

MATERIALS AND APPLICATIONS – PART 2

**WELDING
HANDBOOK**

EIGHTH EDITION



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WELDING HANDBOOK

Eighth Edition

Volume 4

MATERIALS AND APPLICATIONS – PART 2

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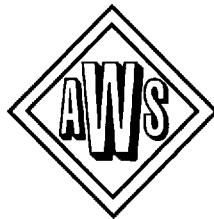
4) MATERIALS AND APPLICATIONS – PART 2

WELDING HANDBOOK

Eighth Edition

Volume 4

MATERIALS AND APPLICATIONS PART 2



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PREFACE

This is the fourth and final volume of the Eighth Edition of the *Welding Handbook*. The title of Volume Four is Materials and Applications—Part 2. Publication of this volume not only completes the Eighth Edition, it also concludes publication of the *Welding Handbook* for the 20th Century. The first edition of the *Welding Handbook* was published in 1938. In this volume, the American Welding Society recognizes those who worked in developing, interpreting, and sharing the technologies described in these editions by serving as chairmen of the Welding Handbook Committee (see facing page). The Eighth Edition of the *Welding Handbook* is a fitting tribute to their legacy, as it is the result of thousands of hours of preparation by current volunteers.

Originally the Welding Handbook Committee had planned to publish Materials and Applications as a single volume. However, it became evident during compilation of the text that the material was too voluminous to be contained in a single volume. Evidence of this is that the final two volumes exceed 1100 pages, compared to 547 smaller pages in the Seventh Edition.

Volume Four contains ten chapters supplementing the ten chapters contained in Volume Three. Both of these volumes represent a considerable expansion of the information in the previous editions. In many instances, it is new material never before published by the American Welding Society.

One example of new content is the chapter on coated steels. It is 85 pages in the Eighth Edition, compared to 11 in the previous edition. The chapters on stainless steels, tool and die steels, and titanium also have been revised extensively. The stainless steels chapter provides an overview of ferrite, its effects, and its measurement. The tool and die steels chapter presents previously proprietary information. The titanium chapter greatly expands the previous treatment of welding metallurgy.

It should be noted that the *Welding Handbook* is unique, in that it is a far more lengthy dissertation on broader subject areas than other peer-reviewed AWS publications. Volumes Three and Four of the *Welding Handbook* have a high level of technical content, yet this material is presented in a manner understandable to typical readers. The authors drew on industry sources to independently confirm that the information represents the latest technology. Volumes Three and Four should stand as authoritative texts for welding information on the vast array of materials welded in the world.

This volume, like the others, was a voluntary effort. The title page of each chapter bears the names of the Chapter Committee members and the Welding Handbook Committee members responsible for that chapter. Other individuals also participated in a variety of ways, particularly in chapter reviews. Preparation of this volume alone required the collaboration of more than 100 volunteers. All participants contributed generously of their time and talent, and the American Welding Society expresses its sincere appreciation to them and to the employers who supported their work. They have enabled the Welding Handbook Committee to realize its goal of issuing the *Welding Handbook* as a peer-reviewed and peer-approved publication.

The Welding Handbook Committee expresses its appreciation to the AWS staff members who assisted with this volume, especially Bill Oates and Alex Saitta for editorial assistance, the Technical Division staff engineers for their technical assistance, and the Publication Services Division staff for graphics assistance.

The Welding Handbook Committee welcomes your comments on the *Welding Handbook* as well as your potential interest in contributing to future volumes. Communications may be addressed to the Editor, *Welding Handbook*, American Welding Society, 550 N. W. LeJeune Road, Miami, Florida, 33126.

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CHAPTER 1

CARBON AND LOW-ALLOY STEELS

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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 their widespread use. Because of these attributes, carbon and low-alloy steels are an excellent choice for appliances, vehicles, bridges, buildings, machinery, pressure vessels, offshore structures, railroad equipment, ships, and a wide range

of consumer products. The extensive use of carbon and low-alloy steels means that welding, brazing and thermal cutting of such steels is quite common. This chapter provides information on: steel compositions and properties; weldability considerations; good practices and procedures for welding, thermal cutting, and brazing of carbon and low-alloy steels, with guidance on how to avoid problems when welding these steels; and typical applications.

WELDING CLASSIFICATION

FROM A WELDABILITY standpoint, carbon and low-alloy steels can be divided into five groups according to their composition, strength, heat treatment, or high-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 a subheading of this chapter, are identified as:

- (1) Carbon steels
- (2) High-strength low-alloy steels
- (3) Quenched and tempered steels
- (4) Heat-treatable low-alloy steels
- (5) Chromium-molybdenum 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, since weldability primarily is a function of these three factors. Although most steels are used in wrought form, the same considerations apply to the welding, brazing, and thermal cutting of 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 composition of carbon steels typically include weight percentages of up to 1.00 carbon, up to 1.65 manganese, and up to 0.60 silicon. Wrought carbon steels normally are used in the as-rolled condition, although some may be in the annealed or normalized condition.

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 42 to 80 ksi (289 to 551 MPa). 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 are generally heat treated by the producer to provide yield strengths in the range of 50 to 150 ksi (345 to 1034 MPa). In addition, they are designed to be welded in the heat-treated condition. Normally, the weldments receive no postweld heat

treatment, 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 contents 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 crack-susceptible in the heat-affected zone. 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 1300 °F (704 °C) to resist creep and corrosion in applications such as power plants, chemical plants, or petroleum refineries. They may be welded in various heat-treated conditions (i.e., annealed, normalized and tempered, or quenched and tempered). Postweld heat treatment often is required by fabrication codes to improve ductility, toughness, and corrosion resistance and to reduce stresses caused by welding.

GENERAL CONSIDERATIONS

CARBON AND LOW-ALLOY steels can be welded by arc, oxyfuel, resistance, electron beam, laser beam, electroslog, and solid-state welding processes. These steels also can be joined by brazing, soldering, and adhesive bonding. Later sections of this chapter will discuss the most commonly used joining processes for each of the five groups described in the previous section. The following sections address other important considerations.

FILLER METALS

SUITABLE WELDING FILLER metals are available for all groups of carbon and low-alloy steels. Filler metals should be selected to provide the mechanical properties (tensile strength, yield strength, ductility, and notch toughness) that are required for the intended service conditions. Chemical composition, corrosion resistance, and heat treatment response are other important considerations in choosing a filler metal for certain carbon and low-alloy steels. The diffusible weld metal hydrogen level of welding electrodes and filler metals is particularly important when welding carbon and low-alloy steels, and this is described specifically in a later section. Further details on welding filler metals, as well as recommendations for brazing filler metals and fluxes, are

given in the section of this chapter on carbon steels and in the section for each group of steels.

WELDABILITY

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 (or HAZ). The resulting microstructure in the HAZ will depend upon the composition of the steel and the rate at which the steel is heated and cooled.

With some steels, the thermal cycle may result in the formation of martensite in the weld metal and HAZ.¹ The amount of martensite formed and the hardness of the steel depend upon carbon content, as well as the time at elevated temperature and the cooling rates. Figure 1.1 gives the relationship between hardness and carbon content for steels that are 50 or 100% martensite

1. Refer to the *Welding Handbook*, Volume 1, 8th Edition, 94-102, for additional information on the effects of deformation and heat treatment.

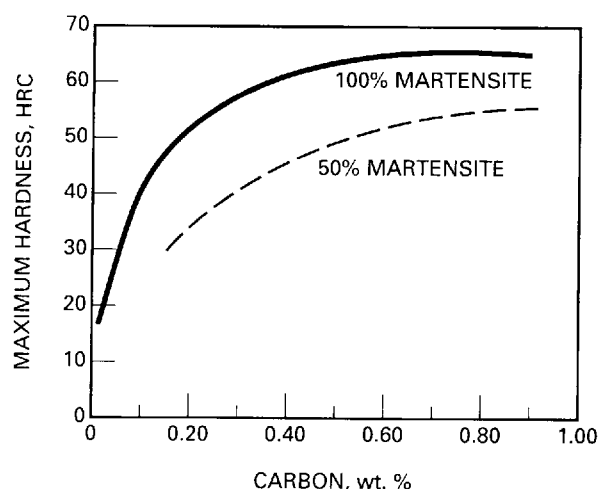


Figure 1.1—Relationship Between Carbon Content and Maximum Hardness of Steels with Microstructures of 50% and 100% Martensite

after quenching. Martensitic transformation and the resulting high hardness can lead to cracking in the weld or HAZ if the metal cannot yield to relieve welding stresses. The degree of hardening in the HAZ is an important consideration determining the weldability of a carbon or low-alloy steel. Weldability and resistance to hydrogen cracking generally decreases with increasing carbon or martensite in the weld metal or the HAZ, or both.

Although carbon is the most significant alloying element affecting weldability, 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). One empirical formula that may be used for judging the risk of underbead cracking in carbon steels is:

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (1.1)$$

Figure 1.2 shows the general relationships between carbon steel composition (CE) and hardness, underbead cracking sensitivity, or weldability based upon slow-bend capability 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 crack sensitivity.

Hydrogen Cracking

HYDROGEN CRACKING (also known as underbead, cold, or delayed cracking) can occur when welding carbon and low-alloy steels.² The potential for hydrogen cracking in the weld metal, the heat-affected zone (HAZ), or both depends on their composition, hydrogen content, and stress level. It generally occurs at a temperature below 300 °F (150 °C) immediately upon cooling or after a period of several hours. This time also depends upon the type of steel, the magnitude of the welding stresses, and the hydrogen content of the weld metal and HAZ.

Hydrogen cracking or cold cracking results when both hydrogen and tensile stresses are present in a crack-susceptible microstructure of the weld metal or HAZ. Sometimes cracking may occur in the weld metal, particularly when the yield strength is over 90 ksi (620 MPa); in general, however, alloy steels are more likely to crack in the HAZ. Diffusion of hydrogen into the HAZ from the weld metal during welding contributes to cracking in this zone. Microstructure of the steel and tensile stresses are also contributing factors.

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

- (1) The presence of atomic (diffusible) hydrogen in the steel
- (2) A susceptible microstructure, generally accepted to be partly or wholly martensitic
- (3) A tensile stress at the sensitive location
- (4) A temperature below 300 °F (150 °C)

Hydrogen cracking will not take place if one or more of these conditions is absent. Further discussion on the conditions for hydrogen cracking is provided in the following subsections.

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 at or near its melting temperature is high. Therefore, the molten weld metal can rapidly pick up atomic hydrogen from the hot gas in the arc. Once in the weld metal, hydrogen atoms can diffuse rapidly into the HAZ of the base metal.

The absorbed hydrogen is rejected from the steel during cooling and phase transformation, whereupon it

2. For additional information, refer to the *Welding Handbook*, Volume 1, 8th Edition, 103-11, 1991; and Linnert, G. E., *Welding Metallurgy*, Volume 2, 3rd Edition, 250-76, 1967, published by the American Welding Society.

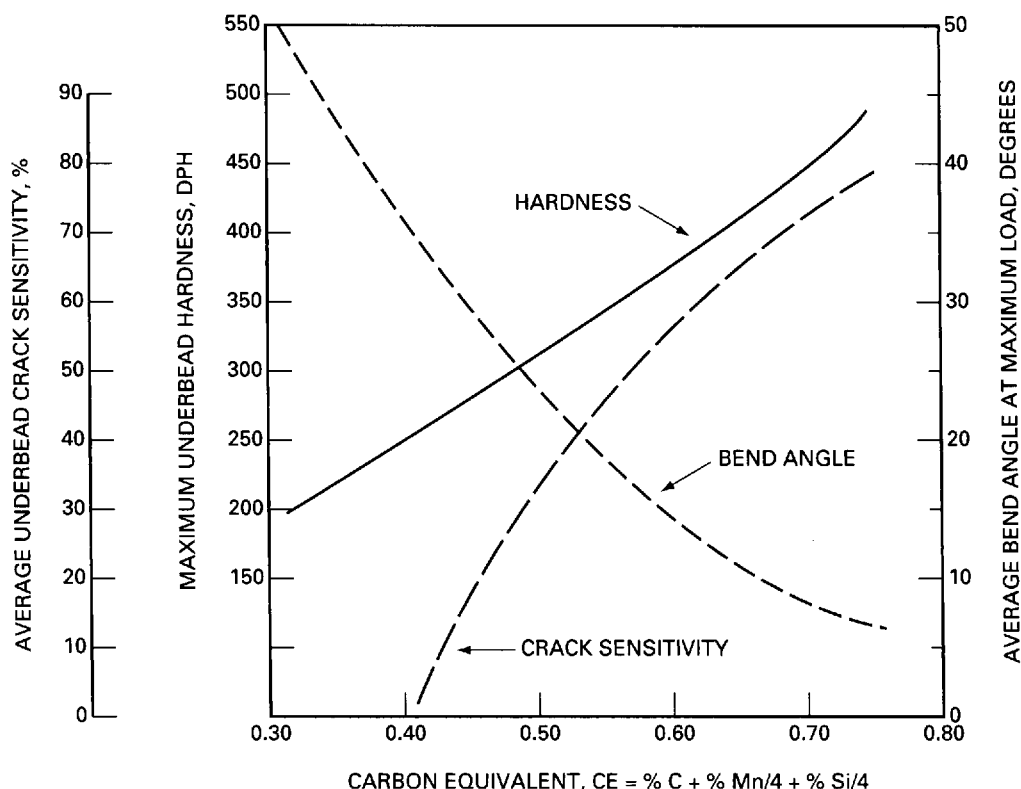


Figure 1.2—Relationship Between Composition and Underbead Hardness, Crack Sensitivity, and Notched-Weld-Bead Bend Angle for 1 in. (25.4 mm) Thick C-Mn Steel Plate Welded with E6010 Covered Electrodes

tends to concentrate at microstructural dislocations and voids in the matrix. The driving force to form diatomic or molecular hydrogen in the voids is very great, and a high pressure can occur. This induces localized tensile stresses that add to residual tensile stresses.

There are several possible sources of moisture and other hydrogenous compounds that can dissociate in the welding arc and introduce diffusible hydrogen in the weld metal. Sources include the filler metal, moisture in the electrode covering, welding flux, shielding gas, or contaminants on the filler or base metal. The filler wire or rod itself may be contaminated from lubricants used during the wire-drawing operation.

ANSI/AWS A4.3 describes methods for measuring the diffusible hydrogen content of welds deposited by shielded metal arc welding (SMAW), gas metal arc welding (GMAW), flux cored arc welding (FCAW), and submerged arc welding (SAW) processes.³ As a result of

3. See ANSI/AWS A4.3, *Standard Methods for Determination of the Diffusible Hydrogen Content of Martensitic, Bainitic, and Ferritic Steel Weld Metal Produced by Arc Welding*.

standardized testing given in this specification, a diffusible hydrogen designator — H16, H8, H4, or H2 — can be attached to 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 logarithmic scale of hydrogen content limits as shown in Table 1.1.

A low-hydrogen electrode which bears one of these designators is certified to meet the corresponding hydrogen limit under standardized test conditions specified in ANSI/AWS A4.3.

Furthermore, electrodes which resist moisture pickup for extended time periods under conditions of high atmospheric humidity are designated with an “R” in the electrode classification. ANSI/AWS D1.1, *Structural Welding Code—Steel*, permits longer exposure times for such electrodes. So a moisture resistant E7018 low-

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

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, the manufacturers of electrodes, as well as the most recent versions of ANSI/AWS A5.1 and A5.5, should be consulted for the latest information.

Microstructure. Cracking is most likely to be promoted by hydrogen 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 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, any localized area with this sort of mixed microstructure, in the presence of sufficient hydrogen, will be susceptible to HAZ cracking.

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. Cooling rate depends upon section thickness, 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.

High-heat-input welds, such as electroslag 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 fluxes was found to be 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.

Underbead Cracking. The greatest problem with hydrogen-induced cracking arises in the HAZ of hardenable steel. Cracking in this particular location is called *underbead cracking* when it is present a short distance from the weld interface, as illustrated in Figure 1.3. Sometimes, the crack will initiate in the HAZ but follow some other path as it propagates through unaffected base metal.

Weld Metal Cracking. Weld metal normally presents fewer problems with hydrogen cracking than base

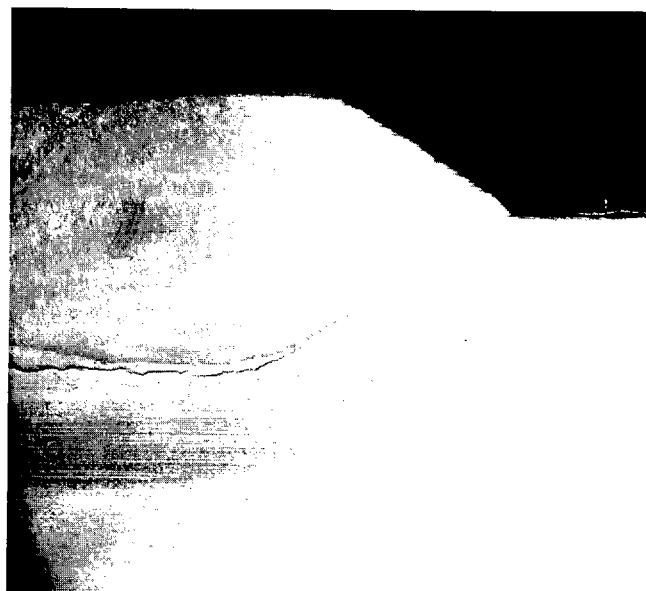


Figure 1.3—Underbead Crack in a Low-Alloy Steel Bead-on-Plate Weld (10% Nital Etch) (x8)

metal. This is probably a result of the general use of filler metal with a lower carbon content. Nevertheless, hydrogen can embrittle the weld metal to a significant extent. In particular, some recently developed high-strength low-alloy (HSLA) steels designed for naval applications have demonstrated significantly lower resistance to weld metal cracking than to HAZ hydrogen cracking, using the current consumables available for naval fabrication. Thus, for these new steels, preheat requirements are dictated by the weld metal rather than the parent steel.

Weld metal hydrogen cracking 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 also, or they can occur as *chevron cracks* which lie at an angle that is 45° to the surface.

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 a pupil in 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 heat treatment to the weldment for at least 20 minutes at temperatures ranging from 200 to 600 °F (93 to 316 °C). The elevated temperature serves several purposes. It speeds the diffusion of the atomic hydrogen out of the weld region. It reduces the driving force to form molecular hydrogen. It also permits the stresses in the weld region to relax. Longer times or higher temperatures, or both, should be applied in cases where there is increased hydrogen contamination and higher alloy content.

Microcracks may be observed in weld metal deposited by SMAW electrodes containing cellulose in the covering, or by low-hydrogen electrodes having 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.

Avoiding Cracking

WHEN THE CARBON OR alloy content of steel is increased to achieve higher strength, the hardness of the martensite in the microstructure is increased as well, and this tends to reduce the steel's tolerance for hydrogen. Residual stresses tend to increase with strength also. For example, low-strength carbon steels [UTS not

exceeding 60 ksi (414 MPa)] may be welded with E6010 or E6011 covered electrodes, which are characteristically high in hydrogen because their coverings contain cellulose and 3 to 7% moisture. Higher-strength quenched-and-tempered steels such as HY-130, on the other hand, must be welded with covered electrodes that contain no more than 0.1% moisture in the covering.⁴ Moisture or hydrogen limitations for covered electrodes vary between these two levels, depending upon the steel being welded.

Hydrogen cracking can be controlled by several means. A welding process or an electrode that produces little diffusible hydrogen can be selected. A combination of welding and thermal treatments that drives off the hydrogen, or produces a microstructure that is less sensitive to such cracking, can be used. Another alternative is simply to apply welding procedures that result in low welding stresses.

Welding Process. Available hydrogen during welding can be limited by using a low-hydrogen process. Primary sources of hydrogen are cellulose, moisture, or both, in the electrode covering with shielded metal arc welding; moisture in the flux with submerged arc welding; moisture in core ingredients of the flux with flux cored arc welding; and moisture in core ingredients of metal cored electrodes with gas metal arc welding. Other sources of hydrogen are adsorbed moisture, rust, or hydrocarbon contaminants (oil, grease, drawing lubricants, or paint) on the filler metal or the base metal. Shielding gas contaminated with humid air or moisture is yet another source of hydrogen.

The use of low-hydrogen electrodes is recommended for shielded metal arc welding of steels that are susceptible to hydrogen cracking. However, the moisture content of the electrodes must be maintained below the limits stated in the applicable filler metal specification.

Electrodes are manufactured to be 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. Such electrodes can be maintained for many months in these 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. A standardized absorbed-moisture test is described in ANSI/AWS A5.1-92, *Specification for Carbon Steel Electrodes for Shielded Metal*

4. Refer to Table 1.17, Page 38, for the chemical composition of HY-130 alloy steel.

Arc Welding. As a result of passing this exposure test, electrodes may have an "R" designator attached to their classification, or they may be classified as E7018M to indicate moisture resistance.

The low-hydrogen electrodes (EXX15 and EXX16), and low-hydrogen iron-powder electrodes (EXX18, EXX28, and EXX48), are designed to contain the minimum amount of moisture in their coverings. The maximum acceptable moisture level of the filler metal decreases as the strength of the weld metal increases. 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 80 ksi (552 MPa) or higher. Such containers are optional for electrodes of lower strength classifications.⁵

As mentioned earlier, 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 given in the appropriate specification. If there is a possibility that the electrodes have picked up excessive moisture, they may be reconditioned by rebaking. The appropriate time and temperature for rebaking should be requested from the electrode manufacturer. One should be aware that the applicable welding code may place limits on reconditioning. The *Structural Welding Code—Steel*, for example, specifies conditions for baking submerged arc welding flux.⁶

Hydrogen designators, shown in Table 1.1 on Page 6, have been used for several years in AWS specifications to designate the diffusible hydrogen content on covered carbon-steel electrodes and submerged arc low-alloy steel wires and fluxes. More recently, the same hydrogen designators have been applied to other ferritic covered electrodes, submerged arc wires and fluxes, and flux cored wires. Although none of the austenitic stainless steel and nickel alloy electrode specifications contain limits on hydrogen or moisture, special precautions should be exercised when using such 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 they have been contaminated with moisture or any other hydrogen-containing substance.

5. Refer to ANSI/AWS A5.1, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*, or ANSI/AWS A5.5, *Specification for Low-Alloy Steel Covered Arc Welding Electrodes*.

6. ANSI/AWS D1.1, *Structural Welding Code—Steel*, requires that flux be baked at 250 °F (121 °C) for 1 hour if the packaging has been damaged. The top 1 in. (25.4 mm) thick layer of exposed flux in hoppers and wet flux must be discarded. These procedures should be followed for all applications.

Thermal Treatments. Preheating and postheating at or just above the preheat temperature should be considered when there is danger of hydrogen cracking in the welded joint.⁷

Preheating involves raising the temperature of the weldment prior to welding and maintaining an elevated interpass temperature during the entire welding operation in order to:

- (1) Reduce cooling rates and reduce the hardness of HAZs
- (2) Increase the rate at which hydrogen diffuses away from the weld and HAZ
- (3) Reduce stresses near the weld

Preheat may be applied to the entire weldment, or only to the vicinity of the weld joint. 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. High arc energy levels, low hydrogen consumables and heating of the entire part rather than only a local area may permit the use of a lower preheat temperature. Recommendations for minimum preheat temperatures for carbon and low alloy steels can be found in a number of documents, including the ANSI/AWS D1.1, *Structural Welding Code—Steel*. These recommendations are discussed for each type of steel in the following 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 [200 to 600 °F (93 to 316 °C)]. The holding time at postheat temperature depends upon the joint thickness, because the length of the path over which the hydrogen must diffuse to the surface is a controlling factor. Raising the temperature modestly will help reduce the time needed for hydrogen removal.

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

It is recommended that steels not be welded if the steel temperature is below 32 °F (0 °C). If the temperature of the steel is below 32 °F (0 °C), it should be heated to at least 70 °F (15 °C) prior to welding. Under humid conditions, the steel should be heated to a higher temperature in order to dry moisture from its surfaces.

7. When preheating, the metal must be heated to the appropriate temperature throughout the section thickness without intermediate cooling prior to or during welding, unless precautions are taken to avoid cracking.

Interruption of Heating Cycle

WHERE A WELDING procedure employs preheating or postheating, there is sometimes a question 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. There may be operational or economical reasons, however, for not 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, heating of steels with high hardenability should not be interrupted unless appropriate steps are taken to avoid cracking. These procedures are discussed later for the various types of hardenable steels.

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

For the HAZ as well as the weld metal, an increase in section thickness increases both the restraint on the weld and the rate of cooling from welding temperature. Accordingly, the weld area is subjected to 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, an interruption of welding generally is not permitted until some minimum number of weld passes has been completed or a given fraction of the joint thickness has been welded. Wherever 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 preheat temperature.

LAMELLAR TEARING

GROOVE WELDS, FILLET welds, or combinations of these in corner or T-joints can result in high welding stresses in the base metal adjacent to the weld metal. High tensile stresses can develop perpendicular to the

midplane of the steel plate (i.e., the through-thickness direction) as well as parallel to it. The magnitude of these stresses depends upon the size of the weld, the welding procedures, and the restraint imposed on the joint by the weldment design.

When welding steel plate and structural shapes produced by conventional steel-making processes, any high internal tensile stresses developed perpendicular to the surface may cause tearing within the steel. The tears may or may not propagate to exposed surfaces. This tearing usually is associated with poor elongation in the through-thickness direction of plates. It may be aided by microscopic inclusions in the steel. Usually it progresses in a step-like fashion from one inclusion to another. On an etched cross-section through the steel, lamellar tearing is characterized by a step-like or jagged crack nearly parallel to the mid-plane of the plate. Figure 1.4 illustrates a typical joint design where lamellar tearing may take place, and its location with respect to the weld.

There is some evidence that sensitivity to lamellar tearing is increased by the presence of hydrogen in the

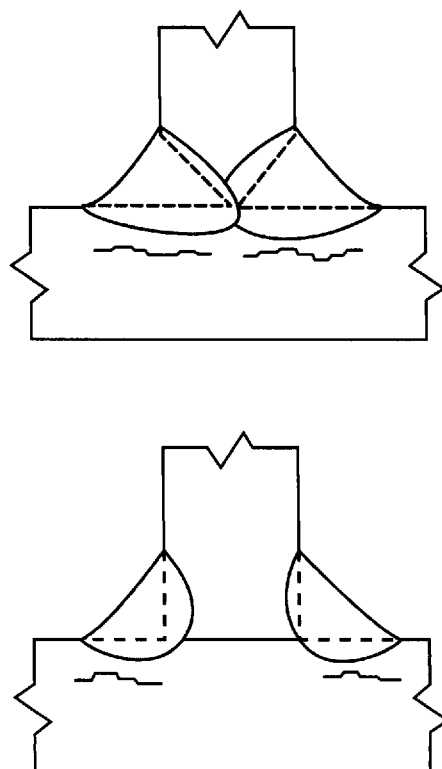


Figure 1.4—Steel Plate Weld Joint Design Prone to Lamellar Tearing and Likely Locations of Tears

10 CARBON AND LOW-ALLOY STEELS

steel. Various types of inclusions also increase the sensitivity of steel to lamellar tearing. Some manufacturers offer steel that is specially produced to reduce the sensitivity to this behavior. Following are some approaches to minimize lamellar tearing:

- (1) Change the location and design of the welded joint to minimize through-thickness strains. This includes selecting fillet welds in place of full-penetration T-joints.
- (2) Reduce the available hydrogen.
- (3) Butter the surface of the plate with weld metal prior to making the weld.
- (4) Use preheat and interpass temperatures of at least 200 °F (93 °C).
- (5) Peen the weld beads.
- (6) Use steel plates which are specially processed to achieve improved through-thickness properties (these are very low sulfur steels or steels with rare-earth additions to control the shape of manganese sulfide inclusions).
- (7) Substitute forgings or castings for the plates.

The most reliable methods for avoiding lamellar tearing are to utilize 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 ultrasonics, it is easy to detect subsurface lamellar tearing.

SOLIDIFICATION CRACKING

SOLIDIFICATION CRACKING IS a type of hot cracking that can occur in carbon and low-alloy steel welds when the solidifying weld metal cannot support thermally or mechanically induced strain during welding. These cracks are interdendritic or intergranular, and they are caused primarily by segregation of low-melting elements such as sulfur, phosphorus, carbon, nickel, niobium, and boron. High sulfur content is one of the most commonly reported causes of solidification cracking in steels. While solidification cracking can occur in almost any of the carbon and low-alloy steels, high-sulfur free-machining steels and some heat-treated low-alloy steels are particularly susceptible.

Manganese and silicon are elements that tend to reduce the solidification crack susceptibility of steel. Therefore, one precaution to reduce solidification cracking involves the use of filler metals with higher manganese or silicon contents.

Solidification cracks are often longitudinal cracks along the centerline of the weld bead. Crater cracks are perhaps the most common form of this type of cracking. However, solidification cracks also can occur in other orientations. Deep, narrow weld beads are more prone

to solidification cracking than other bead shapes, because the solidification pattern concentrates segregates along the centerline of the bead where shrinkage stresses are high. Root passes in narrow grooves are one example of this type of weld. Large weld pools, created by high-heat-input welding procedures, are more susceptible to solidification cracking than low-heat-input procedures.

REHEAT CRACKING

REHEAT CRACKING, ALSO called postweld heat-treatment cracking, strain-age cracking, stress-rupture cracking, and stress-relief cracking, can occur during postweld heat treatment or high-temperature service of some low-alloy and chromium-molybdenum steels. Reheat cracks are intergranular and usually occur in the coarse-grained region of the HAZ, although they sometimes occur in weld metal. Reheat cracking results from embrittlement of prior austenite grain boundaries caused by minor elements such as phosphorus, tin, antimony, and arsenic. Reheat cracking has been reported in some chromium-molybdenum-vanadium steels, in ASTM A508 Class 2 steel, in ASTM A514 and A517 steels, and in some precipitation-hardened ASTM A710 HSLA steels.

WELD BACKING

IN ORDER TO SHIELD the back side of a joint, support the weld metal, and provide the proper root contour, various methods of weld backing are used. Successful weld-backing methods include the use of flux, ceramic tape, ceramic blocks, steel, and copper bars. Copper has relatively high thermal conductivity, and some high-strength weld metals have a tendency to crack when they contact a cold backing bar; therefore, an alternative backing material should be used when welding high-strength materials. Copper also is not recommended for backing when a relatively high preheat temperature is required. Its rapid absorption of heat increases the likelihood that the weld metal will fuse to it. The use of steel backing shall conform to the requirements of the applicable code or specification.

SAFE PRACTICES

SAFE PRACTICES FOR welding, brazing, soldering, and cutting of carbon and low-alloy steels are contained in Chapter 16, "Safe Practices," *Welding Handbook*, 8th Ed., Vol. 1; as well as in the latest edition of ANSI/ASC Z49.1, *Safety in Welding, Cutting and Allied Processes*. Special care may be required when arc welding alloys that contain higher percentages of chromium and nickel, as these may have greater potential fume hazards. Proper controls also are required for protection against fumes from brazing filler metals and fluxes.

CARBON STEELS

DESCRIPTION

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 indicated in Table 1.2. The properties and weldability of these steels depend mainly on carbon content; other elements have only a limited effect.

Deoxidation practice and the steel-making process will have an effect upon the characteristics and properties of steel. Thus, carbon steel can be classified according to various deoxidation practices: *rimmed*, *capped*, *semikilled*, or *killed* steel. The great majority of steels produced today are continuously cast, and these steels are aluminum-killed.

AISI-SAE carbon steels are the 10XX, 11XX, 12XX, and 15XX groups. The 10XX group has a maximum of 1.0% manganese, while manganese in the 15XX group ranges from 1.00 to 1.65%. The 11XX resulfurized steels and the 12XX resulfurized and rephosphorized steels are used for improved machinability. Fusion welding is difficult with these materials, however, because of their solidification-cracking tendencies.

ASTM standards designate carbon steels on the basis of chemical or mechanical properties, or both, in conjunction with the product form and the intended

application. ASTM A830 covers AISI/SAE carbon steel plates, while ASTM A576 covers AISI/SAE carbon steel bars. Typical ASTM carbon steels used in construction, pressure vessels, and piping are listed in Table 1.3.

WELDABILITY CONSIDERATIONS

THE WELDABILITY OF a carbon steel is determined primarily by its sensitivity to hydrogen cracking; although solidification cracking susceptibility and deoxidization practice also can affect the weldability of some grades, as explained later in this chapter.

Carbon Content

SEVERAL POINTS STATED previously in the general considerations section bear repeating here. First, sensitivity to hydrogen cracking increases with increasing carbon equivalent, weld hydrogen content, and section thickness. Also, carbon is the alloying element with the greatest effect on hydrogen cracking sensitivity, and the effects of carbon and other elements on hydrogen cracking susceptibility can be estimated using the carbon equivalent formula. Finally, carbon steels exhibit increasing susceptibility to hydrogen cracking as the carbon content exceeds about 0.15%; steels with less than 0.15% carbon are not immune to this problem, however, especially when thick sections are welded.

Table 1.2
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 1.3
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	ksi	MPa	ksi	MPa
Structural Steels									
Welded buildings, bridges, and general structural purposes	A36	—	0.29	0.80-1.20	0.15-0.40	58-80	440-552	36	248
Welded buildings and general purposes	A529	—	0.27	1.20	—	60-85	414-586	42	290
General purpose sheet and strip	A570	30,33,36, 40,45,50	0.25	0.90	—	49-55	338-379	30	207
			0.25	1.35	—	60-65	414-448	45	310
General purpose plate (improved toughness)	A573	58	0.23	0.60-0.90	0.10-0.35	58-71	440-489	32	221
		65	0.26	0.85-1.20	0.15-0.40	65-77	448-531	35	241
		70	0.28	0.85-1.20	0.15-0.40	70-90	483-621	42	290
Pressure Vessel Steels									
Plate, low and intermediate tensile strength	A285	A	0.17	0.90	—	45-65	310-448	24	165
		B	0.22	0.90	—	50-70	345-483	27	186
		C	0.28	0.90	—	55-75	379-517	30	207
Plate, manganese-silicon	A299	—	0.30	0.90-1.40	0.15-0.40	75-95	517-655	40	276
Plate, low-temperature applications	A442	55	0.24	0.60-0.90	0.15-0.40	55-75	379-517	30	207
		60	0.27	0.60-0.90	0.15-0.40	60-80	414-552	32	221
Plate, intermediate and high-temperature service	A515	55	0.28	0.90	0.15-0.40	55-75	379-517	30	207
		60	0.31	0.90	0.15-0.40	60-80	414-552	32	221
		65	0.33	0.90	0.15-0.40	65-85	448-586	35	241
		70	0.35	1.20	0.15-0.40	70-90	483-621	38	262
Plate, moderate and low-temperature service	A516	55	0.26	0.60-1.20	0.15-0.40	55-75	379-517	30	207
		60	0.27	0.85-1.20	0.15-0.40	60-80	414-552	32	221
		65	0.29	0.85-1.20	0.15-0.40	65-85	448-586	35	241
		70	0.31	0.85-1.20	0.15-0.40	70-90	483-621	38	262
Plate, carbon-manganese-silicon heat-treated	A537	1 ^b	0.24	0.70-1.60	0.15-0.50	65-90	448-621	45	310
		2 ^c	0.24	0.70-1.60	0.15-0.50	75-100	517-689	55	379
Piping and Tubing									
Welded and seamless pipe, black and galvanized	A53	A	0.25	0.95-1.20	—	48 min.	331	30	207
		B	0.30	0.95-1.20	—	60 min.	414	35	241
Seamless pipe for high-temperature service	A106	A	0.25	0.27-0.93	0.10 min.	48 min.	331	30	207
		B	0.30	0.29-1.06	0.10 min.	60 min.	414	35	241
		C	0.35	0.29-1.06	0.10 min.	70 min.	483	40	276
Structural tubing	A501	—	0.26	—	—	58 min.	400	36	248

a. Single values are maximum unless otherwise noted.

b. Normalized condition.

c. Quenched and tempered condition.

d. Normalized and tempered condition.

Table 1.3 (continued)
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	ksi	MPa	ksi	MPa
General use	A27	60-30	0.30	<u>Cast Steels</u> 0.60	0.80	60 min.	414	30	207
Valves and fittings for high-temperature service	A216	WCA	0.25	0.70	0.60	60-85	207-586	30	207
		WCB	0.30	1.00	0.60	70-95	483-655	36	248
		WCC	0.25	1.20	0.60	70-95	483-655	40	276
Valves and fittings for low-temperature service	A352	LCA ^{c,d}	0.25	0.70	0.60	60-85	414-586	30	207
		LCB ^{c,d}	0.30	1.00	0.60	65-90	448-621	35	241
		LCC ^{c,d}	0.25	1.20	0.60	70-95	483-655	40	276

a. Single values are maximum unless otherwise noted.

b. Normalized condition.

c. Quenched and tempered condition.

d. Normalized and tempered condition

Weld Cooling Rates

WHEN ARC WELDING thick sections, the weld metal and HAZ can be hardened significantly as a result of quenching 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 section thickness and joint geometry, the base-metal temperature before welding commences, and heat input. Consequently, the use of higher welding current, slower welding speed (high heat input), or preheating of the base metal will reduce the cooling rate of the weld zone. Preheat should be maintained during the welding of successive beads.

With higher carbon content or increased section 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.⁸ 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.

Nonmetallic Inclusions

NORMAL SULFUR AND phosphorus contents in carbon steels do not promote weld solidification cracking. However, when large amounts of these elements are added, as in the case of 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 weld metal porosity.

Lead 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. Lead may, on occasion, cause porosity and embrittlement of steel. Another concern with lead is its presence in the welding fumes and its toxicity. This requires special precautions to assure good ventilation during welding.

Normally, free-machining steels should not be welded. If one of these steels must be welded, low-hydrogen electrodes and low welding currents should be used to limit dilution, porosity, and cracking.

8. For a comprehensive preheating guide for steels, see Ott, C. W. and Snyder, D. J. "Suggested arc-welding procedures for steels meeting standard specifications." Bulletin 191 (Revised). New York: Welding Research Council, March 1978.

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 they are easily joined by welding, brazing, or soldering.

According to Figure 1.1, a carbon steel containing 0.15% carbon is capable of being hardened to 30 to 40 HRC when cooled at a very high rate. However, this would require a welding process with a high energy density. For most welding processes, the cooling rate is too low for a weld heat-affected zone 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 (as with the resistance spot welding process, for example), the carbon content of the steel should be low. More than 0.08% carbon is sufficient to develop substantial hardness for resistance spot welds in thin steel sheet. Spot weld hardness is not a serious problem with these steels, except for some critical applications.

The deoxidation practice used in steel-making 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 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 molten weld pool. Weld-metal porosity in these steels can be minimized by adding a filler metal containing sufficient deoxidizers (e.g., aluminum, manganese, or silicon) to scavenge oxygen from the molten 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.⁹ The covering on shielded metal arc welding electrodes usually contains sufficient deoxidizers for welding rimmed or capped steels. Special aluminum 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 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.¹⁰ 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. Such steels can be welded without preheat, postheat, or special welding procedures when the joint thickness is less than 1 in. (25.4 mm) and when joint restraint is not severe.

As the carbon and manganese contents increase to about 0.30 and 1.40%, respectively, weldability of the steels remains good; however, the welds are susceptible to hydrogen cracking because of increased hardenability and strength. Welding with a low-hydrogen process is recommended. Preheating and control of interpass temperature may be required as well, particularly when the joint thickness is greater than 1 in. (25.4 mm) or when 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.

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 65 to 100 ksi (448 to 689 MPa) depending upon the carbon and manganese content and the heat treatment.

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

Normal 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 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 low welding-heat input. In fact, allowing the HAZ to cool rapidly may be preferable. Higher welding heat input or higher preheat and interpass temperatures, 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

9. Refer to ANSI/AWS A5.18, *Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding*, for additional information.

10. Refer to ANSI/AWS A5.17, *Specification For Carbon Steel Electrodes And Fluxes For Submerged Arc Welding*, for additional information.

cooling (e.g., electroslog welding), then the weldment may require postweld heat treatment (e.g., normalizing or tempering) to restore good strength and toughness to the HAZ. When heat treatment of the weldment is uneconomical or impractical, 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 are arc welded without preheat. However, a preheat should be used when the metal temperature is below about 50 °F (10 °C), and a preheat of about 100 °F (38 °C) or higher should be used if the plate thickness is over 1 in. (25.4 mm) or if the joint is highly restrained.

Dilution must be considered when selecting a filler metal to provide specified joint mechanical properties in a selected steel. Weld-metal mechanical properties specified in AWS A5 standards are for undiluted weld metal. 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 heat-affected zone.

In a butt joint, the filler metal should be selected to 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. 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 steel takes place when the carbon content is in the 0.30 to 0.50% range. Steels containing about 0.30% carbon and a relatively low percentage of manganese have good weldability. As the carbon content of the steel is increased, the welding procedures must be designed to avoid formation of large amounts of hard martensite in the 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.

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 upon the carbon equivalent of the steel, the joint thicknesses, and the welding procedure. In general, preheat temperature requirements increase with higher carbon equivalent (CE), 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 200 to 400 °F (93 to 204 °C) range is recommended, depending upon the welding process and the joint thickness. The interpass temperature should be the same as the preheat temperature.

A stress-relief heat treatment is recommended immediately after welding — especially with thick sections, high joint restraint, or service conditions involving impact or dynamic loading.¹¹ If possible, the welded joint should be heated to stress-relief temperature without intermediate cooling to ambient temperature. This may be accomplished by transferring the weldment to a preheated furnace. Slow cooling to room temperature following stress-relief is recommended to avoid introduction of thermal stresses.

When immediate stress relief is impractical, the welded joint should be maintained at or slightly above the specified preheat temperature for 2 to 3 h/in. (5 to 7 min/mm) 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.

Low-hydrogen welding procedures are mandatory with these steels. 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 weld metal hardness, 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, low heat input generally is recommended for the first few layers in a multiple-pass weld. 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 HAZs of previously deposited weld beads, especially those in the base metal. However, postweld heat treatment is still a requirement with this technique.

Medium-carbon steels are used extensively in machinery and tools. Often these steels are selected for

11. For recommended preheat and stress-relief heat treatment temperatures for specific steels, refer to Ott, C. W. and Snyder, D. J. "Suggested arc-welding procedures for steels meeting standard specifications." Bulletin 191 (Revised). New York: Welding Research Council, March 1978.

16 CARBON AND LOW-ALLOY STEELS

their wear resistance rather than high strength, and parts frequently must be heat treated to meet in-service strength requirements. Welding may be performed before or after final heat treatment; however, 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 properties and base-metal properties after heat treatment. If welding is required on a previously heat-treated component, precautions are necessary to avoid cracking. A hard component may crack during welding if a suitable preheat is not used. The welding heat will soften the HAZ, and reheat treatment of the weldment may be required to restore desired properties in the HAZ.

HIGH-CARBON STEEL

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

Selection of an appropriate filler metal depends upon 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-based filler metals such as E309, E312, or ENiCrFe-3 also may be used. Effects of dilution on the response of the weld metal 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 repair welding of broken parts. Successful welding requires 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

Shielded Metal Arc Welding

MOST CARBON STEELS can be welded with covered electrodes provided that appropriate welding procedures (including preheat, when required) are used. Covered electrodes are classified according to the type of covering as well as the chemical composition and mechanical properties of undiluted weld metal. Carbon-steel covered electrodes that produce weld metal with 60 or 70 ksi (414 or 482 MPa) minimum tensile strength are classified as E60XX and E70XX, respectively.¹²

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 produced with low-hydrogen coverings, and they should not be used for welding steels that are sensitive to hydrogen cracking.

E70XX covered electrodes are produced with both regular and low-hydrogen coverings. They should be used where 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 E120XX-X, are designed to produce weld metals with minimum tensile strengths of 70 to 120 ksi (482 to 827 MPa).¹³ These electrodes are also produced with both regular and low-hydrogen coatings. The carbon content of the deposited weld metal will be 0.15% or less, depending upon the electrode type. Low-hydrogen electrodes can be selected from this group to match the tensile strength of a medium 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

CARBON AND LOW-ALLOY steel bare electrodes and welding rods are available for use with the gas

12. Refer to ANSI AWS A5.1, *Specification for Carbon Steel Electrodes for Shielded Metal Arc Welding*.

13. Refer to ANSI/AWS A5.5, *Specification for Low Alloy Steel Covered Arc Welding Electrodes*.

metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) processes.¹⁴ The electrodes are classified on the basis of chemical composition and mechanical properties of undiluted weld metal. Minimum tensile strengths range from 70 to 120 ksi (483 to 827 MPa). Selection of a bare electrode is made using the same considerations as for a covered electrode.

Shielding gases commonly used for GMAW of carbon steels are carbon dioxide (CO₂), argon with carbon dioxide, and argon with oxygen¹⁵. Selection of a gas mixture depends primarily upon the electrode composition and the type of metal transfer desired (i.e., spray, globular, or short-circuiting). Generally, carbon dioxide shielding is suitable for low-carbon and mild steels. A mixture of argon-oxygen or argon-CO₂ is suitable for all carbon steels and is recommended 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 speed with automatic welding.

The low-hydrogen characteristics of gas-shielded arc welding processes will be lacking if the filler metal or shielding gas are 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 shielding gases from being contaminated 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 earlier for SMAW electrodes are identified by the same designators, whether they are solid or tubular metal cored. The designator is applied based upon testing in the shielding gas with which the electrode is classified.

Flux Cored Arc Welding

FLUX CORED ARC welding electrodes consist of a steel tube surrounding a core of fluxing ingredients and sometimes alloying additions. They are designed to deposit either carbon-steel or low-alloy-steel weld

metal.¹⁶ Some electrode classifications are self-shielding, while other classifications use CO₂ or argon-CO₂ mixtures for shielding.

Flux cored electrodes meeting the same diffusible hydrogen limits indicated earlier for SMAW electrodes are identified by the same hydrogen designators. Electrodes that meet the lowest hydrogen limits are not available for all classifications. Electrode manufacturers need to be contacted to determine specific availability. It should be noted that flux cored electrodes can absorb moisture when exposed to high humidity for prolonged time periods. This absorbed moisture can increase the hydrogen entering the weld metal, resulting in higher diffusible hydrogen or even porosity. To prevent this, it is advisable to return unused wire to protective packaging if the wire will remain unused overnight or longer. If wire is exposed for longer periods of time, the manufacturer should be consulted regarding probable damage to low-hydrogen characteristics and possible reconditioning procedures.¹⁷

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

Carbon-steel FCAW electrodes are designed to produce undiluted weld metal with a minimum tensile strength of 60 or 70 ksi (414 or 483 MPa). These are suitable for welding low-carbon and mild steels. Medium- 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 70 ksi (483 MPa), a suitable low-alloy-steel FCAW electrode should be used. Electrodes are available that can deposit undiluted weld metal with tensile strengths ranging from 60 to 120 ksi (414 to 827 MPa).

Submerged Arc Welding

SUBMERGED ARC WELDING 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. Carbon-steel and low-alloy-steel solid-wire electrodes are classified according to

14. Refer to ANSI/AWS A5.18, *Specification for Carbon Steel Filler Metals for Gas Shielded Arc Welding*, or ANSI/AWS A5.28, *Specification for Low Alloy Steel Filler Metals for Gas Shielded Arc Welding*.

15. Refer to ANSI/AWS C5.10, *Recommended Practices for Shielding Gases for Welding and Plasma Arc Cutting*.

16. The electrode specifications are in ANSI/AWS A5.20, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*, and ANSI/AWS A5.29, *Specification for Low Alloy Steel Electrodes for Flux Cored Arc Welding*.

17. Refer to ANSI/AWS A5.20, *Specification for Carbon Steel Electrodes for Flux Cored Arc Welding*.

chemical composition. The classification of metal-cored low-alloy-steel electrodes is based on the chemical composition of deposited weld metal using an appropriate flux.¹⁸ Likewise, fluxes are classified 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, weld metal mechanical properties 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 60 or 70 ksi (414 or 483 MPa). These combinations are recommended for welding low-carbon and mild steels as well as medium-carbon, high-carbon, and low-alloy steels when high strength is not required in the weld joint. Low-alloy-steel electrode and flux combinations 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 previously, flux must be kept clean and dry to maintain low-hydrogen welding conditions, and it must be of a sufficient depth to provide adequate shielding. Also, the electrode must be clean and free of contaminants, as discussed previously for the gas shielded arc welding processes.

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

Electroslag and Electrogas Welding

ELECTROSLAG WELDING AND electrogas welding are used primarily for producing single-pass groove welds in the vertical position. Electroslag welding uses a resistance-heated, molten slag pool to melt the electrode. This process generally is used for welding steel plates of 1.25 to 12 in. (32 to 305 mm) in thickness. Electrogas welding is a variation of gas metal arc welding (GMAW) or flux cored arc welding (FCAW), depending upon the type of electrode. This process is best suited for welding plates over 0.5 in. (13 mm) in thickness.

These processes are used mostly to weld low-carbon and mild steels, but medium-carbon steels may be welded also. Generally, when the weldment requires postweld heat treatment, an electrode composition is selected which will produce weld metal that responds satisfactorily to heat treatment. Dilution by the base metal must be considered during selection.

Electrodes and fluxes for electroslag welding (ESW) are classified in a manner similar to that for submerged arc welding.¹⁹ Both solid and metal-cored ESW electrodes can produce weld metal with a minimum tensile strength of 60 ksi (414 MPa) or higher, depending upon 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.²⁰ Welding may be accomplished using either CO₂, argon mixed with CO₂, or argon mixed with oxygen. One of the carbon-steel flux-cored electrode classifications 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, 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. On the other hand, the cooling rate in the weld zone will be comparatively slow.

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

Carbon steels containing more than 0.35% carbon require special precautions with oxyacetylene welding. Preheating with a torch or another heat source is recommended to retard the cooling rate of the weld and heat-affected zone. In some cases, postweld heat

18. Refer to ANSI/AWS A5.17, *Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding*, and ANSI/AWS A5.23, *Specification for Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding*.

19. Refer to ANSI/AWS A5.25, *Specification for Carbon and Low Alloy Steel Electrodes and Fluxes for Electroslag Welding*.

20. Refer to ANSI/AWS A5.26, *Specification for Carbon and Low Alloy Steel Electrodes for Electrogas Welding*.

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 and low-alloy steels.²¹ They are classified on the basis of the minimum tensile strength of as-deposited weld metal. Type R45 welding rods are recommended to deposit low-carbon-steel weld metal for general applications. Type R60 welding rods should be used for steels having tensile strengths in the range of 50 to 65 ksi (345 to 448 MPa). Type R65 rods are best for welding either carbon or low-alloy steels with tensile strengths in the range of 65 to 75 ksi (345 to 517 MPa). Carbon and low-alloy steel welding rods designed for gas tungsten arc welding (GTAW) can also 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., spot, seam, projection, flash, upset, and high-frequency welding. 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 a steel must be considered when selecting the process and the welding procedures.

The weld and heat-affected zone (HAZ) are quenched by a water-cooled copper-alloy electrode bearing onto the workpieces. The quench severity depends upon the length of the heat conduction path, the size of the electrode contact area, and the duration of quenching. Quenching is more severe when spot, seam, or projection welding thin sheet; and when flash or upset welding with rod or wire that has a small cross-section. Retraction of the electrodes from the weldment as soon as practical will reduce the quenching rate. With some processes, such as seam 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, postheat or tempering in the welding machine may reduce the hardness to an acceptable level. In some cases, heat treatment of the weldment in other equipment may be appropriate.

Low-Carbon Steel. Low-carbon steel is readily joined by all resistance welding processes because it has low hardenability. Welds normally have adequate ductility for the application. Spot and seam welds in thin sheet can have relatively high hardness when the carbon content exceeds about 0.08%. If this is objectionable,

then sheet with a nominal carbon content of 0.08% or less should be specified.

Suggested schedules for spot, seam, and projection welding low-carbon steel sheet are given in Tables 1.4 through 1.7.²² Variation from these conditions will be necessary to account 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 flash welding of carbon steel shapes are given in the chapter covering the process.²³ Recommended procedures for high-frequency and upset welding should be obtained from the equipment manufacturer.

Mild and Medium-Carbon Steels. When resistance welding these steels, control of the cooling rate from welding temperature or from a subsequent tempering cycle is usually necessary 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 1.8 gives examples of quench-and-temper cycles when spot welding AISI 1020, 1035, and 1045 carbon-steel sheet. As expected, the shear strength of the spot welds increases as the carbon content of the steel increases.

Normally, mild and medium-carbon steels can be flash welded without cracking. Preheat or postheat is not required, but application of one or both can improve weld joint ductility. When flash welding small or thin cross sections, postheat 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 metallurgical structure 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 their high hardenability, and because there is a limited use for products where these processes are applicable. The procedures given for welding mild and medium-carbon steels are applicable also to high-carbon steels, with appropriate adjustments to accommodate the higher hardenability.

21. Refer to ANSI/AWS A5.2, *Specification for Carbon and Low Alloy Steel Rods for Oxyfuel Gas Welding*.

22. Appropriate projection designs for steel are discussed in the *Welding Handbook*, Vol. 2, 8th Ed., 561-2.

23. Refer to the *Welding Handbook*, Vol. 2, 8th Ed., 582-97.

Table 1.4
Suggested Schedules for Spot Welding Low-Carbon Steel Sheet

Thickness ^a		Electrode Face Diam. ^b		Static Electrode Force		Weld Time, Cycles ^c	Approx. Welding Current kA ^d	Approximate Nugget Diameter		Minimum Pitch ^e		Minimum Shear Strength When Base Metal Tensile Strength is			
												Below 70 ksi (483 MPa)		Above 70 ksi (483 MPa)	
in.	mm	in.	mm	lb	N			in.	mm	in.	mm	lb	N	lb	N
0.010	0.25	0.13	3.30	200	890	4	4.0	0.10	2.54	0.25	6.4	130	578	180	801
0.021	0.53	0.19	4.82	300	1334	6	6.5	0.13	3.30	0.37	9.4	320	1423	440	1957
0.031	0.79	0.19	4.82	400	1779	8	8.0	0.16	4.06	0.50	12.7	570	2535	800	3559
0.040	1.02	0.25	6.35	500	2224	10	9.5	0.19	4.82	0.75	19.1	920	4092	1200	5338
0.050	1.27	0.25	6.35	650	2891	12	10.5	0.22	5.58	0.87	22.1	1350	6005	—	—
0.062	1.57	0.25	6.35	800	3559	14	12.0	0.25	6.35	1.00	25.4	1850	8229	—	—
0.078	1.98	0.31	7.87	1100	4893	17	14.0	0.29	7.36	1.25	31.8	2700	12 010	—	—
0.094	2.39	0.31	7.87	1300	5783	20	15.5	0.31	7.87	1.50	38.0	3450	15 346	—	—
0.109	2.77	0.38	9.65	1600	7117	23	17.5	0.32	8.12	1.62	41.2	4150	18 460	—	—
0.125	3.18	0.38	9.65	1800	8007	26	19.0	0.33	8.38	1.75	44.5	5000	22 241	—	—

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 1.5
Suggested Schedules for Multiple-Impulse Spot Welding 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	
						Single Spot	Multiple Spot Spacing						
							in.	mm		in.	mm	lb	N
0.125	3.18	0.44	11.18	1800	8007	3	5	4	18.0	0.37	9.4	5000	22 241
0.188	4.76	0.50	12.70	1950	8674	6	20	14	19.5	0.56	14.2	10 000	44 482
0.25	6.35	0.56	14.22	2150	9564	12	24	18	21.5	0.75	19.1	15 000	66 723
0.31	7.87	0.62	15.74	2400	10 675	15	30	23	24.0	0.87	22.1	20 000	88 964

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.

Table 1.6
Suggested Schedules for Seam Welding 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
in.	mm	in.	mm	lb	N			in./min	mm/s	in.	mm	
0.010	0.25	0.19	4.82	400	1779	2	1	80	33.8	15	381	8.0
0.021	0.53	0.19	4.82	550	2447	2	2	75	31.7	12	305	11.0
0.031	0.79	0.25	6.35	700	3114	3	2	72	30.0	10	254	13.0
0.040	1.02	0.25	6.35	900	4003	3	3	67	28.6	9	228	15.0
0.050	1.27	0.31	7.87	1050	4671	4	3	65	27.5	8	203	16.5
0.062	1.57	0.31	7.87	1200	5338	4	4	63	26.7	7	177	17.5
0.078	1.98	0.38	9.65	1500	6672	6	5	55	23.3	6	152	19.0
0.094	2.39	0.44	11.18	1700	7562	7	6	50	21.2	5.5	139.7	20.0
0.109	2.77	0.50	12.7	1950	8674	9	6	48	20.3	5	127	21.0
0.125	3.18	0.50	12.7	2200	9786	11	7	45	19.1	4.5	114.3	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.

Electron and Laser Beam Welding

LOW-CARBON STEELS ARE readily welded by electron and laser beam welding. The rapid heating and cooling rates associated with these processes result in weld and heat-affected zones (HAZ) that have relatively small grain size compared to those in arc welds. Also, the HAZ is much narrower. Fully killed steel is preferred for applications involving these welding processes.

Friction Welding

LOW-CARBON STEELS ARE joined readily by friction welding. 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

Processes and Equipment

CARBON STEELS CAN be joined by virtually all of the brazing processes. Torch, furnace, and induction heating methods are used commonly. 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, then automatically applied with pressurized dispensing equipment. For torch brazing, the equipment would include a standard oxyfuel torch. Brazing furnaces can be either batch or conveyor type, with or without control of the atmosphere.

Filler Metals

CARBON STEELS CAN be brazed with copper, gold, nickel, and silver filler metals.²⁴ All silver brazing filler metals (BAg) are suitable with carbon steel. Those containing nickel usually have better wettability and are preferred for good joint strength.

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

24. Refer to ANSI/AWS A5.8, *Specification for Filler Metals for Brazing and Braze Welding*, and ANSI/AWS A5.31, *Specification for Fluxes for Brazing and Braze Welding*.

Table 1.7A
Suggested Schedules for Projection Welding Low-Carbon Steel Sheet
 (U.S. Customary Units)

Thickness, t in. _d	Projection		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.	Min. Pitch, in.	Min. Contact Overlap, 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% 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 1.7B
Suggested Schedules for Projection Welding Low-Carbon Steel Sheet
(Metric Units)

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

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 $f_t = 1.5 (T/t) - 0.5$.

(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
Typical Spot Welding Schedules for Medium-Carbon and Low -Alloy Steel Sheet

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

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

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

Fluxes and Atmospheres

A PROPER ATMOSPHERE or flux generally is required when brazing steels. Selection will depend upon the brazing filler metal. AWS brazing flux Type 3A, 3B, or 4 is suitable for BAg filler metals. Type 5 flux normally is used with the RBCuZn filler metals. Fluxes and atmospheres may be used together. Flux can be used in either paste or powder form, or it can be combined with the filler metal. In a face-fed operation, the hand-held filler metal can be coated with the appropriate flux. In atmosphere brazing, the filler metal is preplaced in or near the joint, and the assembly is charged into the brazing chamber. Brazing temperature and time must be controlled to ensure proper melting and flow of the filler metal into the joint.

Joint Clearance

JOINT CLEARANCES IN the range of 0.002 to 0.005 in. (0.05 to 0.127 mm) produce the best mechanical

properties with most filler metals when using a mineral flux. Light press fits are preferred for BCu and other filler metals when furnace brazing with a protective atmosphere. Filler metals with relatively narrow melting ranges are required for close-fitting joints. Conversely, filler metals with wide melting ranges have good bridging characteristics when wide clearances are involved. Furnace dew point can be used to control the fluidity of BCu filler metal when brazing joints with large gaps.

Metallurgical Considerations

THE MECHANICAL PROPERTIES of the heated area in cold-worked steel may be impaired as a result of annealing during brazing. With hot-rolled steel, brazing above the austenitizing temperature will alter the metal's mechanical properties. These changes in properties may result from decarburization of the steel in some furnace atmospheres, or a change in grain size, or both. Original grain size can be restored by subsequent heat treatment below the remelt temperature of the filler metal. Loss of carbon through decarburization usually is unimportant in low-carbon steels. In medium- and

high-carbon steels, however, decarburization may lower surface hardness substantially.

Brazing of high-carbon steel is best accomplished prior to or during the hardening operation, since brazing after hardening will soften the steel. The hardening temperature for carbon steels normally is in the range of 1400 to 1600 °F (760 to 871 °C). If brazing is performed prior to the hardening operation, the filler metal must melt well above the hardening temperature so that the brazed joints will have sufficient strength during that operation. Copper filler metal is used frequently for this purpose.

At times, the high temperature [2000 to 2100 °F (1093 to 1149 °C)] required for copper brazing adversely affects the metallurgical structure of the steel. In such cases, silver and copper-zinc filler metals with brazing temperatures in the range of 1700 to 1800 °F (927 to 982 °C) can be used.

When brazing and hardening operations are combined, a filler metal that solidifies above the austenitizing temperature of the steel generally is used. The brazement is cooled to below the filler metal solidus temperature, and then it is quenched to harden the steel. Particular attention must be given to the brazement design and the handling procedures, because the brazed joint strength will be very low at the austenitizing temperature. The brazement design should place the joint in compression rather than tension during quenching.

THERMAL CUTTING CARBON STEELS

CARBON STEELS ARE cut or gouged easily by oxy-fuel gas, air-carbon arc, plasma arc, and other thermal cutting processes. Low-carbon and mild steels are cut using standard procedures. With medium- and high-carbon steels, however, significant quench-hardening may occur in the heat-affected zone during cutting. Preheating, postheating, or both may be necessary for controlling the hardness of the cut edge to avoid cracking or heat checking.

Preheat temperatures similar to those recommended for welding with a low-hydrogen process are normally satisfactory for cutting. The temperature must be nearly uniform through the section when using oxyfuel gas cutting. If it is not, the oxidation reaction will proceed faster in the hotter zone, resulting in a rough cut surface.

The cut surface may be heat treated to relieve stresses, reduce hardness, or alter the metallurgical structure. Furnace heating or local torch heating may be suitable.

Air-carbon arc gouging may leave areas of carburized steel on the cut surface when improper cutting procedures are used. These high-carbon areas may result in excessive hardening of the steel during welding if they are not removed beforehand. When air-carbon arc gouging is performed manually, it is good practice to grind to clean metal afterward in order to remove any carburized areas on the surface. This procedure normally is not required with mechanized gouging.

HIGH-STRENGTH LOW-ALLOY STEELS

DESCRIPTION

FROM A METALLURGICAL standpoint, the group of steels known as *high-strength low-alloy (HSLA)* or *microalloyed steels* are simply low-alloy steels, despite the fact that they historically have been marketed to industry as high-end carbon steels. HSLA steels are formulated with small amounts of some alloying elements to provide higher strength, better toughness and weldability, and in some cases greater resistance to corrosion in specific environments, than ordinary carbon steels. One of the first HSLA steels was COR-TEN.²⁵ Introduced in the 1930s, COR-TEN has atmospheric corrosion resistance about five times superior to normal carbon steel. Modern HSLA steels are tailored to

possess specific properties. For instance, some HSLA steels used in pipelines and pressure vessels are resistant to H₂S degradation (i.e., hydrogen-induced stepwise cracking).

HSLA steels are used mainly in the as-rolled or normalized conditions. The rolling process is integral in the development of final mechanical properties; however, normalizing or quenching and tempering may improve toughness in thick sections or extend the strength range of some grades. Special rolling practices have been devised such as controlled rolling, sometimes performed with water cooling on the run-out table. The use of such practices is known as thermo-mechanical controlled processing (designated TMCP in American Petroleum Institute plate specifications).

HSLA steels are strengthened by a combination of ferrite grain refinement, precipitation hardening, and substructural strengthening. Substructural strengthening

25. Trademark of USX Corporation.

26 CARBON AND LOW-ALLOY STEELS

occurs as dislocation arrays and ferrite subgrains influence the steel's strength favorably. Because of these alternative strengthening mechanisms, HSLA steels do not rely on high-carbon products such as pearlite, martensite, or bainite for strength. The low-carbon content, in turn, contributes to the excellent weldability of most HSLA steels.

The principal strengthening additions in HSLA steel are niobium and vanadium, added singly or in combination, with maximum contents around 0.10%. For some applications, where thicker sections or higher strengths are involved, nickel or molybdenum may be used to complete the alloy formulation. Early steels often had nitrogen added in combination with vanadium; however, this practice has been eliminated in most steels due to detrimental effects of nitrogen on toughness, particularly in the heat-affected zone (HAZ). In fact, modern steels often include titanium in amounts of up to 0.025% in order to combine with residual nitrogen, thereby producing HAZ grain refinement and better toughness overall.

Early HSLA steels were made by ingot casting practices and were either fully killed or semi-killed. However, most steel today is cast continuously, which necessitates the use of fully killed steel. However, some mills, especially those in recently industrialized countries, still may be producing semi-killed ingot castings for low-strength applications.

Typical yield strengths of HSLA steels are in the range of 42 to 110 ksi (289 to 760 MPa). Tensile strengths are in the range of 60 to 120 ksi (414 to 830 MPa). Apart from higher strength and better toughness, HSLA steels often have strict control of impurities (e.g., sulfur, phosphorus, and oxygen) so as to enhance other properties such as formability, resistance to lamellar tearing, and notch toughness.

COMPOSITION AND PROPERTIES

MATERIAL SPECIFICATIONS FOR most HSLA steels that are used in the as-rolled or normalized condition are provided by the American Society for Testing and Materials (ASTM). Specifications for other HSLA steels appear in SAE Recommended Practice J410c and in MIL-S-24645A (HSLA-80/100). These steels are designed to provide improved strength, corrosion resistance, or notch toughness versus mild steels while retaining good weldability. Niobium, copper, molybdenum, nickel, titanium, and vanadium are used in various combinations.

Table 1.9 lists a number of ASTM specifications covering structural-quality HSLA steels together with their alloying elements and tensile strength ranges. Table 1.10 lists several ASTM HSLA steels for pressure-vessel applications. Tubing and castings with similar mechanical

properties and chemical compositions are covered by other ASTM specifications.

Table 1.11 presents material specifications for HSLA linepipe, provided by the American Petroleum Institute (API). Other API specifications cover plate used in the fabrication of offshore structures. Representative chemical compositions of modern linepipe and plate produced to API specifications are shown in Table 1.12.

HSLA steels are used in pipelines, buildings, bridges, offshore structures, construction equipment and machinery, railroad equipment, automobile and truck frames, and ships. ASTM, API, SAE, and MIL specifications cover chemical compositions and additional testing and procedures relevant to each application. Supplementary testing may be ordered by a user for special or critical applications. For example, notch toughness testing may be conducted on components to be used in low-temperature service. Also, weldability prequalification (API RP2Z) is used to verify HAZ properties in heavy plate intended for critical components in offshore structures.

As-rolled HSLA steels may have poor or variable notch toughness unless proper processing is used. During rolling, the finishing temperature and the amount of deformation is strictly controlled (i.e., *controlled rolling*) to achieve the necessary grain refinement. Additional strength may be obtained by using water to accelerate the cooling of plate (thermo-mechanical controlled processing). Aside from processing, however, enhanced notch toughness requires additional measures such as lower carbon and sulfur contents. Typical carbon contents for linepipe, as an example, have dropped well below API allowable limits in recent years (see Figures 1.5 and 1.6).

WELDING HSLA STEELS

Preheat

PREHEAT REQUIREMENTS, if any, depend upon the type of HSLA steel and its thickness as well as the filler metal and welding process to be used. The *Structural Welding Code—Steel* (ANSI/AWS D1.1) requires preheat for some mild steels and HSLA steels depending on their thickness, their carbon equivalent, and the welding process used. Successful welding of HSLA steels requires both consideration of preheat and careful control of hydrogen in the welding process. Preheat is beneficial in controlling the cooling rate of the weld, which reduces or avoids martensite transformation in the heat-affected zone (HAZ). This in turn controls the hardness of the HAZ. Preheat also tends to reduce welding stresses and help in the evolution of hydrogen from the weld.

Table 1.9
ASTM Specifications for High-Strength Low-Alloy Structural Steels

ASTM Speci- fication	Type or Grade	Composition, % ^a										Minimum Tensile Strength		Minimum Yield Strength	
		C	Mn	P	S	Si	Cr	Ni	Mo	V	Other	ksi	MPa	ksi	MPa
A242	1	0.15	1.00	0.15	0.05	—	—	—	—	—	0.20 min Cu	63-70	434-482	42-50	289-344
A441	—	0.22	0.85-1.25	0.04	0.05	0.30	—	—	—	—	0.20 min Cu, 0.02 min V	60-70	413-482	40-50	275-344
A572	42 ^b	0.21	1.35	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	60	413	42	289
	50 ^b	0.23	1.35	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	65	448	50	344
	60 ^b	0.26	1.35	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	75	517	60	413
	65 ^b	0.26	1.65	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	80	551	65	448
A588	A	0.10- 0.19	0.90-1.25	0.04	0.05	0.15-0.30	0.40-0.65	—	—	0.02-0.10	0.25-0.40 Cu	63-70	434-482	42-50	289-344
	B	0.20	0.75-1.25	0.04	0.05	0.15-0.30	0.40-0.70	0.25-0.50	—	0.01-0.10	0.20-0.40 Cu	—	—	—	—
	C	0.15	0.80-1.35	0.04	0.05	0.15-0.30	0.30-0.50	0.25-0.50	—	0.01-0.10	0.20-0.50 Cu	—	—	—	—
	D	0.10- 0.20	0.75-1.25	0.04	0.05	0.50-0.90	0.50-0.90	—	—	—	0.30 Cu, 0.05-0.15 Zr, 0.04Nb	—	—	—	—
	E	0.15	1.20	0.04	0.05	0.15-0.30	—	0.75-1.25	0.10- 0.25	0.05	0.50-0.80 Cu	—	—	—	—
	F	0.10- 0.20	0.50-1.00	0.04	0.05	0.30	0.30	0.40-1.10	0.10- 0.20	0.01-0.10	0.30-1.00 Cu	—	—	—	—
	G	0.20	1.20	0.04	0.05	0.25-0.70	0.50-1.00	0.80	0.10	—	0.30-0.50 Cu; 0.07 Ti	—	—	—	—
	H	0.20	1.25	0.035	0.040	0.25-0.75	0.10-0.25	0.30-0.60	0.15	0.02-0.10	0.20-0.35 Cu; 0.005-0.030 Ti	—	—	—	—
A633	J	0.20	0.60-1.00	0.04	0.05	0.30-0.50	—	0.50-0.70	—	—	0.30 min Cu; 0.03-0.05 Ti	—	—	—	—
	A	0.18	1.00-1.35	0.04	0.05	0.15-0.50	—	—	—	—	0.05 Nb	63-83	434-572	42	289
	C	0.20	1.15-1.50	0.04	0.05	0.15-0.50	—	—	—	—	0.01-0.05 Nb	65-90	448-620	46-50	317-344
	D	0.20	0.70-1.60	0.04	0.05	0.15-0.50	0.25	0.25	0.08	—	0.35 Cu	65-90	448-620	46-50	317-344
A710	E	0.22	1.15-1.50	0.04	0.05	0.15-0.50	—	—	—	0.04-0.11	0.01-0.03 N	75-100	517-689	55-60	379-413
	A	0.07	0.40-0.70	0.025	0.025	0.35	0.60-0.90	0.70-1.00	0.15- 0.25	—	1.00-1.30 Cu; 0.02 min Nb	65-90	448-620	55-85	379-586
A710	B	0.06	0.40-0.65	0.025	0.025	0.20-0.35	—	1.20-1.50	—	—	1.00-1.30 Cu; 0.02 min Nb	88-90	606-620	75-85	517-586

a. Single values are maximum unless otherwise noted.

b. These grades may contain niobium, vanadium, or nitrogen.

Table 1.10
ASTM Specifications for High-Strength Low-Alloy Steels for Pressure-Vessel Plate

ASTM Specification	Type or Grade	Composition, %*										Minimum Tensile Strength		Minimum Yield Strength	
		C	Mn	P	S	Si	Cr	Ni	Mo	V	Other	ksi	MPa	ksi	MPa
A202	A	0.17	1.05-1.40	0.035	0.040	0.60-0.90	0.35-0.60	—	—	—	—	75-95	517-655	45	310
	B	0.25	1.05-1.40	0.035	0.040	0.60-0.90	0.35-0.60	—	—	—	—	85-110	586-758	47	324
A203	A	0.23	0.80	0.035	0.040	0.15-0.30	—	2.10-2.50	—	—	—	65-85	448-586	37	255
	B	0.25	0.80	0.035	0.040	0.15-0.30	—	2.10-2.50	—	—	—	70-90	482-620	40	275
	D	0.20	0.80	0.035	0.040	0.15-0.30	—	3.25-3.75	—	—	—	65-85	448-586	37	255
	E	0.23	0.80	0.035	0.040	0.15-0.30	—	3.25-3.75	—	—	—	70-90	482-620	40	275
A204	A	0.25	0.90	0.035	0.040	0.15-0.30	—	—	0.45-0.60	—	—	65-85	448-586	37	255
	B	0.27	0.90	0.035	0.040	0.15-0.30	—	—	0.45-0.60	—	—	70-90	482-620	40	275
	C	0.28	0.90	0.035	0.040	0.15-0.30	—	—	0.45-0.60	—	—	75-95	517-655	43	296
A225	C	0.25	1.60	0.035	0.040	0.15-0.40	—	0.40-0.70	—	0.13-0.18	—	105-135	723-930	70	482
	D	0.20	1.70	0.035	0.040	0.10-0.50	—	0.40-0.70	—	0.10-0.18	—	75-105	517-723	55-60	379-413
A302	A	0.25	0.95-1.30	0.035	0.040	0.15-0.30	—	—	0.45-0.60	—	—	75-95	517-655	45	310
	B	0.25	1.15-1.50	0.035	0.040	0.15-0.30	—	—	0.45-0.60	—	—	80-100	551-689	50	344
	C	0.25	1.15-1.50	0.035	0.040	0.15-0.30	—	0.40-0.70	0.45-0.60	—	—	80-100	551-689	50	344
	D	0.25	1.15-1.50	0.035	0.040	0.15-0.30	—	0.70-1.00	0.45-0.60	—	—	80-100	551-689	50	344
A353	—	0.13	0.90	0.035	0.040	0.15-0.30	—	8.50-9.50	—	—	—	100-120	689-827	75	517
A735	—	0.06	1.20-2.20	0.04	0.025	0.40	—	—	0.23-0.47	—	0.20-0.35 Cu;0.03-0.09 Nb	80-115	551-792	65-80	448-551
A736	—	0.07	0.40-0.70	0.025	0.025	0.35	0.60-0.90	0.70-1.00	0.15-0.25	—	1.00-1.30 Cu;0.02 min Nb	72-105	496-723	55-75	379-517
A737	B	0.20	1.15-1.50	0.035	0.030	0.15-0.50	—	—	—	—	0.05 Nb	70-90	482-620	50	344
	C	0.22	1.15-1.50	0.035	0.030	0.15-0.50	—	—	—	0.04-0.11	0.03 Nb	80-100	551-689	60	413

* Single values are maximum unless otherwise noted.

A recommended minimum preheat and interpass temperature for arc welding a particular HSLA structural steel should be based on that steel's specific carbon equivalent (CE) or composition parameter (P_{cm}), as well as the filler material. These values can be calculated easily from the chemistry data using the following formulas:

$$CE = C + \frac{(Mn + Si)}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (1.2)$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (1.3)$$

P_{cm} is a composition parameter. This formula was introduced to deal with evolving carbon steels being introduced in the early 1970s. It was shown that the conventional CE formula developed by IIW did not accurately predict the cracking tendencies of low-carbon, mechanically processed steels, especially those that were being utilized in the oil and gas industry for linepipe and structural plate. The susceptibility index

Table 1.11
Chemical Composition and Mechanical Property Requirements for API Linepipe

Grade and Class	Alloying Elements, % (limit)							Minimum Yield Strength		Ultimate Tensile Strength			
	C (max)	Mn (max)	P (max)	S (max)	Nb* (min)	V* (min)	Ti* (min)	ksi	MPa	Minimum		Maximum	
										ksi	MPa	ksi	MPa
X-56	0.26	1.35	0.04	0.05	0.005	0.005	0.005	56	386	71	489	—	—
X-60	0.26	1.35	0.04	0.05	0.005	0.005	0.005	60	413	75	517	—	—
X-65	0.26	1.40	0.04	0.05	0.005	0.005	0.005	65	448	77	530	—	—
X-70	0.23	1.60	0.04	0.05	—	—	—	70	482	82	565	—	—
X-80	0.18	1.80	0.030	0.018	—	—	—	80	551	90	620	120	827

* Either niobium, vanadium, or titanium, or a combination thereof, shall be used at the discretion of the manufacturer.

Table 1.12
Representative Chemical Compositions of API Plate and Pipe

Alloying Elements, %								
API Grade	C	Mn	Al	S	P	Nb	V	Condition
Pipe								
X-52	0.15	1.30	0.02	0.012	0.015	0.02	—	As-rolled
X-60	0.12	1.35	0.02	0.010	0.015	0.03	—	As-rolled
X-70	0.10	1.60	0.02	0.008	0.015	0.04	0.06	As-rolled
X-80	0.06	1.65	0.02	0.005	0.010	0.04	0.08	As-rolled
Plate								
2H	0.15	1.30	0.02	0.012	0.015	0.02	—	Normalized
2W	0.10	1.40	0.02	0.005	0.012	0.02	—	TMCP
2Y	0.10	1.45	0.02	0.005	0.015	0.02	—	Q&T

shown below was devised as a guideline to prevent cracking in the HAZ of structural steels, but it also has been adopted as a guide for welding pipeline steels.

$$\text{Susceptibility index} = 12 P_{cm} + \log_{10} H \quad (1.4)$$

where

H = diffusible hydrogen level, mL/100g of weld metal

P_{cm} = composition parameter

Tables 1.13 and 1.14 give the minimum preheat and interpass temperatures for various CE and P_{cm} values at three different levels of restraint. Actual minimum preheat and interpass temperatures may vary depending on the welding process and filler material selected. This information is detailed in *ANSI/AWS D1.1*, Appendix 11.

The preheat temperature must be high enough to prevent cracking from restraint of the joint, or the presence of hydrogen in varying amounts, or both. When welding two different HSLA steels, the higher of the two preheat temperatures should be used. The base metal on each side of the joint must be thoroughly preheated to temperature over a distance equal to the section thickness or 3 in. (76.2 mm), whichever is larger. Note that ASTM A-710, A-736 (wrought products), and A-707 (forged products) are nickel-copper-niobium steels that are quenched and aged. These HSLA steels normally are quite low in carbon and have relatively high strength. The lower carbon content will reduce the calculated CE and P_{cm} values; therefore, the material will have lower preheat and interpass temperatures. Care should be exercised, because the weld metal for these specific HSLA steels may be stronger and subject to hydrogen cracking problems.

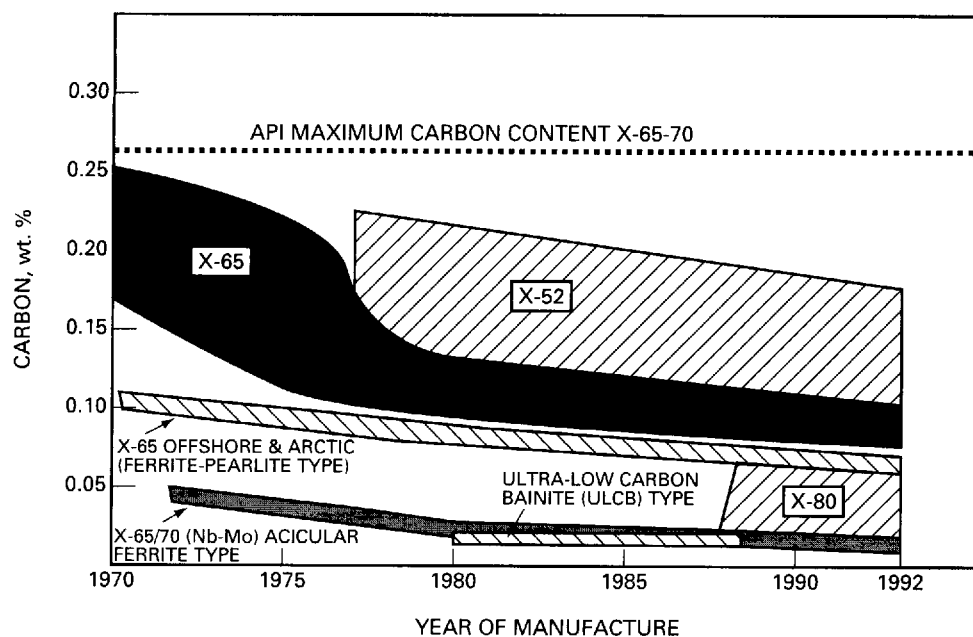
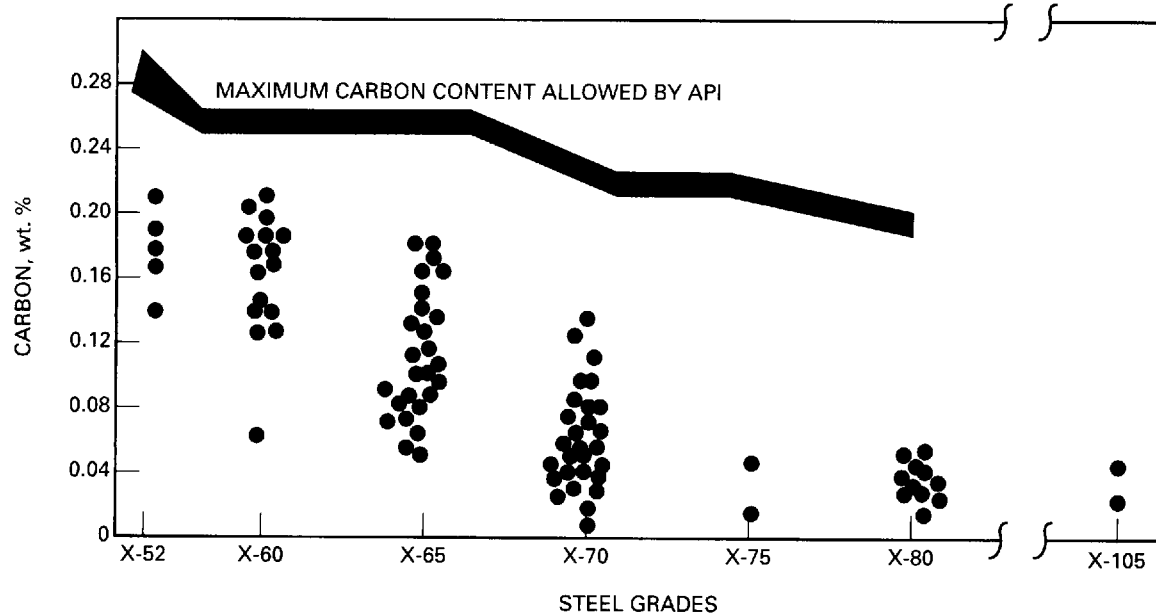


Figure 1.5—Trend Toward Reduced Carbon Content by Year of Manufacture



Note: Data compiled for 89 different steels produced by 25 manufacturers.

Figure 1.6—Trend Toward Reduced Carbon Content with Increasing Strength of Linepipe

Table 1.13
Minimum Preheat and Interpass Temperature for Three Levels of Restraint

Restraint Level	Thickness ^b		Minimum Preheat and Interpass Temperature													
			Susceptibility Index Grouping ^a													
	in.	mm	A		B		C		D		E		F		G	
			°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
Low ^c	<0.38	<9.5	<65	<18	<65	<18	<65	<18	<65	<18	140	60	280	138	300	149
	0.38-0.75	9.5-19.1	<65	<18	<65	<18	65	18	140	60	210	99	280	138	300	149
	0.75-1.50	19.1-38.1	<65	<18	<65	<18	65	18	175	80	230	110	280	138	300	149
	1.50-3.0	38.1-76	65	18	65	18	100	38	200	93	250	121	280	138	300	149
	>3.0	>76	65	18	65	18	100	38	200	93	250	121	280	138	300	149
Medium ^d	<0.38	<9.5	<65	<18	<65	<18	<65	<18	<65	<18	160	71	280	138	320	160
	0.38-0.75	9.5-19.1	<65	<18	<65	<18	65	18	175	80	240	116	290	143	320	160
	0.75-1.50	19.1-38.1	<65	<18	65	18	165	74	230	110	280	138	300	149	320	160
	1.50-3.0	38.1-76	65	18	175	80	230	110	265	130	300	149	300	149	320	160
	>3.0	>76	200	93	250	121	280	138	300	149	320	160	320	160	320	160
High ^e	<0.38	<9.5	<65	<18	<65	<18	<65	<18	100	38	230	110	300	149	320	160
	0.38-0.75	9.5-19.1	<65	<18	65	18	150	66	220	104	280	138	320	160	320	160
	0.75-1.50	19.1-38.1	65	18	185	85	240	116	280	138	300	149	320	160	320	160
	1.50-3.0	38.1-76	240	116	265	130	300	149	300	149	320	160	320	160	320	160
	>3.0	>76	240	116	265	130	300	149	300	149	320	160	320	160	320	160

a. Susceptibility index values for groupings: A, 3.0; B, 3.1-3.5; C, 3.6-4.0; D, 4.1-4.5; E, 4.6-5.0; F, 5.1-5.5; G, 5.6-7.0.

b. Thickness is that of the thicker part welded.

c. Low restraint describes welded joints in members with reasonable freedom of movement.

d. Medium restraint describes welded joints with reduced freedom of movement (for example, those attached to other structures).

e. High restraint describes welded joints where there is almost no freedom of movement (for example, with thick material or repair welds).

Table 1.14
Susceptibility Index Grouping as a Function of Hydrogen Level and Composition Parameter, P_{cm}

Diffusible Hydrogen, mL/100g of Deposited Metal	Susceptibility Index Grouping*				
	Carbon Equivalent, P_{cm}				
	<0.18	<0.23	<0.28	<0.33	<0.38
5	A	B	C	D	E
10	B	C	D	E	F
30	C	D	E	F	G

* For susceptibility index groupings, see Table 1.13, footnote a.

Welding Processes

HIGH-STRENGTH LOW-ALLOY steels can be welded by all of the commonly used arc welding processes. Shielded metal arc, gas metal arc, flux cored arc, and submerged arc welding are used for most applications. Low-hydrogen practices should be employed with all processes when carbon equivalents or P_{cm} values indicate a susceptibility towards cracking.

High-heat-input welding processes such as electroslag, electrogas, and multiple-wire submerged arc can be used to weld these steels. However, the advantage of their use warrants careful evaluation where notch toughness in the weld metal and HAZ is a requirement.

The HSLA steels also can be joined by resistance spot, seam, projection, upset, or flash welding. When using spot, seam, or projection welding, these steels can be welded with current and time settings similar to those used with low-carbon steel. Higher electrode force may be needed, however, because of the higher strength of the steel. Higher upsetting force may be required with flash or upset welding for the same reason, but the other welding variables should be similar to those used for low-carbon steel. Preheat or postheat cycles may be helpful during resistance welding of some HSLA steels to avoid excessive hardening of the weld and HAZ.

In general, the welding processes used to join HSLA steels should be selected with consideration for the following:

- (1) Strength requirements of weld metal
- (2) Weld metal behavior during multipass welding (i.e., tempering effect of each pass on the previous passes)
- (3) Toughness requirements
- (4) Propensity for weld-metal and HAZ cracking

Filler Metals

THE CONSIDERATIONS GOVERNING the choice of filler metals for welding HSLA steels are often very similar to those for welding structural carbon steels, except that it is necessary to use low-hydrogen welding practices with HSLA. The amount of hydrogen carried by the filler metal to the weld pool should be evaluated with reference to the carbon equivalent (CE) and composition parameter (P_{cm}) discussed earlier. Generally, a higher hydrogen potential suggests that a higher preheat value is required.

The lower-carbon HSLA steels, such as some API grades of linepipe steel (Table 1.12), may allow use of cellulosic electrodes (EXX10) with or without preheat, depending on the relevant CE or P_{cm} .

For normalized HSLA steels that have good notch toughness, additional consideration must be given to choose an arc welding electrode and procedure that will provide adequate levels of notch toughness in both the weld metal and the HAZ. For all of the commonly used arc welding processes, filler metals are available that can produce weld metal with various levels of notch toughness. In some cases, the weld metal composition can be similar to that of the steel. The specific welding procedures used (preheat, heat input, bead sequence, bead size, etc.) can have an effect on the notch toughness of both the weld metal and the HAZ. If notch toughness in these areas is of concern, a welding procedure should be developed, tested, and then rigorously followed during fabrication in order to assure

that satisfactory mechanical properties will be achieved in the welded joint.

Suggested electrodes for arc welding several HSLA steels for structural and pressure-vessel applications are given in Tables 1.15A, B, and C.

The electrodes shown in a particular table (A, B, or C) generally match the steels shown in that table with regard to composition and strength. Similar consumables are available for other welding processes. For ASTM A242 and A588 steels used in the bare, unpainted condition, welding electrodes should be specified that will provide weld metal with similar corrosion resistance and color match in the weathered condition. Welding filler metals are available to provide various weld-metal compositions for meeting those requirements. Table 1.16 suggests specific welding consumables for these steels that will provide suitable weld metal for such applications.

In the case of ASTM A353 steels, nickel or stainless-steel electrodes can be used when weld metal with good toughness at cryogenic temperatures is required. However, consideration must be given to the difference between the base metal and the austenitic stainless-steel weld metal with regard to thermal expansion characteristics. Also, the yield strength of the weld metal is likely to undermatch that of the base metal. The welded joint must be capable of withstanding the stresses developed at the weld interface if it is thermally cycled in service.

Low-alloy steel electrodes are available for electroslag and the electrogas welding of HSLA Steels. A flux is used in combination with an electrode in electroslag welding. The flux is classified on the basis of the mechanical properties of weld deposit made with a particular electrode. With both processes, the weld metal is required to have a tensile strength, as-welded, in the range of 70 to 90 ksi (482 to 620 MPa) and a minimum yield strength of 50 ksi (345 MPa).

When welding ASTM A242 or A588 for bare exposed service, the deposited weld metal is required to have a chemical composition similar to that obtained from one of the shielded metal arc welding electrodes listed in Table 1.16.

Postweld Heat Treatment

WELDMENTS IN STRUCTURES of HSLA steels are seldom postweld heat treated. However, a heat treatment may be required if the weldment must maintain dimensions during machining, if it is exposed to an environment that can cause stress-corrosion cracking, or if it requires softening to improve ductility. For proprietary steels, the recommendations of the producer should be followed. Some fabrication codes require that welded joints or the entire weldment be heat-treated for certain applications. Caution should be exercised when any heat treatment is planned on a quenched-and-

Table 1.15A
Recommended Base Metal-Filler Metal Combinations for Matching Electrode
Tensile Strengths Nominally of 70 ksi (483 MPa) Minimum

Steels						Matching Filler Metals				
Steel Specification ^{a,b}		Minimum Yield Point/Strength		Tensile Strength Range		Electrode Specification ^c	Minimum Yield Point/Strength		Tensile Strength Range	
		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa
ASTM A203	Grade A	37	255	65-85	448-586	Shielded Metal Arc Welding (See AWS A5.1 or A5.5) ^e				
	Grade B	40	276	70-90	483-620					
	Grade D	37	255	65-85	448-586	E7015, E7016, E7018, E7028	60	414	72 min.	496 min.
	Grade E	40	276	70-90	483-620					
ASTM A204	Grade A	37	255	65-85	448-586	E7015-X, E7016-X, E7018-X	57	390	70 min.	483 min.
	Grade B	40	276	70-90	483-620					
ASTM A242	—	42-50	290-345	63-70	435-483	E7010-X ^d	60	414	70 min.	483 min.
ASTM A441	—	40-50	275-345	60-70	415-483	Submerged Arc Welding (See AWS A5.17 or A5.23) ^e				
ASTM A572	Grade 42	42	290	60 min.	415 min.	F7XX-EXXX or F7XX-EXX-XX	58	400	70-95	483-660
	Grade 50	50	345	65 min.	450 min.					
ASTM A588	4 in. (102 mm) and under	50	345	70 min.	483 min.	Gas Metal Arc Welding (See AWS A5.18)				
ASTM A633	Grade A	42	290	63-83	430-570	ER70S-X	60	414	72 min.	496 min.
	Grades C and D 2.5 in. (64 mm) and under	50	345	70-90	483-620					
						Flux Cored Arc Welding (See AWS A5.20)				
ASTM A710	Grade A, Class 2, under 2 in. (51 mm)	55	380	65 min.	450 min.	E7XT-X (except -2, -3, -10, -GS)	60	414	72 min.	496 min.
API 2H	Grade 42	42	290	62-80	430-550					
	Grade 50	50	345	70 min.	483 min.					
API 5L	Grade X-52	52	360	66-72	455-495					
	Grade X-56	56	386	71-75	489-517					
	Grade X-60	60	414	75-78	517-537					

a. In joints involving base metals of different groups, low-hydrogen filler metal requirements applicable to lower strength group may be used. The low-hydrogen processes shall be subject to the technique requirements applicable to the higher strength group.

b. Match API Standard 2B (fabricated tubes) according to steel used.

c. When welds are to be stress-relieved, the deposited weld metal shall not exceed 0.05% vanadium.

d. Cellulose electrodes for field pipeline welding.

e. Deposited weld metal shall have a minimum impact strength of 20 ft•lb (27.1 J) at 0 °F (-18 °C) when Charpy V-notch specimens are required.

Table 1.15B
Recommended Base Metal-Filler Metal Combinations for Matching Electrode
Tensile Strengths Nominally of 80-90 ksi (552-620 MPa) Minimum

Steel Specification ^{a,b}		Steels				Matching Filler Metals				
		Minimum Yield Point/Strength		Tensile Strength Range		Electrode Specification ^c	Minimum Yield Point/Strength		Tensile Strength Range	
		ksi	MPa	ksi	MPa		ksi	MPa	ksi	MPa
ASTM A202	Grade A	45	310	75-95	517-655	<u>Shielded Metal Arc Welding (See AWS A5.5)^e</u>				
	Grade B	47	324	85-110	586-758					
ASTM A204	Grade C	43	296	75-95	517-655	E8015-X, E8016-X, E8018-X	67	460	80 min.	552 min.
ASTM A302	Grade A	45	310	75-95	517-655	E8010-G ^d	67	460	80 min.	552 min.
	Grade B	50	345	80-100	552-689	E9010-G ^d	70	483	90 min.	620 min.
	Grade C	50	345	80-100	552-689	<u>Submerged Arc Welding (See AWS A5.23)^e</u>				
	Grade D	50	345	80-100	552-689					
ASTM A572	Grade 60	60	414	75 min.	515 min.	F8XX-EXX-XX	68	470	80-100	552-690
	Grade 65	65	450	80 min.	552 min.	<u>Gas Metal Arc Welding (See AWS A5.28)^e</u>				
ASTM A633	Grade E	55-60	380-414	75-100	517-689	ER80S-X	68	470	80 min.	552 min.
ASTM A710	Grade A, Class 2, 2 in. (51 mm) and under	60-65	414-450	72 min.	495 min.	<u>Flux Cored Arc Welding (See AWS A5.29)^e</u>				
	Grade A, Class 3, above 2 in. (51 mm)	60-65	414-450	70 min.	483 min.					
ASTM A736		55-75	379-517	72-105	496-724	E8XTX-X	68	470	80-100	552-690
ASTM A737	Grade B	50	345	70-90	483-620					
	Grade C	60	414	80-100	552-689					
API 5L	X-65	65	450	77-80 min.	530-552					
	X-70	70	483	82 min.	565					

a. In joints involving base metals of different groups, low-hydrogen filler metal requirements applicable to lower strength group may be used. The low-hydrogen processes shall be subject to the technique requirements applicable to the higher strength group.

b. Match API Standard 2B (fabricated tubes) according to steel used.

c. When welds are to be stress-relieved, the deposited weld metal shall not exceed 0.05% vanadium.

d. Cellulose electrodes for field pipeline welding.

e. Deposited weld metal shall have a minimum impact strength of 20 ft•lb (27.1 J) at 0 °F (-18 °C) when Charpy V-notch specimens are required.

Table 1.15C
Recommended Base Metal-Filler Metal Combinations for Steels With
Tensile Strengths Nominally of 100 ksi (689 MPa) Minimum

Steel Specification ^{a,b}		Steels		Filler Metals	
		Minimum Yield Point/Strength		Tensile Strength Range	
		ksi	MPa	ksi	MPa
ASTM A225	Grade C	70	483	105-135	724-931
	Grade D	55-60	379-414	75-105	517-724
ASTM A710	Grade A, Class 1, 0.75 in. (19 mm) and under	80	552	90 min.	620 min.
	Grade A, Class 3, 2 in. (51 mm) and under	75	517	85 min.	586 min.
ASTM A735	—	65-80	448-552	80-115	552-793
API 5L ^e	X-80	80	552	90 min.	620 min.
ASTM A353 ^f	—	75	517	100-120	689-827
		Shielded Metal Arc Welding (See AWS A5.5) ^d E10015-X, 87 600 100 min. 690 min. E10016-X, E10018-X			
		Submerged Arc Welding (See AWS A5.23) ^d F10XX-EXX-XX 88 610 100-120 690-830			
		Gas Metal Arc Welding (See AWS A5.28) ^d ER100S-X 88-102 610-700 100 min. 690 min.			
		Flux Cored Arc Welding (See AWS A5.29) ^d E10TX-X 88 605 100-120 690-830			
		Shielded Metal Arc Welding (See AWS A5.11) ^g E310 60 414 80 550 ENiCrFe-2 45 310 80 550 ENiCrMo-3 60 414 110 760			
		Gas Metal Arc Welding (See AWS A5.14) ^g ERNiCr-3 40 276 80 550 ERNiCrFe-6 40 276 80 550			

a. In joints involving base metals of different groups, low-hydrogen filler metal requirements applicable to lower strength group may be used. The low-hydrogen processes shall be subject to the technique requirements applicable to the higher strength group.

b. Match API Standard 2B (fabricated tubes) according to steel used.

c. When welds are to be stress-relieved, the deposited weld metal shall not exceed 0.05% vanadium.

d. Deposited weld metal shall have a minimum impact strength of 20 ft•lb (27.1 J) at 0 °F (-18 °C) when Charpy V-notch specimens are required.

e. Undermatching cellulose electrodes may be used for root and cap passes for field pipeline welding.

f. Applicable electrodes for welding this steel are only the stainless steel and nickel-alloy electrodes (AWS A5.11 and A5.14) shown in lower right.

g. Yield strength may not match base metal properties.

Table 1.16
Suggested Welding Filler Metals for Exposed Applications of ASTM A242 and A588 Steels^a

Shielded Metal Arc Welding (AWS A5.5)	Submerged Arc Welding (AWS A5.23)	Gas Metal Arc Welding (AWS A5.28)	Flux Cored Arc Welding (AWS A5.29) ^c
E8016 or 18-G ^{b,c}	F7XX-EXXX-W ^{c,d}	ER80S-G ^c	E80T1-W
E8016 or 18-B1 ^c	—	ER80S-B2 ^{c,d}	E81T1-B1
E8016 or 18-B2 ^c	F7XX-EXXX-B2 ^{c,d}	ER70S-B2L ^{c,d}	E8XTX-B2
E7015 or 18-B2L ^c	—	—	E80T5-B2L
E8016 or 18-C1	F7XX-EXXX-Ni1 ^d	ER80S-Ni1 ^d	EXTX-Ni1
E8016 or 18-C2	F7XX-EXXX-Ni2 ^d	ER80S-Ni2 ^d	EXTX-Ni2
E8016 or 18-C3	F7XX-EXXX-Ni3 ^d	ER80S-Ni3 ^d	E80T5-Ni3
E7018-W2	F7XX-EXXX-Ni4 ^d	—	—
E8018-W2	—	—	—

a. See Table 3.3, Page 48, ANSI/AWS D1.1-96, *Structural Welding Code—Steel*.

b. Deposited weld metal shall have the following chemical composition percent: 0.12 C max, 0.50-1.30 Mn, 0.03 P max, 0.04 S max, 0.35-0.80 Si, 0.30-0.75 Cu, 0.40-0.80 Ni, 0.45-0.70 Cr.

c. Deposited weld metal shall have a minimum Charpy V-notch impact strength of 20 ft-lb (27.1 J) at 0 °F (-18 °C) for bridges.

d. The use of the same type of filler metal having next higher mechanical properties as listed in the AWS specifications is permitted.

tempered or quenched-and-aged steel. The postweld heat treatment temperature should never exceed the temperature used in the temper or aging process.

The evolution of low-carbon HSLA steels with relatively low HAZ hardness is well documented (API 5L X-60, X-65, X-70, and X-80). Cracking tendencies in

the HAZ of these steels have been dramatically reduced. The weld metal for joining these higher strength HSLA steels still must be considered prone to hydrogen cracking, however. Postweld hydrogen-release treatments are commonly used to prevent hydrogen buildup and subsequent cracking in higher-strength weld metal.

BRAZING HSLA STEELS

HIGH-STRENGTH LOW-ALLOY steels can be brazed with the same brazing filler metals, processes and procedures used for carbon steels. When selecting a brazing filler metal and a brazing process, the effects of the proposed brazing cycles on the mechanical properties of the steel must be considered. Exposure of a steel, especially a heat-treated steel, to a particular brazing cycle may alter its mechanical properties. In most cases, the brazing temperature should be below the lower transformation temperature of the steel.

THERMAL CUTTING HSLA STEELS

THERMAL CUTTING OF high-strength low-alloy steels can be performed using conventional oxyfuel gas, air-carbon arc, plasma arc, and other processes. The procedures are the same as those used for carbon steels, described previously. Preheating temperatures suggested for arc welding in Table 1.13 are recommended also for cutting operations to minimize cracking in the cut edge.

The cut surface should be clean and free of cracks for subsequent welding. Oxide or other residue on the surface should be removed mechanically, along with any cracks which may have formed during cutting.

QUENCHED AND TEMPERED STEELS

DESCRIPTION

QUENCHED AND TEMPERED steels are designed especially for welded construction and fabrication. They are furnished from steel producers in the heat-treated condition, with yield strengths ranging from 50 to 150 ksi (344 to 1034 MPa) depending on their chemical composition, thickness, and type of heat treatment. The heat treatment for most of these steels consists of austenitizing, quenching, and tempering. A few are given a precipitation-hardening (i.e., aging) treatment following hot rolling or some other thermal treatment.

Some quenched and tempered steels fall within the structural carbon-steel classification, some within the

low-alloy steel classification, and some within other alloy-steel classifications of the American Iron and Steel Institute (AISI). Welded structures fabricated from these steels generally do not need further heat treatment, except for a postweld heat treatment (i.e., stress relief) in special situations.

COMPOSITION AND PROPERTIES

QUENCHED AND TEMPERED steels can combine high yield and tensile strengths with good notch toughness, ductility, corrosion resistance, or weldability. The various steels in this group possess different combinations of these characteristics, depending on their

intended applications. The chemical compositions and strengths of typical quenched and tempered steels are given in Table 1.17. These steels are covered by ASTM specifications; however, a few steels such as HY-80, HY-100, and HY130, are covered by military specifications. The steels listed are used primarily as plate, although some of these and other similar steels are produced as forgings or castings.

ASTM A514 and A517 plate, and ASTM A592 forgings, are used in a wide range of applications requiring good notch toughness and moderate-to-high yield strength [about 100 ksi (689 MPa)]. Typical applications are earth-moving equipment, pressure vessels, bridges, steel mill and mining equipment, TV towers, fans, and ships.

ASTM A533 Grade B steel is used for nuclear pressure-vessel construction. At its highest strength level (Class 3), it may be used for thin-wall or multiple-layer pressure vessels. ASTM A537 Class 2 carbon steel is intended for use in pressure vessels where high notch toughness and a minimum yield strength of 60 ksi (414 MPa) are required.

ASTM A543 Type B, Classes 1 and 2 steel are modifications of HY-80 and HY-100 steels. These steels are intended for nuclear-reactor vessels and other applications requiring high yield strength and good toughness. HY-80 and HY-100 steels are used in construction of ships, submarines, and other marine equipment. HY130 steel is similar to the other two HY steels, but it has a higher yield strength and better toughness.

ASTM A553 steels contain 8 or 9% nickel. They are essentially quenched-and-tempered variations of ASTM A353, a high-strength low-alloy steel also containing 9% nickel. The welding considerations are the same for both types of steels regardless of heat treatment. Therefore, the information presented in the previous section for ASTM A353 high-strength low-alloy steel is applicable to A553 steel.

ASTM A678 quenched-and-tempered carbon steel is similar to ASTM A537 Class 2 steel, but it is intended for structural applications where good toughness and a yield strength of about 60 ksi (414 MPa) are required.

The carbon content of quenched and tempered steels generally does not exceed 0.22% for good weldability. The other alloying elements are carefully selected to provide the most economically heat-treated steel with the desired properties and acceptable weldability. Table 1.18 gives the heat treatment and the resulting microstructure for selected steels in Table 1.17. Austenitizing and tempering temperatures for other quenched and tempered steels may be obtained from the applicable specification or the producer.

METALLURGICAL CONSIDERATIONS

THE WAY IN WHICH quenched and tempered steels respond to heat treatment and welding depends upon their composition and thickness. In general, the steels are alloyed to favor the formation of tempered martensite and lower-bainite structures (see Table 1.18). Some of the metallurgical features of quenched and tempered steels are discussed below using ASTM A514 or A517 steels as an example. These ASTM steels are frequently specified for high-strength welded structures.

Isothermal Transformation

AN ISOTHERMAL TRANSFORMATION diagram for a typical ASTM A514 or A517 steel is shown in Figure 1.7. The transformation behavior of this steel has several significant features. One feature is the length of time that passes before transformation of austenite to pearlite begins in the temperature range of about 1100 to 1300 °F (593 to 704 °C). This long duration precludes forming of upper bainite, ferrite, and pearlite unless the cooling rate is very slow. Thus the presence of these microstructures, and their detrimental effect on strength and toughness, is avoided.

Other features of quenched and tempered steels are that a moderately long period of time elapses before transformation to ferrite, and that upper bainite starts in the temperature range of about 950 to 1100 °F (510 to 593 °C). These permit the quenching of plates up to at least 2 in. (51 mm) thick with little or no transformation in this temperature range. Transformation to ferrite and upper bainite is best avoided because the remaining austenite, enriched in carbon, may be retained or transformed to high-carbon martensite or bainite during cooling to room temperature. If considerable transformation occurs in the temperature range of 950 to 1100 °F (500 to 600 °C) as a result of slow cooling, then the final microstructure will consist of a heterogeneous mixture of ferrite, upper bainite, and retained austenite, together with high-carbon martensite or bainite. Such a combination of soft and hard microconstituents, even when tempered, will not have a high level of toughness.

If the steel is cooled at a relatively rapid rate, transformation to lower bainite occurs in a relatively short period at temperatures below 900 °F (480 °C). Such a microstructure is essentially homogeneous and has good toughness, particularly after tempering. Martensite begins to form at a relatively high temperature of 740 °F (400 °C). This characteristic is a significant factor in the ability of these steels to resist quench cracking. It is also an important consideration in welding because the cooling of martensite from such a relatively high temperature provides some degree of self-tempering.

Table 1.17
Typical Quenched and Tempered Steels

Common Designation or Class	Grade	Composition, % ^a										Minimum Tensile Strength		Minimum Yield Strength	
		C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Others	ksi	MPa	ksi	MPa
A514 or A517	A	0.15-0.21	0.80-1.10	0.035	0.04	0.40-0.80	0.50-0.80	—	0.18-0.28	—	Zr, 0.05-0.15; B, 0.0025	A514	100-130 689-896	A514	90-100 620-689
	B	0.12-0.21	0.70-1.00	0.035	0.04	0.20-0.35	0.40-0.65	—	0.15-0.25	—	V, 0.03-0.08; Ti, 0.01-0.03; B, 0.0005-0.005				
A533	C	0.10-0.20	1.10-1.50	0.035	0.04	0.15-0.30	—	—	0.20-0.30	—	B, 0.001-0.005	A517	105-135 723-930	A517	90-100 620-689
	D	0.13-0.20	0.40-0.70	0.035	0.04	0.20-0.35	0.85-1.20	—	0.15-0.25	0.20-0.40	Ti, 0.004-0.10 ^b ; B, 0.0015-0.005				
	E	0.12-0.20	0.40-0.70	0.035	0.04	0.20-0.35	1.40-2.00	—	0.40-0.60	0.20-0.40	Ti, 0.04-0.10 ^b ; B, 0.0015-0.005				
	F	0.10-0.20	0.60-1.00	0.035	0.04	0.15-0.35	0.40-0.65	0.70-1.00	0.40-0.60	0.15-0.50	V, 0.03-0.08; B, 0.0005-0.006				
	G	0.15-0.21	0.80-1.10	0.035	0.04	0.50-0.90	0.50-0.90	—	0.40-0.60	—	Zr, 0.05-0.15; B, 0.0025				
	H	0.12-0.21	0.95-1.30	0.035	0.04	0.20-0.35	0.40-0.65	0.30-0.70	0.20-0.30	—	V, 0.03-0.08; B, 0.0005-0.005				
	J	0.12-0.21	0.45-0.70	0.035	0.04	0.20-0.35	—	—	0.50-0.65	—	B, 0.001-0.005				
	K	0.10-0.20	1.10-1.50	0.035	0.04	0.15-0.30	—	—	0.45-0.55	—	B, 0.001-0.005				
	L	0.13-0.20	0.40-0.70	0.035	0.04	0.20-0.35	1.15-1.65	—	0.25-0.40	0.20-0.40	Ti, 0.04-0.10 ^b ; B, 0.0015-0.005				
	M	0.12-0.21	0.45-0.70	0.035	0.04	0.20-0.35	—	1.20-1.50	0.45-0.60	—	B, 0.001-0.005				
	N	0.15-0.21	0.80-1.10	0.035	0.04	0.40-0.90	0.50-0.80	—	0.25	—	Zr, 0.05-0.15; B, 0.0005-0.0025				
	P	0.12-0.21	0.45-0.70	0.035	0.04	0.20-0.35	0.85-1.20	1.20-1.50	0.45-0.60	—	B, 0.001-0.005				
	Q	0.14-0.21	0.95-1.30	0.035	0.04	0.15-0.35	1.00-1.50	1.20-1.50	0.40-0.60	—	V, 0.03-0.08				
A537	A	0.25	1.15-1.50	0.035	0.040	0.15-0.30	—	—	0.45-0.60	—	—	80-125	551-862	50-83	344-569
	B	0.25	1.15-1.50	0.035	0.040	0.15-0.30	—	0.40-0.70	0.45-0.60	—	—	80-125	551-862	50-83	344-569
	C	0.25	1.15-1.50	0.035	0.040	0.15-0.30	—	0.70-1.00	0.45-0.60	—	—	80-125	551-862	50-83	344-569
	D	0.25	1.15-1.50	0.035	0.040	0.15-0.30	—	0.20-0.40	0.45-0.60	—	—	80-125	551-862	50-83	344-569
A543	2	0.24	0.70-1.60	0.035	0.040	0.15-0.30	0.25	0.25	0.08	0.35	—	70-100	482-689	46-60	317-414
	B	0.23	0.40	0.020	0.020	0.20-0.40	1.50-2.00	2.60-4.00 ^c	0.45-0.60	—	V, 0.03	90-135	620-930	70-100	482-689
A553	1	0.13	0.90	0.035	0.035	0.15-0.40	1.20-1.50	2.25-3.50	0.45-0.60	—	V, 0.03	90-135	620-930	70-100	482-689
	2	0.13	0.90	0.035	0.035	0.15-0.40	—	8.50-9.50	—	—	—	100-120	690-825	85	585
A678	A	0.16	0.90-1.50	0.04	0.05	0.15-0.50	0.25	0.25	0.08	0.20 ^d	—	100-120	690-825	85	585
	B	0.20	0.70-1.60	0.04	0.05	0.15-0.50	0.25	0.25	0.08	0.20 ^d	—	70-90	482-620	50	344
	C	0.22	1.00-1.60	0.04	0.05	0.20-0.50	0.25	0.25	0.08	0.20 ^d	—	80-100	551-689	60	414
HY-80		0.12-0.18	0.10-0.40	0.025	0.025	0.15-0.35	1.00-1.80	2.00-3.25	0.20-0.60	0.25	V, 0.03; Ti, 0.02	85-115	586-792	65-75	448-517
HY-100		0.12-0.20	0.10-0.40	0.025	0.025	0.15-0.35	1.00-1.80	2.25-3.50	0.20-0.60	0.25	V, 0.03; Ti, 0.02	—	—	80	551
HY-130		0.12	0.60-0.90	0.010	0.015	0.15-0.35	0.40-0.70	4.75-5.25	0.30-0.65	—	V, 0.05-0.10	—	—	100	689
												—	—	130	896

a. When a single value is shown, it is a maximum limit.

c. Limiting values vary with the plate thickness.

b. Vanadium may be substituted for part or all of titanium content on a one-for-one basis.

d. When specified.