 45° chevron cracks.

One form of hydrogen-induced cracking that occurs in weld metal appears as small bright spots on the fractured faces of broken specimens of weld metal. These spots are called *fisheyes*. The fisheye usually surrounds some discontinuity in the metal, such as a gas pocket or a nonmetallic inclusion, which gives the appearance of the pupil of an eye.

Conditions that lead to the formation of fisheyes in weld metal can be minimized by using dry, low-hydrogen electrodes, by increasing the preheat temperature, or by applying immediate postweld hydrogen release treatment to the weldment for at least 20 minutes at temperatures ranging from 95°C to 320°C (200°F to 600°F). The elevated temperature serves to speed the diffusion of atomic hydrogen away from the weld region. Longer times or higher temperatures, or both, should be applied when there is increased hydrogen contamination and higher alloy content.

Microcracks may be observed in weld metal deposited by shielded metal arc welding (SMAW) electrodes containing cellulose in the covering, or by low-hydrogen electrodes that have excessive moisture in the covering. These microcracks generally are oriented transverse to the axis of the weld. They are less likely to occur in weld metal deposited with dry low-hydrogen electrodes. Even with this precaution, however, weld metal cracking can occur at higher levels of strength or carbon equivalence.

Methods of Avoiding Hydrogen Cracking

When the carbon content of steel is increased, the hardness of any martensite formed within its microstructure is also increased. When the alloy content of steel is increased for greater quench hardenability, the likelihood and thus the quantity of martensite are consequently increased. Both of these effects tend to reduce the hydrogen tolerance of steels.

Residual stresses, being limited by yielding, also tend to increase with yield strength. Susceptibility to hydrogen cracking increases with increasing residual stress, although this may also reflect the more susceptible microstructure. For example, carbon steels with an ultimate tensile strength (UTS) that does not exceed 410 MPa (60 ksi) can be welded with E6010 or E6011 covered electrodes, which are characteristically high in hydrogen because the coverings contain cellulose and 3% to 7% moisture. Conversely, higher-strength quenched and tempered steels

such as HY-130 must be welded with covered electrodes that contain no more than 0.1% moisture in the covering. (Refer to Table 1.18 for the chemical composition of HY-130.) Moisture or hydrogen limits for covered electrodes vary between these two levels, depending on the type of steel being welded.

Hydrogen cracking can be controlled by several means. A welding process or an electrode that produces minimal diffusible hydrogen can be selected. A combination of welding heat input and thermal treatments can be used to drive off the hydrogen, or produce a microstructure that is less sensitive to it. Another alternative is to use joint designs and welding procedures that minimize restraint and thus minimize residual stresses.

Welding Process

The amount of diffusible hydrogen produced during welding can be limited by using an inherently low-hydrogen process such as GMAW. For processes that employ a flux, such as SMAW, low-hydrogen electrodes are recommended for the welding of crack-susceptible steels. However, the moisture content of these electrodes must be maintained below the limits stated in the applicable filler metal specification.

Electrodes are manufactured for use within acceptable moisture limits consistent with the type of covering and strength of the weld metal. Low-hydrogen electrodes are packaged in containers that provide the moisture protection necessary for the type of covering and the application. These electrodes can be maintained for many months in these protective containers when stored at room temperature with the relative humidity at 50% or less. Unpackaged, they can be stored in electrode-holding ovens for short times. However, if the containers are removed or damaged and the electrodes are improperly stored, the coverings may absorb excessive moisture.

Some covered electrodes are designed to resist moisture pickup during exposure to the atmosphere. A standardized absorbed-moisture test is described in *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*, AWS A5.1/A5.1M:2004, and *Specification for Low-Alloy Steel Electrodes for Shielded Metal Arc Welding*, AWS A5.5/A5.5M:2006.²⁶ As a result of passing this exposure test of 9 hours at 27°C (80°F) and 80% relative humidity, electrodes may have an “R” designator attached to the classification; AWS A5.1 electrodes may be classified as E7018M to indicate moisture resistance.

The low-hydrogen electrodes (EXX15 and EXX16) and low-hydrogen iron powder electrodes (EXX18,

26. See Reference 24.

EXX28, and EXX48) are designed to contain a minimal amount of moisture in the coverings. The maximum acceptable moisture level of the filler metal decreases in proportion to the increase in the strength of the weld metal. To maintain this low moisture level in the covering, hermetically sealed containers are mandatory for electrodes that deposit weld metal with a tensile strength of 550 MPa (80 ksi) or higher. These containers are optional for electrodes of lower-strength classifications.²⁷

As previously mentioned, electrodes that have been exposed to a humid atmosphere for an extended time may absorb excessive moisture. The moisture content of electrodes that have been exposed to the atmosphere should not exceed the limits stated in the appropriate specification. If there is a possibility that the electrodes have picked up excessive moisture, they may be reconditioned by baking in an oven. The appropriate time and temperature for baking should be requested from the electrode manufacturer. The user should be aware that the applicable welding code may place limits on reconditioning. For example, *Structural Welding Code—Steel*, AWS D1.1 specifies conditions for baking submerged arc welding flux.²⁸

The hydrogen designators shown in Table 1.1 are used in AWS specifications to designate the diffusible hydrogen content of covered carbon steel electrodes and submerged arc low-alloy steel welding wires and fluxes. The same hydrogen designators also apply to other ferritic covered electrodes, submerged arc wires and fluxes, and flux-cored wires. Although none of the specifications for austenitic stainless steel and nickel alloy electrodes contain limits on hydrogen or moisture, special precautions should be exercised when using these electrodes to weld high-strength and alloy steels. Flux-cored electrodes, in particular, should not be used to weld steels that are sensitive to hydrogen cracking if the electrodes have been contaminated with moisture or any other hydrogen-containing substance.

Thermal Treatments

Preheating and postheating at or just above the preheat temperature should be considered when there is a significant risk of hydrogen cracking in the welded joint. Preheating involves raising the temperature of the weldment prior to welding, and maintaining an elevated

interpass temperature during the entire welding operation. Controlling preheat and interpass temperatures achieves the following conditions:

1. Reduces cooling rates and thus reduces the hardness of heat-affected zones,
2. Increases the rate at which hydrogen diffuses away from the weld and heat-affected zone, and
3. Reduces residual stresses in and near the weld.

Preheat may be applied to the entire weldment or to a band of specified width that includes the weld joint. The selection of preheat temperature and the degree to which preheat must be applied involves a number of considerations. In general, preheat temperatures must increase with increasing carbon equivalent, plate thickness, restraint, and hydrogen levels. Conversely, the use of high levels of arc energy and low-hydrogen consumables may permit the use of a lower preheat temperature. Recommendations for minimum preheat temperatures for carbon steels and low-alloy steels are published in a number of documents, including the standard, *Structural Welding Code—Steel*, AWS D1.1, and Bailey et al, *Welding Steels without Hydrogen Cracking*.^{29,30} These recommendations are discussed for each type of steel in subsequent sections of this chapter.

Postheating should be performed immediately after welding, while the weldment is still at the preheat temperature. The postheat temperature may be the same used for preheating: 95°C to 320°C (200°F to 600°F). The holding time at postheat temperature depends on the joint thickness, because the length of the path over which the hydrogen must diffuse to the surface is a controlling factor.

Weldments of steels that are quenched and tempered to achieve desired properties require special treatment. They must be either welded with a low-hydrogen process, or heat treated after welding and prior to the hardening treatment.

It is recommended that steels not be welded if the steel temperature is below 0°C (32°F). If the temperature of the steel is below 0°C (32°F), it should be heated to at least 20°C (70°F) prior to welding. Under humid conditions, the steel should be heated to a higher temperature to drive off any surface moisture.

Limits on Heat-Affected Zone Hardness

The hardness of the heat-affected zone (HAZ) is often used as an indicator of susceptibility to hydrogen cracking. A Vickers hardness number of 350 HV is a

27. See Reference 24.

28. *Structural Welding Code—Steel*, AWS D1.1 (see Reference 17), requires that flux be baked at 120°C (250°F) for 1 hour if the packaging has been damaged. A 25 mm (1 in.) thick layer of exposed flux in hoppers and wet flux must be discarded. These procedures should be followed for all applications.

29. See Reference 17.

30. Bailey, N. et al, 1993, *Welding Steel without Hydrogen Cracking*, Cambridge, England: Abington Publishing.

widely used value, below which it is generally agreed that hydrogen cracking is not expected to occur. Both API 1104 and CSA Z662 indicate that procedures producing HAZ hardness greater than 350 HV should be evaluated regarding the risk of hydrogen-cracking.^{31,32} They do not indicate that HAZ hardness greater than 350 HV is unacceptable, but neither do they provide guidance pertaining to how HAZ hardness greater than 350 HV should be evaluated. The Australian standard AS 2885 prohibits hardness in the HAZ in excess of 350 HV.³³ The generally regarded notion that 350 HV is a hardness level below which hydrogen cracking is not expected dates back to work in the 1940s for welds with a diffusible hydrogen content of approximately 16 ml (100 g) of deposited weld metal.³⁴ Nevertheless, the critical hardness level, or the hardness level below which hydrogen cracking is not expected, depends on the hydrogen level typically produced by the welding process being used, and on the chemical composition (carbon content or carbon equivalent [CE] level) of the workpieces. The risk of hydrogen cracking increases as the hydrogen level increases. Lower limits on hardness are required when higher hydrogen levels are anticipated. Conversely, closer control of hydrogen level allows higher hardness to be tolerated. Many modern low-hydrogen electrodes, such as AWS EXX18, particularly the H4R variety, produce hydrogen levels of less than 4 ml/100 g in the weld. For this reason, a hardness limit of 350 HV may be highly conservative for some in-service welding applications.

While HAZ hardness is often used as an indicator of cracking susceptibility, the true susceptibility depends on the microstructures present in the HAZ. A better indicator of cracking susceptibility might be the volume fraction of martensite in the HAZ. For a material of a given chemical composition, HAZ hardness is a good indicator of the relative amount of martensite present in the HAZ. However, the hardness of martensite depends on the carbon level of the material being welded. The measured hardness in the HAZ of a low-carbon material that consists mostly of martensite may be lower than the measured hardness in a higher carbon material with a much lower volume fraction of martensite, yet the cracking susceptibility in the lower carbon material might be higher. In other words, materials with lower

carbon content tend to crack at lower hardness levels. Conversely, higher hardness can be tolerated when welding higher carbon content materials.

A HAZ hardness of 350 HV may be overly conservative for some in-service welding applications and not conservative for others. Acceptance criteria that allow trade-offs to be made between HAZ hardness, hydrogen level, and chemical composition for welds made onto in-service pipelines have been proposed.³⁵

Interruption of the Heating Cycle

When a welding procedure employs preheating or postheating, a question sometimes arises as to whether the weldment should be allowed to cool to room temperature during or after welding but before final heat treatment. The effects of interrupting the heating cycle are both metallurgical and mechanical in nature.

Metallurgical effects involve microstructural changes. The mechanical effects involve thermal contraction in the weldment that may produce localized distortion or high residual stresses. Accordingly, the greatest assurance of successful welding requires the use of continuous heating without interruption, postweld heat treatment immediately after completion of welding, or maintenance of preheat until postweld heat treatment can be performed. However, operational or economical reasons may prevent carrying out a continuous heating procedure.

Interrupted operations are necessary in some cases and quite common in many applications. It is difficult to make general rules for when interruptions are permissible, because many factors must be considered. Once welding has started, the heating of steels with high hardenability should not be interrupted unless appropriate steps are taken to avoid cracking. Procedures for the various types of hardenable steels are discussed in the sections on high-carbon steels and high-strength low-alloy steels.

Interruptions in heating are less desirable if a partially completed weld will be subjected to tensile stresses when cooled. All welding and postweld heat treatment should be completed before a weldment is exposed to any type of loading.

For the heat-affected zone and weld metal, an increase in workpiece thickness increases both the restraint on the weld and the rate of cooling from welding temperatures. Accordingly, the weld area is subjected to increasingly high residual stresses.

Once welding has started, it should not be stopped until the weld has enough strength and rigidity to withstand the residual and applied stresses. For this reason,

31. Canadian Standards Association (CSA), 2003, *Oil and Gas Pipeline Systems*, Z662, Toronto, Ontario, Canada: CSA International.

32. American Petroleum Institute. 2005. *Welding of Pipelines and Related Facilities*. API Standard 1104 (R2010). 20th edition. Washington, D.C.: American Petroleum Institute.

33. Australian Standards (AS) 2002, *Pipelines—Gas and Liquid Petroleum*, Part 2, AS2885.2-2002, Sydney: Australian Standards.

34. Dearden, J. and H. O'Neill, 1940, *A Guide to the Selection and Welding of Low Alloy Structural Steels*, Vol. 3, Institute of Welding Transactions.

35. Bruce, W. A., and M. A. Boring, 2005, *Realistic Hardness Limits for In-Service Welding*, Draft Final Report for PRCI Contract No. GRI-8758, EWI Project No. 46344CAP, Columbus, Ohio: American Welding Institute.

an interruption of welding generally is not permitted on heavy sections until some minimum number of weld passes have been completed, or a specified fraction of the joint thickness has been welded. When interruptions are permitted, the weldment must be cooled slowly and uniformly. Welding should not resume until the weld area has been reheated uniformly to the specified pre-heat temperature.

SOLIDIFICATION CRACKING

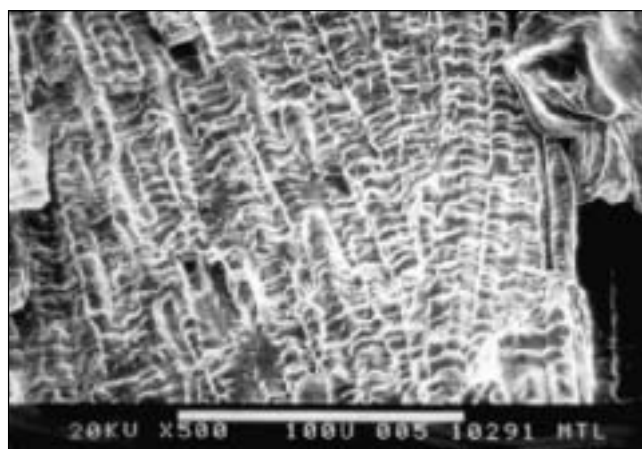
Solidification cracking is a type of hot cracking that can occur in carbon steel and low-alloy steel welds when the weld metal just behind the weld pool is unable to support the tensile strains that develop as it solidifies. Liquid films are required for this type of cracking to occur, and as such, solidification cracks normally appear along grain boundaries (intergranular), although in some cases may be found along dendrite boundaries within grains (interdendritic). These liquid films are created by the segregation of certain elements, especially sulfur or phosphorus, but also lead, tin, antimony, and arsenic, which can form low-melting-point compounds. Fracture surfaces of solidification cracks, as shown in Figure 1.10, typically exhibit an “egg-crate” topography when examined at the high magnification possible in a scanning electron microscope (SEM). These fracture surfaces are created by the separation of intergranular liquid films just before completion of solidification.

While solidification cracking can occur in almost any of the carbon and low-alloy steels, resulfurized free-machining steels and some heat-treated low-alloy steels are particularly susceptible. Solidification cracks often are longitudinal cracks along the centerline of the weld bead. These are often associated with the teardrop shape of the weld pool that can occur at higher travel speeds. Weld beads that are undersized, have a concave profile, or have a high depth-to-width ratio are also more susceptible. As in all forms of weld cracking, joint restraint is an important influence.

Manganese and silicon additions tend to reduce the susceptibility of steel to solidification cracking. Therefore, one precaution to reduce solidification cracking involves the use of filler metals with a higher manganese or silicon content. However, it should be noted that this approach becomes less effective with increasing carbon content. Medium- to high-carbon steel weld metal exhibits a greater tendency toward solidification cracking in spite of elevated manganese or silicon levels.



(A)



(B)

Figure 1.10—(A) Transverse Metallographic Section and (B) SEM Fractograph of Solidification Cracking in an Autogenous Laser Weld in Carburized SAE 8620 Steel

LIQUATION CRACKING

Cracking along grain boundaries in the heat-affected zone due to wetting of the boundaries by liquid is called *HAZ liquation cracking*. This cracking normally occurs in the partially melted zone (PMZ) of the HAZ, which is the region of the HAZ that borders the fusion zone and in which some localized melting or liquation occurs. Liquation cracking may be caused by the penetration of the grain boundary by a liquid constituent (a liquating particle or molten weld metal) or the formation of liquid at the grain boundary from the segre-

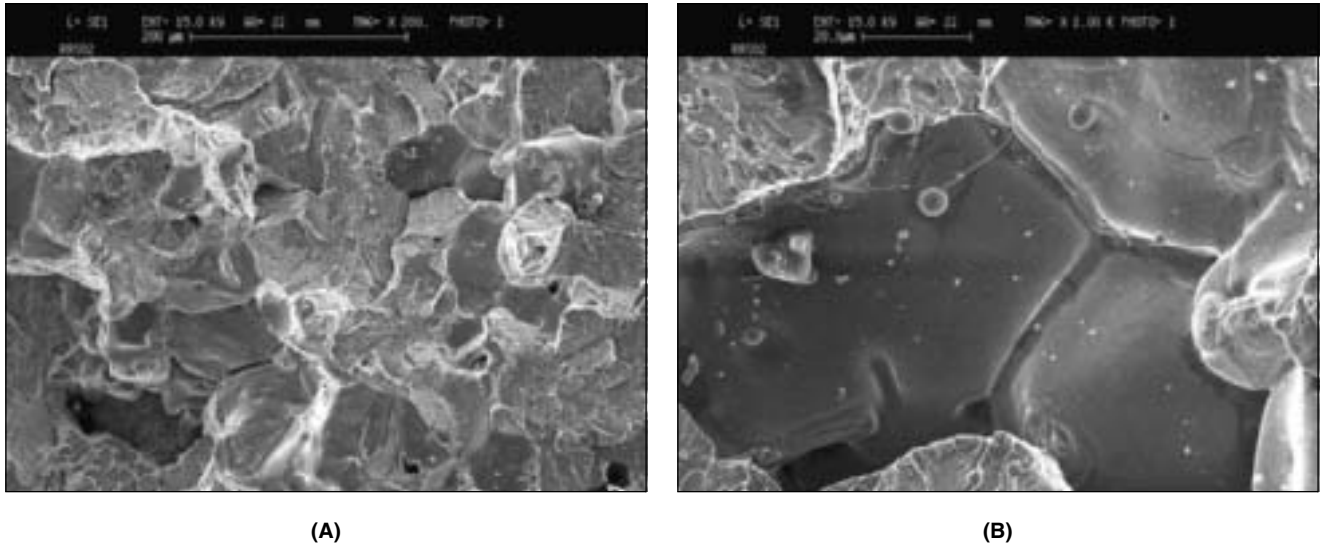


Figure 1.11—SEM Fractographs of Liquation Cracking in the HAZ of a Weld in SAE 1080 Rail Steel

gation of impurity elements to the boundary. In both cases, the liquid wets the boundary and thus reduces its strain capacity. Figure 1.11 contains SEM images, at two different levels of magnification, of a cluster of HAZ liquation cracks that initiated brittle fracture during proof testing of a welded joint in a high-carbon steel.

Weld metal liquation cracking is a special type of HAZ liquation cracking that occurs in the previous passes of multiple-pass welds as subsequent passes are made. Liquation cracking in the HAZ is likely to happen in welds that are also susceptible to solidification cracking.

The risk of liquation cracking in the HAZ can be reduced by using one or a combination of the following methods:

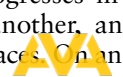
1. Welding on base metal with a low impurity content (e.g., sulfur and phosphorous, but also lead, tin, antimony, and arsenic) to decrease the likelihood of impurity segregation to the grain boundaries;
2. Using high-purity filler metals to limit the chances of low-melting constituents forming in the fusion zone and penetrating the grain boundaries of the HAZ;
3. Solution heat treating of the base metal to reduce the chance of forming liquids around liquating particles in the HAZ;
4. Selecting a base metal of finer grain size, as smaller grains provide greater grain boundary

surface area over which impurities and liquid films can be dispersed; and

5. Reducing the residual stress in the HAZ by using an undermatching filler metal or a solution-annealed base metal to reduce the chances of liquation cracking.

LAMELLAR TEARING

Shrinkage from groove welds, fillet welds, or combinations of these used in corner joints or T-joints can result in tensile stresses in the through-thickness direction of the through member. The resulting through-thickness strains must be accommodated by the base metal that lies within the joint. The magnitude of these stresses and strains depends on the size of the weld, the welding procedures used, and the degree of restraint imposed by the base metal thickness and the joint design.

In steel plate and structural shapes that have been produced by conventional steelmaking processes, manganese sulfide or oxide-silicate inclusions that have been flattened and elongated by the rolling process sometimes occur in clusters around mid-thickness. These can significantly reduce the through-thickness ductility of the steel, making it susceptible to lamellar tearing. This internal tearing progresses in a step-like manner from one inclusion to another, and from there it propagates to exposed surfaces. On an etched cross-section,  **Documents**
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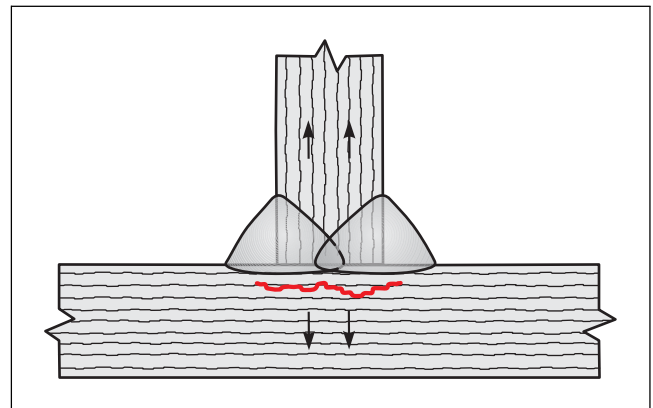
lamellar tearing is evidenced by a step-like or jagged crack with many of its steps oriented parallel to the plate surfaces, as shown in Figure 12(A) and (B). Macroscopically, the fracture surface will appear fibrous or “woody,” as shown in Figure 12(C), and microscopic examination will reveal the planar rupturing of the interfaces that once surrounded the elongated, flattened inclusions.

Figure 1.13 shows three joint designs, (A), (B), and (C), that may be prone to lamellar tearing, along with modified joint designs that should improve their resistance to it. There is some evidence that sensitivity to lamellar tearing is increased by the presence of hydrogen in the steel.

Following are some approaches to minimizing the possibility of lamellar tearing:

1. Change the location and design of the welded joint to minimize through-thickness strains, including selecting fillet welds instead of complete-penetration groove welds in T-joints;
2. Reduce the available hydrogen;
3. Butter the surface of the plate with at least two layers of weld metal prior to making the weld;
4. Use preheat and interpass temperatures of at least 95°C (200°F);
5. Peen the weld beads;
6. Use steel plates especially processed to achieve improved through-thickness properties (very low-sulfur steels—0.010% maximum) or steels with rare-earth additions to control the shape of manganese sulfide inclusions);³⁶ and
7. Substitute forgings or castings for plate.

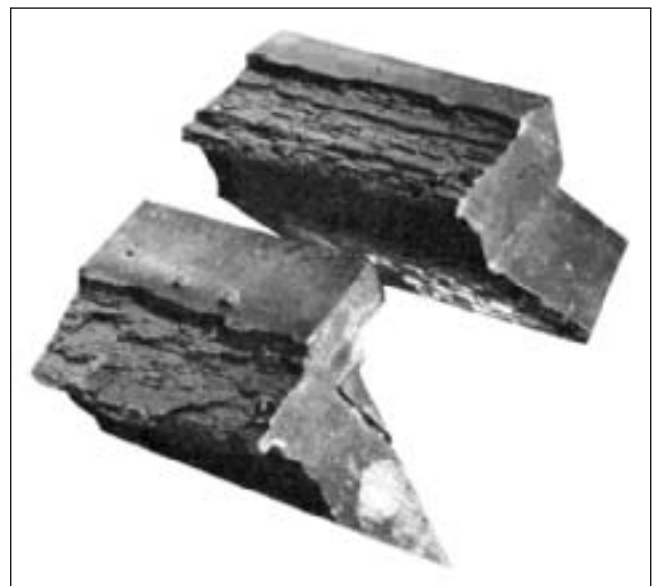
The most reliable methods for avoiding lamellar tearing are to use alternate materials and the buttering technique, and if plate is used, to minimize stresses in the through-thickness direction. It is not possible to detect lamellar tearing prior to welding since it does not exist. However, by employing straight-beam ultrasonic examination, it is relatively easy to detect subsurface laminations that may be susceptible to lamellar tearing. Also, a through-thickness tension test (e.g., ASTM A 770) can be used to determine the susceptibility of a plate to lamellar tearing. A reduction of area in the through-thickness direction greater than 20% in the A 770 test indicates a low likelihood of lamellar tearing.



(A)



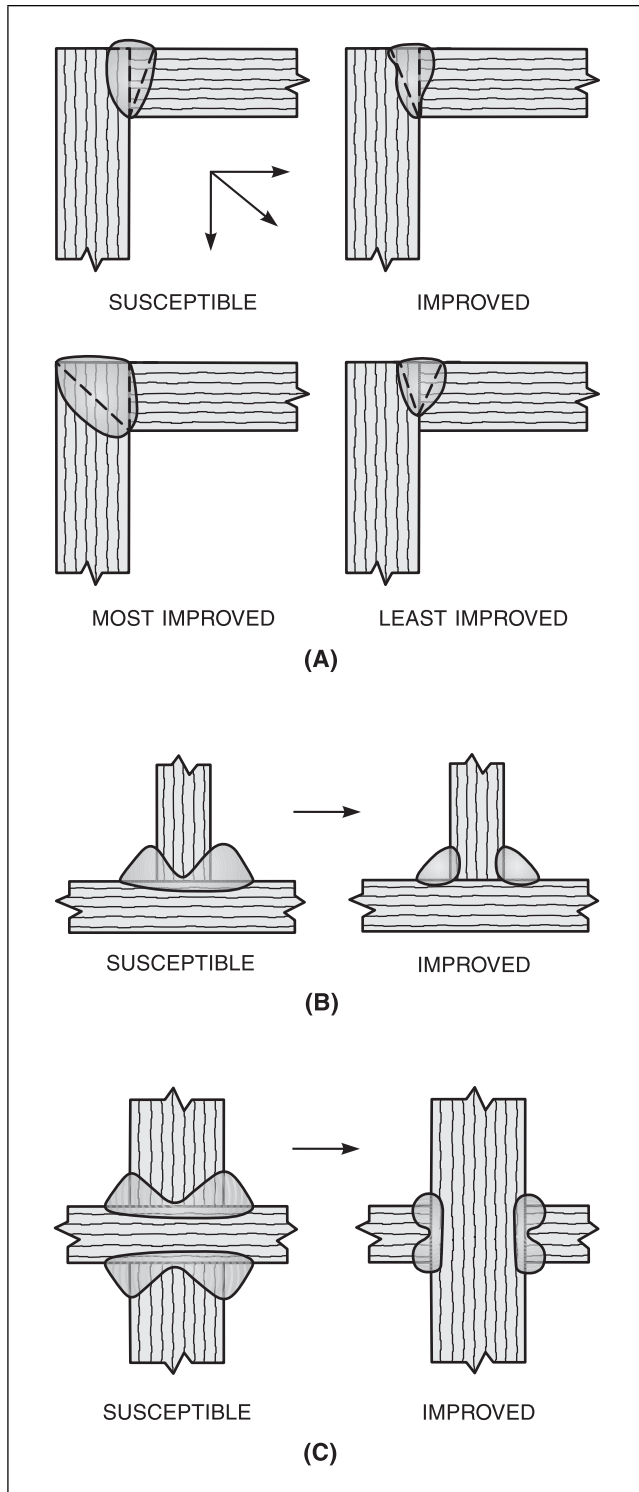
(B)



(C)

Figure 1.12—Lamellar Tearing:
(A) Typical Location, (B) As Shown in a Longitudinal Metallographic Section, and (C) Macroscopic Appearance of Fracture Surfaces

36. American Association of State Highway and Transportation Officials (AASHTO) and American Welding Society (AWS), 2010, *Bridge Welding Code*, AASHTO/AWS D1.5M/D1.5:2010, Miami: American Welding Society, Subclause 12.4.4.1, Optional Through-Thickness and Low-Sulfur Requirements.



Source: Adapted from ASM International (ASM), *ASM Metals Handbook*, Vol. 6, Figure 14, Materials Park, Ohio: ASM International, p 652.

Figure 1.13—Weld Joint Designs Prone to Lamellar Tearing, with Susceptible and Improved Weld Metal Profiles

REHEAT CRACKING

Reheat cracking (also called *strain-age cracking*, *strain relaxation cracking*, *stress-rupture cracking*, or *stress-relief cracking*) can occur in some low-alloy steels and Cr-Mo steels during postweld heat treatment or in high-temperature service. Reheat cracks are intergranular and usually appear in the grain-coarsened region of the HAZ during postweld heat treatment at stress-relieving temperatures, especially in thick workpieces where the combined effects of restraint and residual stress are significant. Dissolution of alloy carbides and nitride particles in the grain-coarsened HAZ during welding is followed by reprecipitation during postweld stress relief. This increases the creep resistance of the grains, making them less able to accommodate the relaxation strains that result from grain boundary sliding. The magnitude of these strains is increased by the coarseness of the grains in this region. Intergranular stresses thus accumulate, particularly at grain-boundary triple points, which may result in the nucleation and growth of intergranular cracks. There is experimental evidence that the diffusional segregation of impurity elements such as phosphorus (P), copper (Cu), tin (Sn), arsenic (As), and antimony (Sb) increases the susceptibility of grain boundaries to reheat cracking by reducing their cohesive strength at stress-relieving temperatures. It has been reported that this occurs in Cr-Mo-V steels, in ASTM A 508 Class 2 steel, in ASTM A 514 and A 517 steels, shown in Table 1.2, and in some precipitation-hardened ASTM A 710 HSLA steels.³⁷ (Refer to Chapter 3 of *Welding Handbook*, Volume 1, for a review of residual stress development.)³⁸

The occurrence of reheat cracking can be reduced by several means, as follows:

1. Reducing joint restraint during welding, which will reduce the overall level of residual stress prior to stress relieving;
2. Eliminating stress concentrations, such as in fillet toes;
3. Using multiple-pass welding, which refines the grains of previous passes; and
4. Using rapid heating and cooling to minimize time spent in the carbide precipitation range.

FATIGUE CRACKING

Although fatigue cracking in welded steel structures is primarily a design issue, its prevalence as a cause of failure justifies mention in this section.

37. Steel classifications are published by ASTM International (ASTM) (formerly American Society for Testing and Materials), 100 Barr Harbor Drive, West Conshohocken, Pennsylvania, 19428-2959. www.astm.org.

38. See Reference 14.

Table 1.2
Susceptibility of Ferritic Alloy Steels to Reheat Cracking

Not Susceptible	Borderline	Susceptible	Very Susceptible
C-Mn	A 517J	A 517E	A 517F
1Cr1/2Mo	A 508/1	A 533B	1/2MoB
5Cr1/2Mo	A 508/3	HY 80	1/2Cr1/2MoV
9Cr1Mo	2-1/4Cr1Mo	HY 130	
A 517A	A 517B	A 508/2	
A 533A			
A 508/2			

Structural weldments, especially those fabricated from plate and structural shapes, contain sharp corners and other abrupt transitions which act as stress concentrators. Unfortunately, these transitions typically (and often necessarily) coincide with the welded joints, which add inherently detrimental features that must also be considered. Although these inherent geometric discontinuities are rarely detrimental to the static or even the impact properties of most welded structures, they are often markedly damaging to the long-term integrity of welded structures in service environments that impose cyclic stresses.

For a given cyclic nominal stress range ($\Delta\sigma = \sigma_{\max} - \sigma_{\min}$), the fatigue life of a sound weld is controlled primarily by the local geometry of the weld toe or weld root, and secondarily by the joint design. Welding-induced tensile residual stresses may or may not have a contributing effect, depending on the applied nominal stress ratio ($R = \sigma_{\min}/\sigma_{\max}$). Unless $R < 0$ or $R > 1$, residual tensile stresses tend to be of little to no consequence. Other factors, such as the tensile strength, yield strength, and microstructure of the weld metal, HAZ and base metal have negligible influence on high-cycle condition.

Figure 1.14 provides an example of this by demonstrating the absence of a yield strength effect for a particular class of weldments. The effects of geometry essentially overwhelm all other factors unless steps are taken to improve the profile of the weld toe by means such as grinding, peening or remelting, and by ensuring complete joint penetration to eliminate the crack-like root geometry of a partial-penetration weld. In many applications, such measures are cost-prohibitive.

Since weld toe and root geometries are largely beyond the control of the structural designer, most design codes for welded steel structures, including AWS D1.1, specify fatigue design rules based only on joint design and nominal stress range. To develop such rules, thousands of fatigue test results obtained from various

joint geometries are assembled and divided into categories for statistical analysis. This produces a series of discrete performance categories based on test-piece geometry. The lower-bound stress-life (S-N) curve derived from each category is typically codified as the basis for fatigue design. Code users then select the category most closely matching each joint design and apply the designated S-N curve. This establishes a permissible stress range for the number of cycles that a joint will be required to perform in service, thereby guiding designers in the sizing of structural members or welds, or both. Conversely, a conservative estimate of the life expectancy of an existing joint can be obtained from the appropriate S-N curve.

For structures known to contain fatigue cracks, the fracture toughness of the steel in which the fatigue cracks are growing determines the most conservative critical crack size for a given loading condition. The critical crack size is the size above which a crack or crack-like flaw becomes unstable, resulting in sudden brittle failure of the component. By increasing this value, high-toughness steel can extend the crack growth portion of the fatigue life of a weldment. However, in many situations this may produce only a modest increase, as illustrated in Figure 1.14. In any case, neither high toughness nor high strength can be expected to provide a significant, reliable improvement in the overall fatigue performance of as-welded steel structures, as illustrated in Figure 1.15.

In situations where fatigue cracking is expected to be a problem, the following guidelines may be helpful:

1. Wherever possible, the weldment should be designed with butt joints instead of fillet or T-joints;
2. Placing welded joints at the same locations as changes in section thickness generally should be avoided;
3. The workpieces should be carefully fitted and aligned to minimize joint misalignment;

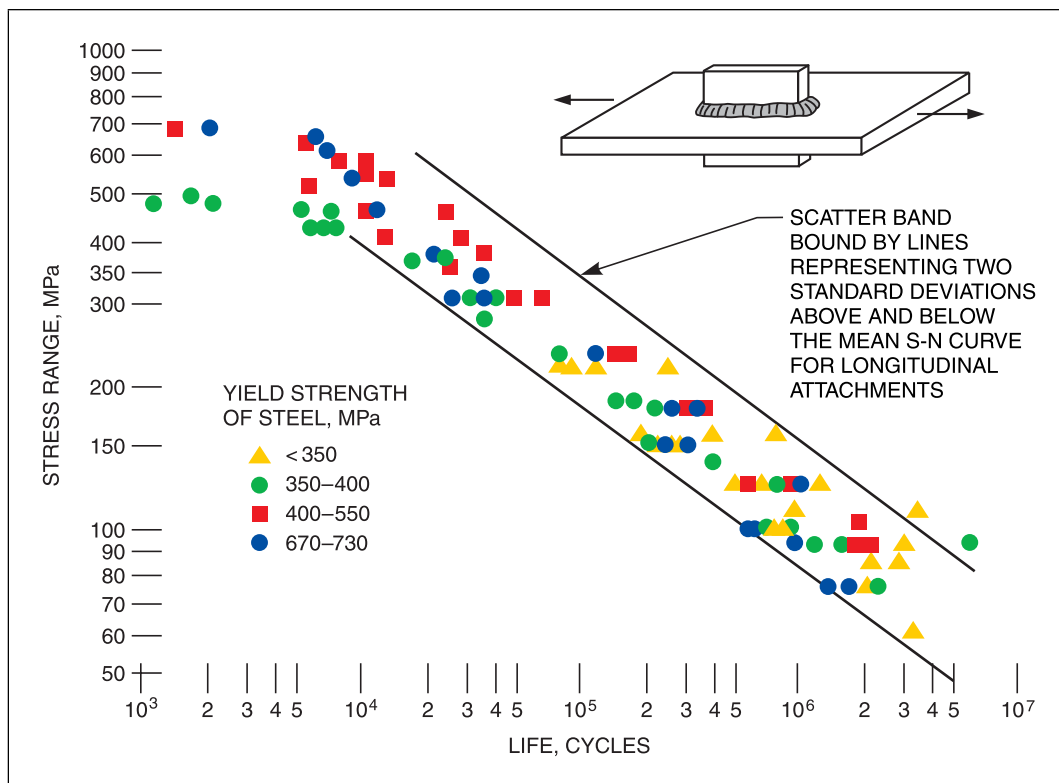


Figure 1.14—Absence of Yield Strength Dependence in High-Cycle Fatigue Performance of Weldments, as Demonstrated by Stress-Life Data Obtained from Test Geometries with Longitudinal Attachments

- Undercut, overlap and excessive weld reinforcement should be avoided; and
- If grinding, peening, or remelting of the weld-toe is necessary, it should be performed in accordance with established procedures.³⁹

CARBON STEELS

Carbon steels are alloys of iron and carbon in which carbon usually does not exceed 1.0%, manganese does not exceed 1.65%, and copper and silicon each do not exceed 0.60%. Other alloying elements normally are not present in more than residual amounts. Carbon steels generally are categorized according to their carbon content, as listed in Table 1.3. The properties and weldability of these steels depend mainly on carbon content; other elements have only a limited effect.

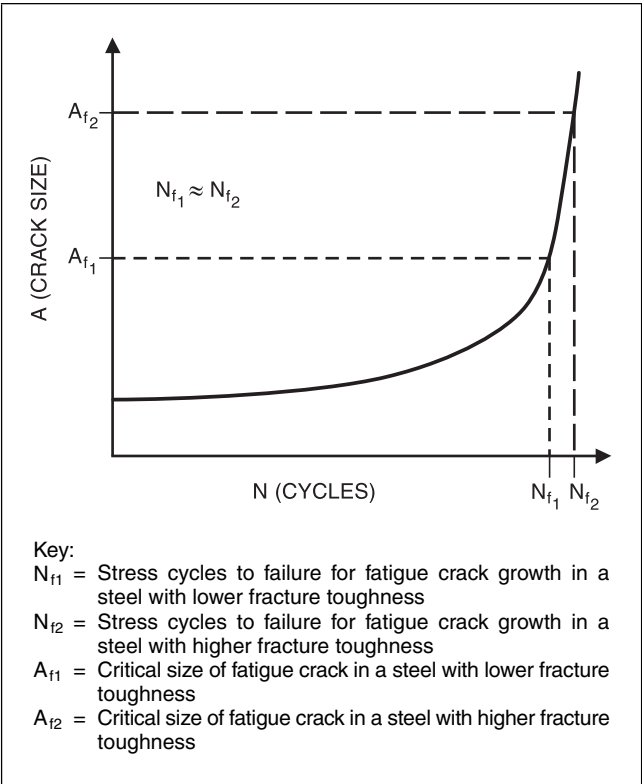
Deoxidation practices in the steelmaking process affect the characteristics and properties of steel. Thus, carbon steel can be broadly classified according to various deoxidation practices: rimmed, capped, semikilled, or killed (deoxidized) steel. The great majority of modern steels are continuously cast steels, fully killed and aluminum-treated for grain size control.

The Society of Automotive Engineers (SAE) carbon steels are classified in the 10XX, 11XX, 12XX, and 15XX groups.⁴⁰ The 10XX group has a maximum of 1.0% manganese; manganese in the 15XX group ranges from 1.00% to 1.65%. The 11XX resulfurized steels and the 12XX resulfurized and rephosphorized steels are designed for improved machinability. Fusion welding is difficult with these materials, however, as they are notably prone to solidification cracking.

Standards published by ASTM designate carbon steels on the basis of chemical or mechanical properties, or

39. See Reference 17.

40. Society of Automotive Engineers (SAE International), 400 Commonwealth Drive, Warrendale, Pennsylvania 15096-0001. www.sae.org.



Source: Bannantine, J. A., J. L. Comer, and J. J. Handrock, 1990, *Fundamentals of Metal Fatigue Analysis*, Upper Saddle River, New Jersey: Prentice-Hall.

Figure 1.15—General Behavior of a Growing Fatigue Crack, Comparing Critical Crack Sizes for Two Steels with Different Values of Fracture Toughness

both, in conjunction with product form and the intended application.⁴¹ The ASTM standard A 830 covers SAE carbon steel plates; ASTM A 576 covers SAE carbon steel bars. Typical ASTM carbon steels used in construction, pressure vessels, and piping are listed in Table 1.4.^{42, 43}

WELDABILITY OF CARBON STEELS

The weldability of a specific type of carbon steel is determined primarily by the sensitivity of the steel to hydrogen cracking; although susceptibility to solidification cracking and deoxidization practice also can affect the weldability of some grades, as previously explained.

Carbon Content

Several points stated in the section titled Fundamentals of Welding Carbon and Low-Alloy Steels bear repeating in this section, as follows:

- 1. Sensitivity to hydrogen cracking increases in proportion to increases in carbon equivalent,

41. See Reference 36.
42. ASTM International (formerly American Society of Testing and Materials), 2006, *Standard Specification for Steel Bars, Carbon, Hot-Wrought, Special Quality*, A 576-90b (2006), West Conshohocken, Pennsylvania: ASTM International.
43. ASTM International (formerly American Society of Testing and Materials), 2006, *Standard Specification for Plates, Carbon Steel, Structural Quality, Furnished to Chemical Composition Requirements A 830-06*, West Conshohocken, Pennsylvania: ASTM International.

**Table 1.3
Classification and Weldability of Carbon Steels**

Common Name	Carbon, %	Typical Hardness	Typical Use	Weldability
Low-carbon steel	0.15 max.	60 HRB	Special plate and shapes, sheet, strip, welding electrodes	Excellent
Mild steel	0.15–0.30	90 HRB	Structural shapes, plate, and bar	Good
Medium-carbon steel	0.30–0.50	25 HRC	Machine parts and tools	Fair (preheat and postheat normally required; low-hydrogen welding process recommended)
High-carbon steel	0.50–1.00	40 HRC	Springs, dies, railroad rail	Poor (low-hydrogen welding process, preheat, and postheat required)

Table 1.4
Composition and Strength Requirements of Typical ASTM Carbon Steels

Application	ASTM Standard	Type or Grade	Typical Composition Limits, % ^a			Tensile Strength		Min. Yield Strength	
			C	Mn	Si	MPa	ksi	MPa	ksi
Structural Steels									
Welded buildings, bridges, and general structural purposes	A 36	—	0.29	0.80–1.20	0.15–0.40	440–550	58–80	250	36
Welded buildings and general purposes	A 529	50 55	0.27 0.27	1.35 1.35	0.40 0.40	485–690 485–690	70–100 70–100	345 380	50 55
General purpose plate (improved toughness)	A 573	58 65 70	0.23 0.26 0.28	0.60–0.90 0.85–1.20 0.85–1.20	0.10–0.35 0.15–0.40 0.15–0.40	400–490 450–530 485–620	58–71 65–77 70–90	220 240 290	32 35 42
Pressure Vessel Steels									
Plate, low and intermediate tensile strength	A 285	A B C	0.17 0.22 0.28	0.90 0.90 0.90	— — —	310–450 345–485 380–515	45–65 50–70 55–75	165 185 205	24 27 30
Plate, manganese-silicon	A 299	—	0.30	0.90–1.40	0.15–0.40	515–655	75–95	275	40
Plate, intermediate and high-temperature service	A 515	60 65 70	0.31 0.33 0.35	0.90 0.90 1.20	0.15–0.40 0.15–0.40 0.15–0.40	415–550 450–585 485–620	60–80 65–85 70–90	220 240 260	32 35 38
Plate, moderate and low-temperature service	A 516	55 60 65 70	0.26 0.27 0.29 0.31	0.60–1.20 0.85–1.20 0.85–1.20 0.85–1.20	0.15–0.40 0.15–0.40 0.15–0.40 0.15–0.40	380–515 415–550 450–585 485–620	55–75 60–80 65–85 70–90	205 220 240 260	30 32 35 38
Plate, carbon-manganese-silicon heat-treated	A 537	1 ^b 2 ^c 3 ^c	0.24 0.24 0.24	0.70–1.60 0.70–1.60 0.70–1.60	0.15–0.50 0.15–0.50 0.15–0.50	450–585 515–655 515–655	65–85 75–95 75–95	310 380 345	45 55 50
Piping and Tubing									
Welded and seamless pipe, black and galvanized	A 53	A B	0.25 0.30	0.95–1.20 0.95–1.20	— —	330 415	48 min. 60 min.	205 240	30 35
Seamless pipe for high-temperature service	A 106	A B C	0.25 0.30 0.35	0.27–0.93 0.29–1.06 0.29–1.06	0.10 min. 0.10 min. 0.10 min.	330 415 485	48 min. 60 min. 70 min.	205 240 275	30 35 40
Structural tubing	A 501	—	0.26	—	—	400	58 min.	250	36
Cast Steels									
General use	A 27	60–30	0.30	0.60	0.80	415	60 min.	205	30
Valves and fittings for high-temperature service	A 216	WCA WCB WCC	0.25 0.30 0.25	0.70 1.00 1.20	0.60 0.60 0.60	415–585 485–655 485–655	60–85 70–95 70–95	205 250 275	30 36 40
Valves and fittings for low-temperature service	A 352	LCA ^c LCB ^c LCC ^c	0.25 0.30 0.25	0.70 1.00 1.20	0.60 0.60 0.60	415–585 450–620 485–655	60–85 65–90 70–95	205 240 275	30 35 40

a. Single values are maximum unless otherwise noted.

b. Normalized condition.

c. Quenched and tempered (Q&T) condition.

- hydrogen content of the weld metal, and work-piece thickness;
2. Carbon is the alloying element that has the greatest effect on sensitivity to hydrogen cracking;
 3. The effects of carbon and other elements on susceptibility to hydrogen cracking can be estimated using the carbon equivalent formula; and
 4. Carbon steels exhibit increasing susceptibility to hydrogen cracking when the carbon content exceeds about 0.15%, although steels with less than 0.15% carbon are not immune to hydrogen cracking, especially when thick sections are welded or high residual stresses are present, or both.

Weld Cooling Rates

When welding thick workpieces with an arc welding process, the weld metal and heat-affected zone can be hardened significantly because they are quenched by the large mass of base metal. The cooling rate and the carbon equivalent of the steel are the controlling factors in determining the degree of hardening. The cooling rate depends primarily on the following factors: the thickness and joint geometry of the workpiece, the base-metal temperature before welding commences, and heat input. Consequently, the use of higher welding current, slower welding speed (resulting in high heat input), or preheating of the base metal will reduce the cooling rate of the weld zone. Preheat should be maintained while successive beads are deposited.

With higher carbon content or increased workpiece thickness, a higher preheat and interpass temperature should be used to decrease the weld cooling rate and thus control the weld hardness and minimize the likelihood of cracking.⁴⁴

In resistance spot welding of carbon steel sheets, the nugget may be hardened as a result of rapid cooling by the water-cooled copper alloy electrodes in contact with the sheet surfaces. Special electronic heat controls can provide a preheat or postweld heating cycle in the welding schedule to control the cooling rate and hardness of the nugget.

Free-Machining Steels

Normal sulfur and phosphorus contents in carbon steels do not promote weld solidification cracking. However, when large amounts of these elements are added, as is the case in some free-machining steels, the steel will have relatively poor weldability because of solidification cracking in the weld metal. Solidification

cracking results from the low-melting constituents enriched in phosphorus and sulfur at the grain boundaries. The grains may be torn apart by thermal stresses during solidification. High sulfur content also promotes porosity in the weld metal.

Lead (Pb) is another element added to some steels to improve machinability. It is nearly insoluble in steel and exists as distinct globules. The lead can melt during welding and volatilize into the weld fumes. Occasionally, lead may cause porosity and embrittlement of steel. Another concern with lead is its toxic presence in the welding fumes. This requires special precautions to ensure good ventilation during welding. (Refer to Appendix A.)

Normally, free-machining steels should not be welded. If a steel of this type must be welded, low-hydrogen electrodes and low welding current should be used to limit dilution, porosity, and cracking.

LOW-CARBON STEEL

Steels with less than 0.15% carbon are known as low-carbon steels. In general, these steels have very low hardenability and are easily joined by welding. As previously noted, a carbon steel containing 0.15% carbon is capable of being hardened to 30 Rockwell Hardness C Scale (HRC) to 40 HRC when cooled at a very high rate. (Refer to Figure 1.7.) However, this would require a welding process with high energy density (e.g., EBW, LBW). For most welding processes, the cooling rate is too low to allow the heat-affected zone of a weld to reach this level of hardness.

Rapidly cooled welded joints in steel containing carbon of about 0.10% and higher can develop cracks during severe cold-forming operations because the weld area is harder than the unaffected base metal. When the welded joint will be subjected to severe cold-forming (for example, when using the resistance spot welding process), the carbon content of the steel should be low; 0.08% carbon is sufficient to develop substantial hardness for resistance spot welds in thin steel sheet. Hardness in spot welds is not a serious problem with these low-carbon steels, except for some critical applications.

The deoxidation practice used in steelmaking is another factor that can influence weld metal soundness in low-carbon steels, particularly with autogenous welding. Rimmed and capped low-carbon steels are not deoxidized. When these steels are remelted during welding without the addition of deoxidizers, carbon and oxygen in the steel react to form carbon monoxide, which can be entrapped as porosity in weld metal. This is particularly true at high welding speeds, because the gas has less time to escape from the weld pool. Weld-metal porosity in these steels can be minimized by using a filler metal containing sufficient deoxidizers (e.g.,

44. For a comprehensive preheating guide for steels, refer to Ott, C. W. and D. J. Snyder, 1987, *Suggested Arc-Welding Procedures for Steels Meeting Standard Specifications*, WRC Bulletin 326 (Revised Bulletin 191), New York: Welding Research Council.

aluminum, manganese, or silicon) to scavenge oxygen from the weld pool.

With gas tungsten arc, plasma arc, or gas metal arc welding, E70S-2 filler metal should be used because it contains large amounts of deoxidizers.⁴⁵ The covering on shielded metal arc welding electrodes usually contains sufficient deoxidizers for welding rimmed or capped steels. Special aluminum-containing paints are available that can be applied to the joint faces to deoxidize the weld metal during autogenous welding. Submerged arc welding of rimmed or capped steel requires the selection of an electrode and flux combination containing sufficient deoxidizers (e.g., silicon or manganese) to produce a sound weld, especially when high welding speeds are used.⁴⁶ Weld metal soundness normally is not a problem with killed, low-carbon steels when good welding practices are used.

MILD STEEL

Carbon steels containing from about 0.15% to 0.30% carbon are commonly called *mild steels*. Underbead cracking or lack of toughness in the heat-affected zone (HAZ) usually is not encountered when welding mild steels containing no more than 0.20% carbon and 1.0% manganese. These steels can be welded without preheat, postheat, or special welding procedures when the joint thickness is less than 25 mm (1 in.) and when joint restraint is not severe.

As the carbon content increases to about 0.30% and manganese content increases to about 1.40%, weldability remains good; however, these weldments become more susceptible to hydrogen cracking due to the increased hardenability and yield strength. Welding with a low-hydrogen procedure is recommended. Preheating and control of the interpass temperature also may be required, particularly when the joint thickness is greater than 25 mm (1 in.) or when extrinsic joint restraint is high. If hydrogen cracking still is a problem with these procedures, hydrogen may be diffused from the joint either by maintaining the preheat temperature or by postheating after welding is complete. A temperature of at least 150°C (300°F) usually is effective for dissipating hydrogen in mild steel weldments. Hold time will increase in proportion to the thickness of the weld, typically 2 to 3 hours per 25 mm (1 in.).

Some mild steels are supplied in the normalized or quenched and tempered condition to provide good toughness or high-strength properties. Tensile strengths

may range from 450 MPa to 690 MPa (65 ksi to 100 ksi), depending on the carbon and manganese content and the heat treatment.

Welding procedures for heat-treated mild steels are guided to a large extent by a need to have some minimum toughness in the weld metal, the HAZ, and the unaffected base metal. Precautions should be taken to ensure that welding is done using low-hydrogen conditions.

Standard procedures are used with shielded metal arc, submerged arc, and gas metal arc welding because the cooling rates in the HAZ are sufficiently rapid to reproduce a microstructure similar to that of the normalized or quenched steel. When the carbon content is limited to about 0.20%, underbead cracking or lack of toughness in the HAZ normally is not a problem. This is true even when very rapid cooling occurs due to the low input of welding heat. In fact, allowing the HAZ to cool rapidly may be preferable. Higher welding heat input or higher preheat and interpass temperatures than normal, which result in a slower rate of cooling, tend to increase the grain size and produce coarser pearlite in the HAZ. These microstructural conditions lead to low strength and poor toughness.

If the welding process or procedure subjects the HAZ to prolonged heating, high temperature and slow cooling (e.g., in electroslag welding), the weldment may require heat treatment (e.g., normalizing and tempering) to restore good strength and toughness to the HAZ. When heat treatment of the weldment is not economical or practical, the rate of cooling in the weld zone must be sufficiently rapid to produce a microstructure of adequate strength and toughness.

In general, heat-treated mild steels can be arc welded without preheat. However, a preheat should be used when the metal temperature is below about 10°C (50°F), and a preheat of about 40°C (100°F) or higher should be used if the plate thickness is over 25 mm (1 in.) or if the joint is highly restrained.

Dilution must be considered when selecting a filler metal to provide specified mechanical properties in the joint in the selected steel. The mechanical properties of weld-metal specified in AWS A5 standards apply to undiluted weld metal.⁴⁷ The properties of the weld metal in an actual fabrication may differ from the reported values because of dilution effects.

Low-alloy steel filler metal may be required to meet mechanical property requirements for heat-treated mild steels. However, the weld-metal strength should not greatly exceed the strength of the base metal. High-strength weld metal may force a softer HAZ to undergo excessive localized strain when the joint is subjected to deformation near room temperature. Under such conditions, fracture may occur prematurely in the HAZ.

45. Refer to American Welding Society (AWS), 2005, *Specification for Carbon Steel Electrodes and Rods for Gas Shielded Arc Welding*, AWS A5.18/A5.18M:2005, Miami: American Welding Society.

46. Refer to American Welding Society (AWS), 2007, *Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding*, AWS A5.17/A5.17M-97 (R2007), Miami: American Welding Society.

47. See Reference 24.

For a butt joint, a filler metal should be selected that will provide weld metal with essentially the same strength as the base metal. For fillet welds, filler metal of lower strength is sometimes used to provide sufficient ductility to accommodate stress concentrations, although the weld size may need to be increased. However, a low-strength filler metal should not be used indiscriminately as a remedy for cracking difficulties.

MEDIUM-CARBON STEEL

A pronounced change in the weldability of carbon steels takes place over the range of carbon content from 0.30% to 0.50%, which identifies medium-carbon steel. Steels containing about 0.30% carbon and less than roughly 1.5% manganese have relatively good weldability. However, as the carbon content is increased, welding procedures must be designed to avoid the formation of large amounts of hard martensite in the heat-affected zone (HAZ). If a steel containing about 0.50% carbon is welded with procedures commonly used for mild steel, the HAZ is likely to be quite hard, low in toughness, and susceptible to hydrogen cracking, as shown in Figure 1.16.

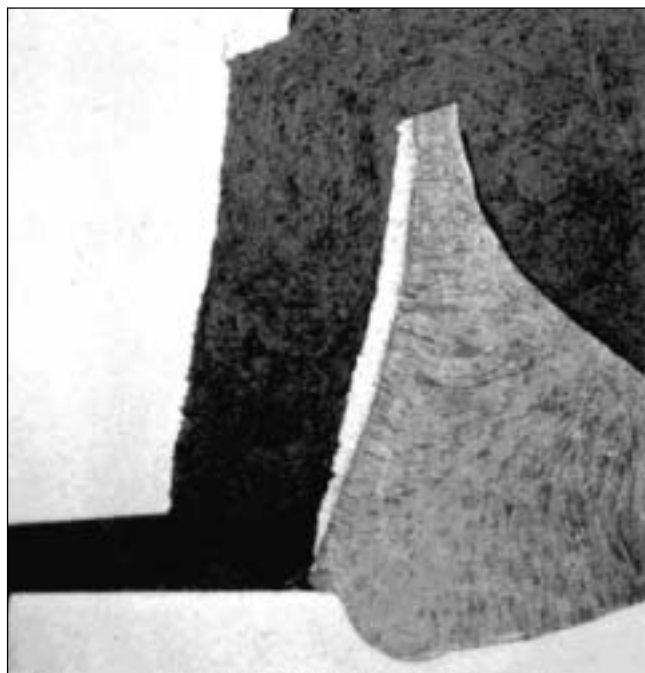


Figure 1.16—Severe Hydrogen Cracking through the HAZ of SAE 1045 Plate 13 mm (1/2 in.) Thick, Preheated at 24°C (75°F) and Welded with GMAW

For most applications, medium-carbon steel should be preheated before welding to control the cooling rate in the weld metal and HAZ, thereby controlling the formation of martensite. The appropriate preheat temperature depends on the carbon equivalent of the steel, the joint thicknesses, and the welding procedure. In general, preheat temperature requirements increase with higher carbon equivalent, greater joint thickness, or increased hydrogen in the arc. With a carbon equivalent in the 0.45 to 0.60 range, a preheat temperature in the range of 95°C to 200°C (200°F to 400°F) is recommended, depending on the welding process and the joint thickness. Figure 1.17 shows how increasing preheat temperature reduces the amount of martensite (light-etching phase) formed in the grain-coarsened HAZ of gas-metal-arc welded SAE 1045 steel plate 13 mm (1/2 in.) thick.

A subcritical stress-relief heat treatment (e.g., 600°C for 1 h/25 mm [1100°F for 1 h/in.]) is recommended immediately after welding—especially with thick workpieces, high joint restraint, or service conditions involving impact or dynamic loading.⁴⁸ When immediate stress relief is impractical, the welded joint should be maintained at or slightly above the specified preheat temperature for 5 min/mm to 7 min/mm (2 h/in. to 3 h/in.) of joint thickness. This procedure promotes the diffusion of hydrogen from the weld zone and reduces the possibility of cracking during intermediate handling. However, it should not be considered a substitute for an appropriate stress-relief heat treatment. Slow cooling to room temperature following stress-relief is recommended to avoid introducing new thermal stresses.

Low-hydrogen welding procedures are mandatory for these steels. The selection of filler metal for arc welding becomes more critical as the carbon content increases. Pickup of carbon by dilution from a steel containing 0.5% carbon usually will result in high hardness in the weld metal, susceptibility to cracking, and a tendency for brittle failure. Dilution can be minimized by depositing small weld beads, or by using a welding procedure that provides shallow penetration, or by buttering the groove faces prior to fitting.

To limit dilution in a multiple-pass weld, low heat input generally is recommended for the first few layers. Higher heat input can be used to complete the joint. It is good practice to deposit the final weld bead, or beads, entirely on previously deposited weld metal without melting any base metal. This practice has the effect of tempering the heat-affected zones of previously deposited weld beads, especially those in the base metal. Optimum tempering is achieved when the heat input of the second layer is approximately 50% greater than that used for the first layer against the base metal. How-

48. See Reference 14 for recommended preheat and stress-relief heat treatment temperatures for specific steels.

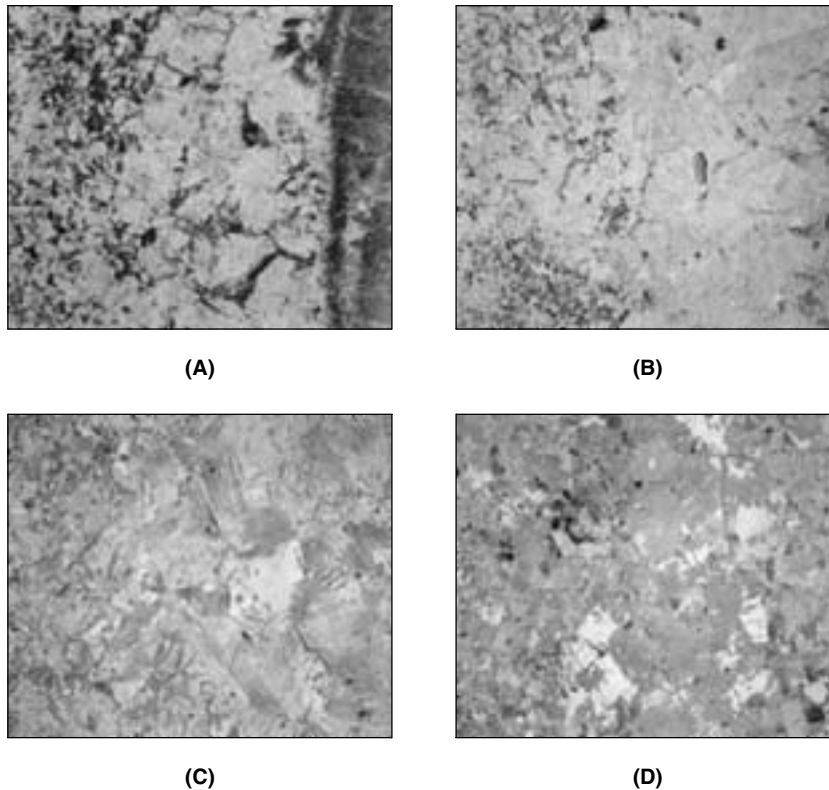


Figure 1.17—Effect of Preheat Temperature on Grain-Coarsened Microstructure in the HAZ of Gas Metal Arc Welds in SAE 1045 Steel, 13 mm (1/2 in.) Plate Thickness

ever, postweld heat treatment still is a requirement with this technique.

Medium-carbon steels are used extensively in the fabrication of machinery and tools. Often these steels are selected for their wear resistance rather than high strength, and workpieces frequently must be heat treated to meet in-service strength requirements. Welding may be performed before or after final heat treatment; however, the selection of filler metal and welding procedures must be considered in this context. If welding is performed prior to heat treatment, special care must be exercised when choosing the filler metal in order to achieve a good match between weld-metal and base-metal properties after heat treatment. A low-alloy filler metal may be required for this purpose. If welding is to be performed on a previously heat-treated component, extra precautions may be necessary. A hardened component can impose additional restraint that increases the likelihood of cracking if a suitable preheat procedure is not used. Also, because the heat of welding will most likely soften the outlying portions of the HAZ,

(grain-refined or tempered, or both) a reheating treatment of the weldment may be required to restore the desired properties.

HIGH-CARBON STEEL

The weldability of high-carbon steels is poor because of the high hardenability and sensitivity to cracking in the weld metal and heat-affected zones in weldments of these steels. Low-hydrogen welding procedures must be used for arc welding. Preheat and interpass temperatures of 204°C (400°F) and higher are required to retard the formation of brittle high-carbon martensite in the weld metal and HAZ. Postweld stress relief is recommended, particularly for welded joints in thick workpieces. The stress relieving procedure described previously for medium-carbon steels should be used.

The selection of an appropriate filler metal depends on the carbon content of the steel, the weldment design, and service requirements. Normally, steel filler metals are not produced with high carbon content. However, a

low-alloy steel filler metal may be suitable for many applications. Austenitic stainless steel or nickel-base filler metals such as E309, E312, or ENiCrFe-3 also may be used. The effects of dilution of the weld metal on the response to postweld heat treatment must be evaluated. Pickup of carbon in an alloy-steel filler metal may significantly increase the hardenability of the weld metal. Consequently, the welding procedures should be designed to minimize dilution.

High-carbon steels are commonly used for applications requiring high hardness or abrasion resistance, which is imparted by heat treatment. The steel should be welded in the annealed condition and then heat treated. Annealing is recommended prior to the repair-welding of broken parts. Successful welding requires the development and testing of specific welding procedures for each application. Service requirements of the weldment must be considered when developing these welding and testing procedures.

WELDING CARBON STEELS

The processes and filler metals used to weld carbon steels are discussed in this section. Processes include shielded metal arc welding (SMAW) and the gas-shielded arc welding processes: gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW). Flux cored arc welding (FCAW), submerged arc welding (SAW), electroslag welding (ESW), electrogas welding (EGW), oxyfuel gas welding (OFW), resistance welding (RW), Electron beam welding (EBW), laser beam welding (LBW), and friction welding (FW) are also discussed.

Filler metals used with these processes are classified by the American Welding Society (AWS) Committee on Filler Metals and Allied Materials, and specifications are published by AWS. Carbon steels also may be joined by several resistance welding and solid state welding processes. All of these processes are discussed in detail in Volumes 2 and 3 of the *Welding Handbook, Welding Processes*, 9th edition. For additional information on welding processes, refer to Appendix B, which provides a resource guide to the various chapters of current *Welding Handbook* volumes.⁴⁹

Shielded Metal Arc Welding

Most carbon steels can be welded with the SMAW process and covered electrodes, provided that appropriate welding procedures (including preheat, when required) are used. Covered electrodes are classified

according to the type of covering and also the chemical composition and mechanical properties of undiluted weld metal. Carbon steel covered electrodes that produce weld metal with 410 MPa (60 ksi) minimum tensile strength are classified as E60XX; those that produce 480 MPa (70 ksi) are classified as E70XX.⁵⁰

A general rule when using SMAW to weld carbon steel is that the weld metal should slightly overmatch the strength of the base material. On this basis, the E60XX classifications are suitable for welding low-carbon and mild steels, provided the weld metal strength is adequate. E60XX covered electrodes are not generally produced with low-hydrogen coverings, and they should not be used for welding steels that are sensitive to hydrogen cracking.

Type E70XX covered electrodes are produced with cellulose, titania, and low-hydrogen coverings. Low-hydrogen electrodes should be used when higher-strength welds or low-hydrogen welding conditions, or both, are required. The low-hydrogen types (E7015, E7016, E7018, E7028, and E7048) must be handled and stored under conditions that prevent moisture pickup in the coating.

Low-alloy steel electrodes, Types E70XX-X through E130XX-X, which are produced with low-hydrogen and other coatings, are designed to produce weld metal with minimum tensile strengths of 480 MPa to 830 MPa (70 ksi to 120 ksi).⁵¹ The carbon content of the deposited weld metal will be 0.15% or less, depending on the electrode type. Low-hydrogen electrodes can be selected from this group to match the tensile strength of a medium-carbon or high-carbon steel. Again, service conditions and the design of the structure will determine whether the weld should match the strength or hardness of the steel. The electrodes must be stored and used under conditions that prevent moisture pickup by the coating, as discussed previously.

Gas-Shielded Arc Welding

The gas-shielded arc welding processes include gas metal arc welding, gas tungsten arc welding, and plasma arc welding. Carbon and low-alloy steel bare electrodes and welding rods are available for use with these processes.⁵² The electrodes are classified on the basis of chemical composition and the mechanical properties of the undiluted weld metal. Minimum tensile strength ranges from 480 MPa to 830 MPa (70 ksi to 120 ksi). The same considerations apply to the selection of a bare electrode as those for a covered electrode.

49. American Welding Society (AWS) Welding Handbook Committee, A. O'Brien, ed., 2004, *Welding Processes, Part 1*, Volume 2 of *Welding Handbook*, 9th ed.; and, 2007, *Welding Processes, Part 2*, Volume 3 of *Welding Handbook*, 9th ed., Miami: American Welding Society.

50. See Reference 24.

51. See Reference 24 (A5.5/A5.5M:2006).

52. Refer to AWS A5.18/A5.18M:2005 (Reference 46), or American Welding Society (AWS), 2005, *Specification for Low-Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding*, AWS A5.18/A5.18M:2005, Miami: American Welding Society.

Shielding gases commonly used for the gas metal arc welding of carbon steels are carbon dioxide (CO₂), argon with carbon dioxide, and argon with oxygen.⁵³ The selection of a gas mixture depends primarily on the electrode composition and the type of metal transfer desired (i.e., spray, globular, or short-circuiting). Generally, CO₂ shielding is suitable for low-carbon and mild steels. A mixture of argon-oxygen or argon-carbon dioxide is suitable for all carbon steels and is recommended for use with low-alloy steel electrodes. Weld metal toughness is improved often, but not always, when one of these gas mixtures is used.

Argon is the shielding gas typically used with GTAW and PAW. However, helium-argon mixtures may be used to provide deeper joint penetration or to permit faster travel speeds with automated welding.

The low-hydrogen characteristics of gas-shielded arc welding processes will be compromised if the filler metal or shielding gas is contaminated. The filler metal may be contaminated with rust, moisture, oil, grease, drawing compounds, or other hydrogen-bearing materials. Therefore, proper cleaning, packaging, rust prevention, and storage are important to avoid hydrogen-induced cracking.

The gas delivery system must be leak-tight to prevent contamination of the shielding gases by moisture or hydrocarbons, and to prevent aspiration of moist air into the system. Only welding-grade (i.e., low dew point) shielding gases should be used.

All GMAW electrodes that meet the same diffusible hydrogen limits indicated for SMAW electrodes are identified by the same designators, whether they are solid or tubular metal-cored. The designator applied to these electrodes is based on testing in the shielding gas with which the electrode is classified.

Flux Cored Arc Welding

Flux cored arc welding (FCAW) electrodes consist of a steel tube surrounding a core of fluxing ingredients and sometimes alloying elements. They are designed to deposit either carbon steel or low-alloy steel weld metal.⁵⁴ Some electrode classifications are self-shielding; other classifications use carbon dioxide or mixtures of argon and carbon dioxide for shielding.

Flux cored electrodes that meet the same diffusible hydrogen limits indicated previously for SMAW electrodes are identified by the same hydrogen designators. Electrodes that meet the lowest hydrogen limits are not available for all classifications. Users should contact electrode manufacturers to determine specific availability. It should be noted that flux cored electrodes can absorb moisture when exposed to high humidity for prolonged time periods. The absorbed moisture can increase the hydrogen entering the weld metal, resulting in higher diffusible hydrogen or porosity in some instances. It is especially important to avoid absorbed moisture when welding medium-carbon and high-carbon steels. Electrode wire that will remain unused overnight or longer should be returned to its protective packaging. If wire is exposed for longer periods of time, the manufacturer should be consulted regarding probable damage to the low-hydrogen characteristics and possible reconditioning procedures.⁵⁵

The operating characteristics of FCAW electrodes vary with the ingredients in the core and the shielding gas, if used. In general, the gas-shielded electrodes provide better notch toughness, particularly with argon-rich shielding mixtures and a basic slag (i.e., class EXXT-5). However, some self-shielded electrodes can provide weld metal with adequate notch toughness for many low-carbon or mild steel applications.

Carbon steel FCAW electrodes are designed to produce undiluted weld metal with a minimum tensile strength of 410 MPa or 480 MPa (60 ksi or 70 ksi). These are suitable for welding low-carbon and mild steels. Medium-carbon and high-carbon steels can be welded with these electrodes if the weld metal will have adequate strength for the application. For weld strength requirements above 480 MPa (70 ksi), a suitable low-alloy steel FCAW electrode should be used. Electrodes are available that can deposit undiluted weld metal with tensile strengths ranging from 410 MPa to 830 MPa (60 ksi to 120 ksi).

Submerged Arc Welding

Submerged arc welding (SAW) is performed with an electrode, either solid or metal-cored, and a granular flux. The flux shields the arc and weld pool from the atmosphere and modifies the composition and mechanical properties of the weld. Solid-wire electrodes made of carbon steel and low-alloy steel are classified according to chemical composition. The classification of metal-cored electrodes made of low-alloy steel is based on the chemical composition of deposited weld metal using an appropriate flux.⁵⁶ Likewise, fluxes are classi-

53. Refer to American Welding Society (AWS), 2003, *Recommended Practices for Shielding Gases for Welding and Cutting*, AWS C5.10/C5.10M:2003, Miami: American Welding Society.

54. For electrode specifications, refer to American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2005, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*, AWS A5.20/A5.20M:2005; and, 2010, *Specification for Low-Alloy Steel Electrodes for Flux Cored Arc Welding*, AWS A5.29/A5.29M:2010, Miami: American Welding Society.

55. See Reference 54.

fied on the basis of the chemical composition and mechanical properties of weld metal deposited with a particular type of electrode.

The welding and heat treatment schedules required for certain applications may produce weld metal with mechanical properties that differ from those required by the filler metal specification. In such cases, the mechanical properties of the weld metal should be determined by appropriate testing. Weld-metal properties may be determined either in the as-welded condition or after a specified postweld heat treatment.

Carbon steel electrode and flux combinations are designed to achieve minimum weld-metal tensile strengths of 410 MPa or 480 MPa (60 ksi or 70 ksi). These combinations are recommended for welding low-carbon and mild steels and also for medium-carbon, high-carbon, and low-alloy steels when high strength is not required in the weld joint. Combinations of low-alloy steel electrodes and fluxes are recommended for welding alloy steels of similar composition, or for welding medium- and high-carbon steels when high-strength joints are needed to meet service requirements.

Response to postweld heat treatment must be considered. As described, flux must be kept clean and dry to maintain low-hydrogen welding conditions, and it must be applied at a sufficient depth to provide adequate shielding. Also, the electrode must be clean and free of contaminants, as discussed for the gas-shielded arc welding processes.

Submerged arc welding flux and wire combinations that meet the same diffusible hydrogen limits indicated for SMAW electrodes are identified by the same hydrogen designators. The welding wire and flux must be considered together.

Electroslag and Electrogas Welding

Electroslag welding (ESW) and electrogas welding (EGW) are used primarily for producing single-pass groove welds in the vertical position. Electroslag welding uses a resistance-heated, slag pool to melt the electrode. This process generally is used for welding steel plates 32 mm to 305 mm (1.25 in. to 12 in.) in thickness. Electrogas welding is similar to gas metal arc welding or flux cored arc welding, depending on the type of electrode. This process is best suited for welding thick plates over 13 mm (1/2 in.).

These processes are used mostly to weld low-carbon and mild steels, but medium-carbon steels also may be welded. Generally, when the weldment requires postweld heat treatment, an electrode composition

should be selected that will produce weld metal that responds satisfactorily to the heat treatment. Dilution by the base metal must be considered during selection.

Electrodes and fluxes for ESW are classified in a manner similar to that for submerged arc welding.⁵⁷ Both solid and metal-cored ESW electrodes can produce weld metal with a minimum tensile strength of 410 MPa (60 ksi) or higher, depending on the specific electrode-and-flux combination and the welding conditions. Most solid electrodes consist of carbon-manganese steels. Metal-cored electrodes generally deposit low-alloy steel weld metal.

Solid carbon steel electrodes for electrogas welding are essentially the same as those used for GMAW. Flux-cored electrodes are designed specifically for use with this process to deposit low-carbon or low-alloy steel weld metal.⁵⁸ Welding may be accomplished using carbon dioxide, argon mixed with carbon dioxide, or argon mixed with oxygen. One of the carbon steel flux-cored electrode classifications, EGXXT-1, can be used without shielding gas. Minimum tensile strength requirements for deposited weld metal are the same as for electroslag welding.

Oxyacetylene Welding

Most low-carbon and mild steels can be joined by oxyacetylene welding (OAW), but the process is much slower than arc welding. The slow heating characteristics of the process result in rather extensive heating of the steel. As a result, mechanical properties developed in the base metal by prior heat treatment or cold working may be impaired. Conversely, the cooling rate in the weld zone will be comparatively slow.

Oxyacetylene welding of steel is performed without flux, and obviously without a shielding gas. Therefore, the weld metal is not protected from the atmosphere by a slag or shielding-gas cover, but is protected only by gases derived from the combustion of the correctly selected mixture of oxygen and acetylene. Welded joints are likely to contain discontinuities that are unacceptable for many applications, and the mechanical properties of the weld metal may be inadequate for the intended service.

Carbon steels containing more than 0.35% carbon require special precautions when welded with oxyacetylene welding. Preheating with a torch or another heat source is recommended to retard the cooling rate of the

56. See Reference 47, and American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2007, *Specification for Low-Alloy Steel Electrodes and Fluxes for Submerged Arc Welding*, AWS A5.23/A5.23M:2007, Miami: American Welding Society.

57. Refer to American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2009, *Specification for Carbon and Low-Alloy Steel Electrodes and Fluxes for Electroslag Welding*, AWS A5.25/A5.25M-97 (R2009), Miami: American Welding Society.

58. Refer to American Welding Society (AWS) Committee on Filler Metals and Related Materials, 2009, *Specification for Carbon and Low-Alloy Steel Electrodes for Electrogas Welding*, AWS A5.26/A5.26M-97 (R2009), Miami: American Welding Society.

weld and heat-affected zone. In some cases, postweld heat treatment may be needed to refine the grain size of the weld zone and improve toughness.

Steel welding rods are available for oxyacetylene welding of carbon steel and low-alloy steels.⁵⁹ They are classified on the basis of the minimum tensile strength of as-deposited weld metal. Type R45 welding rods are recommended for depositing low-carbon steel weld metal for general applications. Type R60 welding rods should be used for steels with tensile strengths in the range of 340 MPa to 450 MPa (50 ksi to 65 ksi). Type R65 rods are best for welding either carbon steels or low-alloy steels with tensile strength in the range of 450 MPa to 520 MPa (65 ksi to 75 ksi). Carbon steel and low-alloy steel welding rods designed for GTAW also can be used for oxyacetylene welding. If a suitable welding rod is not available for welding a specific steel, strips sheared from the base metal may be used as filler metal.

Resistance Welding

Carbon steels can be joined by all of the resistance welding processes, i.e., resistance spot welding (RSW), resistance seam welding (RSEW), projection welding (PW), flash welding (FW) upset welding (UW), high-frequency upset welding (UW-HF), and high-frequency resistance welding (RSEW-HF). The heating and cooling rates for these processes are very high compared to those for arc welding. Consequently, the hardenability and critical cooling rate of the specific steel must be considered when selecting the process and welding procedures.

The weld zone and heat-affected zone are quenched by a water-cooled copper-alloy electrode bearing onto the workpieces. The severity of the quench depends on the length of the heat conduction path, the size of the electrode contact area, and the duration of quenching. Quenching is more severe when welding thin sheet with the resistance spot, seam, or projection processes, and when flash welding or upset welding with a welding rod or wire that has a small cross-section. Retracting the electrodes from the weldment as soon as practical will reduce the quenching rate. With some processes, such as resistance seam welding and high-frequency welding, the weld may be quenched as the electrode is cooled by water spraying or flooding. If the hardness of the weld and HAZ is excessive, postheating or tempering while in the welding machine may reduce the hardness to an acceptable level. In some cases, it may be appropriate to heat treat the weldment in auxiliary equipment.

Low-Carbon Steel. Low-carbon steel is readily joined by all resistance welding processes because these steels have low hardenability. Resistance welds normally have adequate ductility for the application. Spot welds and seam welds in thin sheet steel can have relatively high hardness when the carbon content exceeds about 0.08%. If this is objectionable, sheet with a nominal carbon content of 0.08% or less should be specified.

Suggested schedules for resistance welding of low-carbon steel sheet are provided in the following charts: Table 1.5 for resistance spot welding, Table 1.6 for multiple-impulse resistance spot welding, Table 1.7 for resistance seam welding, and Table 1.8(A) and 1.8(B) for resistance projection welding.⁶⁰ Variation from these conditions will be necessary to adjust for the weldment design and the configuration of the welding machine. Suitable welding conditions for a specific application should be determined by appropriate testing.

Data for the flash welding of carbon steel shapes are provided in Chapter 3 of the *Welding Handbook*, Volume 3, which covers this process (refer to Appendix B).⁶¹ Recommended procedures for high-frequency resistance welding and upset welding should be obtained from the equipment manufacturer.

Resistance Seam Weldability Lobes. The resistance seam weldability of steel can be quantified by a weldability lobe. The weldability lobe defines the welding conditions over which a continuous seam weld can be produced without either damaging the weld integrity or interrupting the process. The weldability lobe generally is depicted in two dimensions representing effective combinations of welding speed and welding current. In three dimensions, this is expanded to include all combinations of welding current, welding speed, and electrode force. The upper limit of the lobe (i.e., excessive heating of the weld) typically is characterized by surface eruption, copper-contamination cracking of the steel, or sticking of the electrodes to the steel. The lower limit of the lobe (i.e., insufficient weld growth) is defined as the point where a continuous seam is no longer found.

Weldability lobes are powerful tools for determining both the process performance of a given application and the weldability of a specific steel. A wide lobe generally is very tolerant of changes in process conditions, while a narrow lobe suggests that even small changes in process conditions will have a significant effect on weld quality.

To illustrate this approach, the weldability lobes of typical 0.80 mm (0.032 in.) thick low-carbon steels and hot-dipped galvanized steels for the most common

59. Refer to American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2007, *Specification for Carbon and Low-Alloy Steel Rods for Oxyfuel Gas Welding*, AWS A5.2/A5.2M: 2007, Miami: American Welding Society.

60. Appropriate projection designs for steel are discussed in Volume 3 of *Welding Handbook*, 9th ed., Chapter 2 (see Reference 50). Refer also to Appendix B of this volume for a list of the contents of current volumes of the *Welding Handbook*.

61. See Reference 50.

Table 1.5
Suggested Schedules for Resistance Spot Welding of Low-Carbon Steel Sheet

Thickness ^a		Electrode Face Diam. ^b		Static Electrode Force		Weld Time, Cycles ^c	Approx. Welding Current ^d	Approximate Nugget Diameter		Minimum Pitch ^e		Minimum Shear Strength When Base Metal Tensile Strength is:			
												Below 70 ksi (480 MPa)		Above 70 ksi (480 MPa)	
mm	in.	mm	in.	N	lb		kA ^d	mm	in.	mm	in.	N	lb	N	lb
0.25	0.010	3.30	0.13	890	200	4	4.0	2.54	0.10	6.4	0.25	578	130	801	180
0.53	0.021	4.82	0.19	1334	300	6	6.5	3.30	0.13	9.4	0.37	1423	320	1957	440
0.79	0.031	4.82	0.19	1779	400	8	8.0	4.06	0.16	12.7	0.50	2535	570	3559	800
1.02	0.040	6.35	0.25	2224	500	10	9.5	4.82	0.19	19.1	0.75	4092	920	5338	1200
1.27	0.050	6.35	0.25	2891	650	12	10.5	5.58	0.22	22.1	0.87	6005	1350	—	—
1.57	0.062	6.35	0.25	3559	800	14	12.0	6.35	0.25	25.4	1.00	8229	1850	—	—
1.98	0.078	7.87	0.31	4893	1100	17	14.0	7.36	0.29	31.8	1.25	12 010	2700	—	—
2.39	0.094	7.87	0.31	5783	1300	20	15.5	7.87	0.31	38.0	1.50	15 346	3450	—	—
2.77	0.109	9.65	0.38	7117	1600	23	17.5	8.12	0.32	41.2	1.62	18 460	4150	—	—
3.18	0.125	9.65	0.38	8007	1800	26	19.0	8.38	0.33	44.5	1.75	22 241	5000	—	—

- a. Thickness of thinnest outside sheet. Data applicable to a total metal thickness of four times the given thickness. Maximum ratio of two adjacent thicknesses is 3 to 1.
b. Flat-faced electrode of RWMA Group A, Class 2 copper alloy.
c. Single-impulse, frequency of 60 Hz.
d. Single-phase ac machine.
e. Minimum spacing between adjacent spot welds between two sheets without adjustment of the welding schedule for shunting.

Table 1.6
Suggested Schedules for Multiple-Impulse Resistance Spot Welding of Low-Carbon Steel Sheet

Thickness ^a		Electrode Face Diameter ^b		Static Electrode Force		No. of Impulses ^c			Approx. Welding Current, kA ^d	Approx. Nugget Diameter		Min. Shear Strength	
						Multiple Spot Spacing							
mm	in.	mm	in.	N	lb	Single Spot	51–102 mm (2–4 in.)	25–51 mm (1–2 in.)		mm	in.	N	lb
3.18	0.125	11.18	0.44	8007	1800	3	4	5	18.0	9.4	0.37	22 241	5000
4.76	0.188	12.70	0.50	8674	1950	6	14	20	19.5	14.2	0.56	44 482	10 000
6.35	0.25	14.22	0.56	9564	2150	12	18	24	21.5	19.1	0.75	66 723	15 000
7.87	0.31	15.74	0.62	10 675	2400	15	23	30	24.0	22.1	0.87	88 964	20 000

- a. Thinnest of two sheets. Maximum ratio of sheet thickness is 2 to 1.
b. Flat-faced electrode of RWMA Group A, Class 2 copper alloy.
c. Heat time is 20 cycles; cool time is 5 cycles (60 Hz).
d. Single-phase ac machine.

current pulsing condition (3-on/1-off) are shown in Figure 1.18 and Figure 1.19. These lobes were developed using RWMA Class II electrodes. The width of the circular electrode (wheel) was 11 mm (0.44 in.); the radius of the electrode face was 13 mm (0.5 in.). The welding conditions (welding current, electrode force, and welding speed) can be selected for each application using

the weldability lobe approach, which clearly indicates the robustness of the process at the various welding conditions.

Mild Steels and Medium-Carbon Steels. When using resistance welding processes to join mild steels and medium-carbon steels, it is usually necessary to

Table 1.7
Suggested Schedules for Resistance Seam Welding of Low-Carbon Steel Sheet

Thickness ^a		Electrode Face Width ^b		Static Electrode Force		Heat Time, Cycles ^c	Cool Time, Cycles ^c	Travel Speed		Welds Per Unit Length		Approx. Welding Current, kA ^d
mm	in.	mm	in.	N	lb			mm/s	in./min	mm	in.	
0.25	0.010	4.82	0.19	1779	400	2	1	33.8	80	381	15	8.0
0.53	0.021	4.82	0.19	2447	550	2	2	31.7	75	305	12	11.0
0.79	0.031	6.35	0.25	3114	700	3	2	30.0	72	254	10	13.0
1.02	0.040	6.35	0.25	4003	900	3	3	28.6	67	228	9	15.0
1.27	0.050	7.87	0.31	4671	1050	4	3	27.5	65	203	8	16.5
1.57	0.062	7.87	0.31	5338	1200	4	4	26.7	63	177	7	17.5
1.98	0.078	9.65	0.38	6672	1500	6	5	23.3	55	152	6	19.0
2.39	0.094	11.18	0.44	7562	1700	7	6	21.2	50	139.7	5.5	20.0
2.77	0.109	12.7	0.50	8674	1950	9	6	20.3	48	127	5	21.0
3.18	0.125	12.7	0.50	9786	2200	11	7	19.1	45	114.3	24.5	22.0

a. Thickness of thinnest outside piece. Data applicable to a total metal thickness of 4 times the given thickness. Maximum ratio of two adjacent thicknesses is 3 to 1.

b. Flat-faced wheel electrode of RWMA Group A, Class 2 copper alloy.

c. Frequency of 60 Hz

d. Single-phase ac machine.

control the cooling rate from welding temperature or from a subsequent tempering cycle to prevent excessive hardness and associated cracking in the weld zone. With mild steels, postheating with a lower current for several cycles (60 Hz) may be sufficient to avoid the formation of hard martensite in the weld. Spot welds in medium-carbon steels can be quenched to martensite and then tempered by resistance heating to soften the martensite and improve ductility. Suitable postheat or quench-and-temper cycles must be established by welding tests. Table 1.9 lists examples of quench-and-temper cycles for the spot welding of SAE 1020, 1035, and 1045 carbon steel sheet. As expected, the shear strength of the spot weld increases in proportion to the increase in the carbon content of the steel.

Normally, low-carbon and medium-carbon steels can be flash welded without the risk of cracking. Preheat or postheat is not required, but the application of one or both can improve ductility in the weld joint. When using flash welding for small or thin cross sections, postheating in the welding machine can be used to control weld hardness. The welding machine should be equipped with appropriate current and time controls to program a postheat cycle. An alternative is to heat treat

the weldment in a furnace to homogenize the microstructure of the weld zone and provide the required mechanical properties.

High-Carbon Steel. High-carbon steels are seldom joined by resistance welding processes because of the high hardenability of these steels, and because applications and products for these processes are limited. However, the procedures provided for welding low-carbon and medium-carbon steels are applicable also to high-carbon steels, with appropriate adjustments to accommodate the higher hardenability.

Electron Beam and Laser Beam Welding

Low-carbon steels are readily welded by electron beam welding (EBW) and laser beam welding (LBW). The rapid heating and cooling rates associated with these processes result in weld metal and heat-affected zones with relatively small grain sizes compared to those found in arc welds. Also, the heat-affected zone is much narrower. Fully killed steel is preferred for applications involving these welding processes.

Table 1.8(A)
Suggested Schedules for Resistance Projection Welding of Low-Carbon Steel Sheet
(Metric Units)

Thickness, t mm ^d	Projection		Min. Pitch, mm	Min. Contact Overlap, mm	Welding Schedule A for Single Projection ^a				Welding Schedule B for 1–3 Projections, per Projection ^b				Welding Schedule C for 3 or More Projections, per Projection ^c			
	Diam., mm	Height, mm			Weld Time, Cycles	Electrode Force, N	Welding Current, A	Shear Strength, N	Weld Time, Cycles ^e	Electrode Force, N	Welding Current, A	Shear Strength, N	Weld Time, Cycles ^e	Electrode Force, N	Welding Current, A	Shear Strength, N
0.56	2.29	0.64	9.7	6.4	3	667	4400	1646	6	667	3850	1446	6	356	2900	1290
0.71	2.29	0.64	9.7	6.4	3	867	5500	2224	6	667	4450	1890	8	445	3300	1513
0.94	2.79	0.89	12.7	9.7	3	1068	6600	3114	6	667	5100	2335	11	556	3800	1890
1.09	2.79	0.89	12.7	9.7	5	1468	8000	4715	10	934	6000	3892	15	712	4300	3203
1.25	3.56	0.97	19.1	2.7	8	1779	8800	5783	16	1201	6500	4893	19	979	4600	3892
1.55	3.81	1.07	19.1	12.7	10	2447	10 300	8007	20	1624	7650	7006	25	1468	5400	5449
1.96	4.57	1.22	22.4	12.7	14	3559	11 850	10 787	28	2358	8850	9564	34	2091	6400	7784
2.34	5.33	1.27	26.9	15.8	16	4537	13 150	14 457	32	3025	9750	12 455	42	2713	7200	10 342
2.72	6.10	1.40	31.8	19.1	19	5560	14 100	17 126	38	3692	10 600	15 346	50	3292	8300	12 900
3.12	6.86	1.47	38.1	20.6	22	6672	14 850	21 351	45	4448	11 300	18 683	60	4003	9200	16 014
3.43	7.62	1.58	41.4	22.4	24	7340	15 300	24 465	48	4893	11 850	21 574	66	4448	9900	18 905

a. Schedule A is usable for welding more than one projection if current is decreased but excessive weld expulsion may result and power demand will be greater than with Schedules B or C.

b. Schedule B is usable for welding more than three projections, but some weld expulsion may result and power demand will be greater than with Schedule C.

c. Schedule C is usable for welding less than three projections with welding current increased approximately 15% and possible objectionable final sheet separation.

d. For unequal sheet thickness ratios, T/t, up to 3 to 1:

1. The weld time, cycles, should be increased by a factor f_t determined by the formula $f_t = 1.5 (T/t) - 0.5$.

2. The welding current per projection should be increased by a factor f_c determined by the formula $f_c = 0.1 (T/t) + 0.9$.

e. Frequency of 60 Hz.

Table 1.8(B)
Suggested Schedules for Resistance Projection Welding of Low-Carbon Steel Sheet
(U.S. Customary Units)

Thickness, t in. ^d	Projection		Min. Pitch, in.	Min. Contact Overlap, in.	Welding Schedule A for Single Projection ^a				Welding Schedule B for 1–3 Projections, per Projection ^b				Welding Schedule C for 3 or More Projections, per Projection ^c			
	Diam., in.	Height, in.			Weld Time, Cycles	Electrode Force, lb	Welding Current, A	Shear Strength, lb	Weld Time, Cycles ^e	Electrode Force, lb	Welding Current, A	Shear Strength, lb	Weld Time, Cycles ^e	Electrode Force, lb	Weld Current, A	Shear Strength, lb
0.022	0.090	0.025	0.38	0.25	3	150	4400	370	6	150	3850	325	6	80	2900	290
0.028	0.090	0.025	0.38	0.25	3	195	5500	500	6	150	4450	425	8	100	3300	340
0.037	0.110	0.035	0.50	0.38	3	240	6600	700	6	150	5100	525	11	125	3800	425
0.043	0.110	0.035	0.50	0.38	5	330	8000	1060	10	210	6000	875	15	160	4300	720
0.049	0.140	0.038	0.75	0.50	8	400	8800	1300	16	270	6500	1100	19	220	4600	875
0.061	0.150	0.042	0.75	0.50	10	550	10 300	1800	20	365	7650	1575	25	330	5400	1225
0.077	0.180	0.048	0.88	0.50	14	800	11 850	2425	28	530	8850	2150	34	470	6400	1750
0.092	0.210	0.050	1.06	0.62	16	1020	13 150	3250	32	680	9750	2800	42	610	7200	2325
0.107	0.240	0.055	1.25	0.75	19	1250	14 100	3850	38	830	10 600	3450	50	740	8300	2900
0.123	0.270	0.058	1.50	0.81	22	1500	14 850	4800	45	1000	11 300	4200	60	900	9200	3600
0.135	0.300	0.062	1.63	0.88	24	1650	15 300	5500	48	1100	11 850	4850	66	1000	9900	4250

a. Schedule A is usable for welding more than one projection if current is decreased, but excessive weld expulsion may result and power demand will be greater than with Schedules B or C.

b. Schedule B is usable for welding more than three projections, but some weld expulsion may result and power demand will be greater than with Schedule C.

c. Schedule C is usable for welding less than three projections with welding current increased approximately 15%; objectionable final sheet separation is possible.

d. For unequal sheet thickness ratios, T/t, up to 3 to 1:

1. The weld time, cycles, should be increased by a factor f_t determined by the formula $f_t = 1.5 (T/t) - 0.5$.

2. The welding current per projection should be increased by a factor f_c determined by the formula $f_c = 0.1 (T/t) + 0.9$.

e. Frequency of 60 Hz.

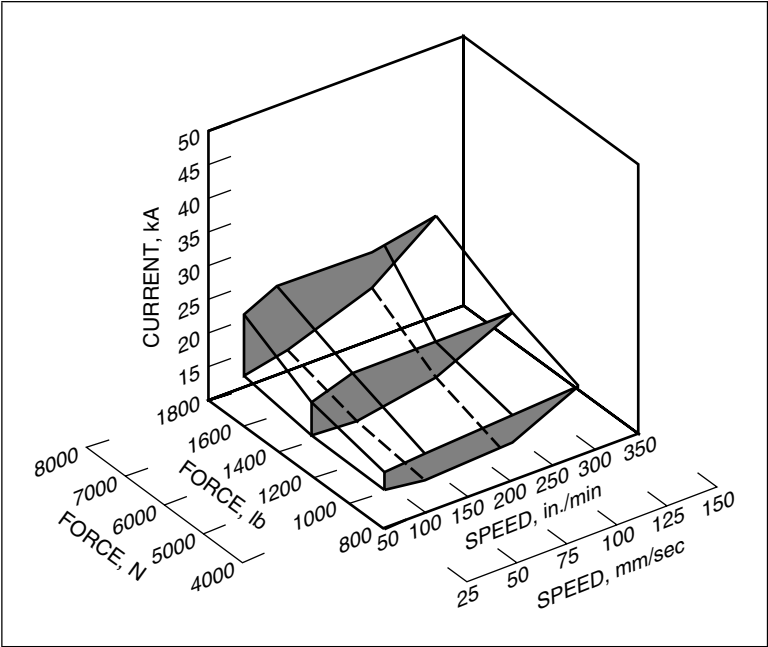


Figure 1.18—The 3-Dimensional Averaged Weldability Lobe for Uncoated Steel Using a 3-On/1-Off Pulsing Schedule

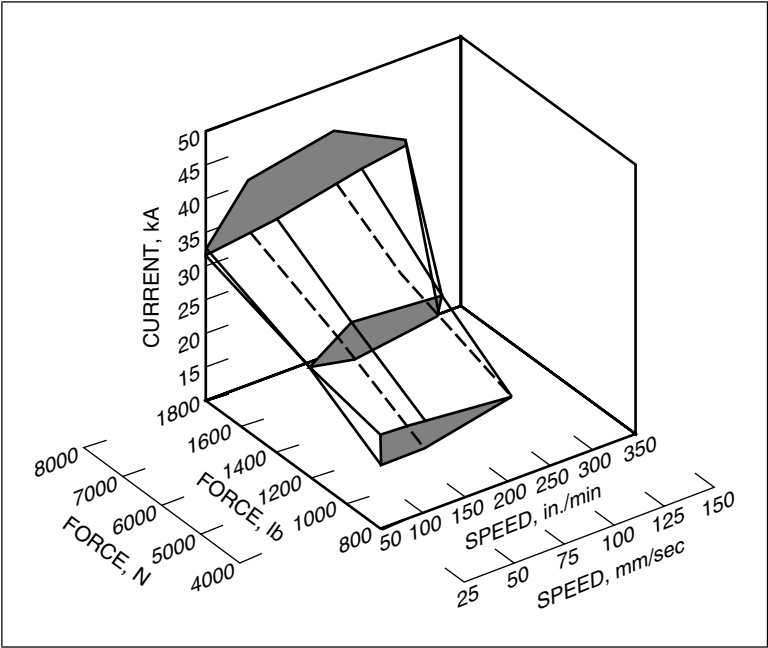


Figure 1.19—The 3-Dimensional Averaged Weldability Lobe for Hot-Dipped Galvanized Steel Using a 3-On/1-Off Pulsing Schedule

Table 1.9
Typical Resistance Spot Welding Schedules for Medium-Carbon and Low-Alloy Steel Sheet

AISI No.	Thickness		Electrode Face Diameter ^b		Electrode Force		Weld Time, Cycles ^c	Quench Time, Cycles ^c	Temper Time, Cycles ^c	Approx. Welding Current, kA ^d	Temper Current, % ^e	Approx. Nugget Diameter		Min. Pitch ^f		Minimum Shear Strength	
	mm	in.	mm	in.	N	lb						mm	in.	mm	in.	N	lb
1020	1.02	0.040	6.35	0.25	6561	1475	6	17	6	16.0	90	5.84	0.23	25.4	1	6050	1360
1035	1.02	0.040	6.35	0.25	6561	1475	6	20	6	14.2	91	5.58	0.22	25.4	1	6939	1560
1045	1.02	0.040	6.35	0.25	6561	1475	6	24	6	13.8	88	5.33	0.21	25.4	1	8896	2000
4130	1.02	0.040	6.35	0.25	6561	1475	6	18	6	13.0	90	5.58	0.22	25.4	1	9430	2120
4340	0.79	0.031	4.82	0.19	4003	900	4	12	4	8.3	84	4.06	0.16	19.0	0.75	4804	1080
—	1.57	0.062	7.87	0.31	8896	2000	10	45	10	13.9	77	6.85	0.27	38.1	1.50	17 081	3840
—	3.18	0.125	16.00	0.63	24 465	5500	45	240	90	21.8	88	13.97	0.55	63.5	2.50	60 940	13 700
8630	0.79	0.031	4.82	0.19	3559	800	4	12	4	8.7	88	4.06	0.16	19.0	0.75	5427	1220
—	1.57	0.062	7.87	0.31	8007	1800	10	36	10	12.8	83	6.85	0.27	38.1	1.50	18 860	4240
—	3.18	0.125	16.00	0.63	20 017	4500	45	210	90	21.8	84	13.97	0.55	63.5	2.50	58 717	13 200

a. Two equal thicknesses.

b. Flat-faced electrode of RWMA Group A, Class 2 copper alloy.

c. Cycle of 60 Hz.

d. Single-phase ac machine.

e. Percentage of welding current with phase-shift heat control.

f. Minimum pitch between adjacent spot welds without adjustment of the welding schedule for shunting.

Friction Welding

Low-carbon steels are readily joined by friction welding (FW). Welding conditions are not critical from a metallurgical standpoint. Medium- and high-carbon steels can be friction welded, but the welding conditions must be controlled within narrow ranges. The heating time for these steels should be relatively long to slow the cooling rate of the weld.

BRAZING CARBON STEELS

Carbon steels can be joined by virtually all of the brazing processes. Torch brazing (TB), furnace brazing (FB), and induction brazing (IB) are commonly used. Filler metals in the form of continuous wire or strip can be applied automatically using electro-mechanical wire feeders. Filler metal in powder form can be blended with flux and paste-forming ingredients, and automatically applied with pressurized dispensing equipment. For torch brazing, the heating equipment includes a standard oxyfuel gas torch. Brazing furnaces can be either a batch type or a conveyor type, with or without control of the atmosphere.

Filler Metals

Carbon steels can be brazed with copper, gold, nickel, and silver filler metals.⁶² All silver (BAg) brazing filler metals are suitable for use with carbon steel. Filler metals containing nickel usually have better wettability and are preferred for good joint strength.

The copper (BCu) filler metals are used mainly for furnace brazing, where preplacement of the workpieces is needed. The RBCuZn filler metals in rod form generally are used with torch brazing, but they also can be used with furnace brazing or induction brazing. The high brazing temperatures tolerated by these filler metals often permit simultaneous brazing and heat-treating operations.

The nickel (BNi) filler metals are used when their unique properties are needed for special applications. Brazing with nickel filler metals normally is done in a controlled atmosphere.

62. Refer to American Welding Society (AWS) Committee on Filler Metals and Allied Materials, 2004, *Specification for Filler Metals for Brazing and Braze Welding*, AWS A5.8/A5.8M:2004; and, 2003, *Specification for Fluxes for Brazing and Braze Welding*, AWS A5.9/A5.9M:2003, Miami: American Welding Society.